MODELING OF GROUNDWATER FLOW AND CONTAMINANT TRANPSORT IN A KARSTIC FORMATION USING FINITE DIFFERENCE APPROACH

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by

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ABSTRACT

Lebanon is considered naturally water rich compared to other countries in the Middle East and North Africa region owing to heavy rainfall and snowfall in winter season and the prevalence of Karstic geology. Though, overexploitation and mismanagement of water resources along with poor sanitation practices have led to water shortage and groundwater contamination. Consequently, there is a need to assess the groundwater flow and contaminant transport in Karstic aquifers in order to have a better understanding of groundwater movement through karst conduits until reaching a certain discharge or abstraction point. The focus in this study is on fast flow regimes or flow through karst conduits and fractures as it governs most groundwater movement in Karstic aquifers. This assessment will help in generating remediation measures promoting safe water practices.

In this study, a 2D experimental model, replicating karst conduits, was constructed and was used to assess the variation of hydraulic head throughout the prototype for different discharge nodes and pumping rates. Seven trials were conducted and hydraulic heads at different nodes were recorded. The prototype was also simulated on a finite difference software model, MODFLOW, with same dimensions and input parameters. The flow field generated in each trial was used to calculate hydraulic heads.

In addition, the variation of ammonia contaminant concentration and contaminant travel time throughout the system were studied. A dyed contaminated water was injected into the system and water samples were collected from four collection nodes. Four trials were conducted, each with different discharge rate, injection rate, initial head, and initial contaminant concentration. For each trial, contaminant concentration at collection nodes

were measured at two time periods using a spectrophotometer and medium range ammonia vials. Additionally, contaminant travel time to reach the collection nodes were recorded for three out of the four trials. The prototype was then simulated on MODFLOW, and the generated flow field in each trial was used along with MT3DMS and MODPATH packages to determine ammonia concentration variation and travel time, respectively.

Hydraulic head and contaminant concentration variation, as well as contaminant travel time generated experimentally were compared to simulated ones. Linear trend line and 95% confidence curves were produced for each experiment and outliers were identified. Results showed that experimental values largely reflect numerical ones despite several encountered human and instrumental errors.

Additionally, a regression model was generated to mathematically predict the contaminant concentration at any node throughout the prototype without the need to conduct experimental trials. A multiple linear regression equation, with six input variables, that best fits experimental data was generated. The precision of the regression model was validated by a strong coefficient of determination R^2. Also, the model was proven to be useful in predicting the assessed value through the F-test. This latter showed higher F-value compared to F-critical and a very low F-distribution meaning that the pattern identified between the set of data is significant.

The experimental and numerical models employed in this study along with the generated regression model can provide a powerful tool to predict the contaminant concentration at any location, knowing the contaminant source and discharge/abstraction point characteristics. This will help in identifying potential groundwater pollution and in designing safe water abstraction locations.

A case study was conducted in order to assess chemical contaminant transport, in karstic formation, towards a contaminated well. Samples were collected from well in Chadra village and were tested in the laboratory using ASTM standard methods. Testing results showed out of range nitrate concentration value (20.54 mg/L > 10 mg/L). The well was modelled with its surrounding on MODFLOW software. A parametric study was conducted by changing porosity, time period, and well abstraction rate variables in order to determine their effects on contaminant path towards the well. These latter were generated using MODPATH package and showed an inversely proportional relationship with porosity, whereas time period and well abstraction rate showed a proportional relationship with contaminant travel distance. Next step was to validate laboratory testing results. Therefore, the nitrate concentration at the well level was calculated using MT3DMS package and was equal to 25 mg/L. Consequently, nitrate-transport modelling reflected the actual field results to a large extent.

The evaluation of chemical contaminant transport towards a well is important to help developing groundwater management guidelines aiming towards preventing water contamination and reducing water usage. In this study, three wells in Chadra village were selected for testing and modeling. Physical, chemical, and bacteriological analysis were conducted on collected samples from each well to determine whether the well is contaminated or not. Then, the three wells were modeled with their surrounding using MODFLOW software and contaminant path lines were generated using MODPATH package. These path lines were used to generate protection measures related to safe well abstraction rate and safe setback distance from source to well. Accordingly, these measures were used to develop operational procedures related to pumping regime, sanitation system, and solid waste disposal. These procedures represent the water management guidelines that should be followed by community members and local authorities, along a transitional phase of 5 years, to ensure water safety.

CHAPTER 1

INTRODUCTION

1.1 Background and Needs

Lebanon has always stood among the water rich nations having relatively more water resources than its neighboring countries. Lebanon's geography favors moderate to high rates of precipitation (800mm of rainfall on average) with the large portion being infiltrated into aquifers and becoming groundwater. This is mainly since major aquifer in Lebanon are contained in Limestone rock formations, Karstic in nature. These latter landforms allow rainwater and snowmelt, the main source of groundwater recharge, to be rapidly absorbed into the subsurface feeding deep underground layers that contain numerous sinkholes. About 65% of Lebanon's surface is covered with carbonates karstic formations (Abi Rizk, J., 2011).

Although Lebanon geography, climate, and karstic geology would seem to provide adequate renewable water resources, the natural recharge rate of aquifers is estimated at around 500MCM/yr, whereas extraction rates are around 700MCM/yr (UNDP, 2014). Several factors make access to potable water difficult: overexploitation of groundwater, historically inadequate national and local governance, increased population, and mismanagement of water resources. A national study conducted in the 1960s and 70s mapped Lebanon's groundwater resources, showed areas where groundwater resources were decreasing and recommended ongoing studies and assessments to explore new sources and capitalize on existing ones. National and International conflict made it difficult to implement the recommendations leading in turn, to further depletion and contamination of the country’s potable water sources. This overexploitation of water resources forms a growing problem especially in Beirut, Tripoli, South Lebanon, and Bekaa (UNHCR, 2018).

Another aspect of the problem is the poor local and national governance. A study led by the UNDP showed that about 55000 to 60000 illegal wells are present in Lebanon, equivalent to 5.6 well per Km^2, almost three times higher than the number of licensed/legal wells (UNDP, 2014).

Syrian conflict, contributed to Lebanon’s groundwater access and management problems through the sudden influx of refugees fleeing to neighboring countries (LME, 2014). As of January 2018, approximately 25% of Lebanon’s population were Syrian refugees (UNHCR, 2018). This influx has resulted in depletion of water resources and increased use of illegal wells and poorly built pit latrines.

On the other hand, chemical contaminants are considered one of the common causes of well contamination (EPA, 2019). These contaminants can be derived from naturally occurring sources and human activities and have several human health impacts. For example, nitrate is present in chemical fertilizers, human sewage, animal waste, and natural sources and can contaminate private well through groundwater movement and surface water seepage. High level of nitrate in drinking water can cause methemoglobinemia or “blue baby syndrome” (EPA, 2019). These substances reduce the blood’s ability to carry oxygen and infants below six month who drink such water can become seriously ill and die.

Water scarcity and groundwater contamination mandate the assessment of groundwater flow in Karstic aquifer in order to tackle all uncertainties of groundwater flow through conduits until reaching the well. Such study will serve as a tool for the design of a newly constructed well and/or improve the performance of an existing well in a Karstic formation. Moreover, understanding groundwater flow will allow tracking of contaminant path lines through the aquifer. The study of contaminant movement can help in generating proactive and remediation measures to prevent groundwater pollution levels. Also, understanding and modeling of flow in karst aquifer will allow evaluation of the effect of hydrogeological and well characteristics on groundwater flow such as hydraulic conductivity, abstraction rate, time period, and so forth.

1.2 Problem Statement

Lebanon is excessively exploiting its aquifer absent any thought for the consequences. The increase use of illegal wells along with poor sanitation systems and solid waste dumpsites led to groundwater contamination from leachate of these latter. This has added to Lebanon's long-standing problems with groundwater contamination. It has also put a significant strain on Lebanon's water resources and contributed to health problems in remote communities. Therefore, abstraction rate regulation along with prevention of contaminants from reaching the groundwater is the best way to reduce health risks associated with poor drinking water quality. This can be done with a better understanding of groundwater flow and contaminant transport through karstic formation.

1.3 Objective

Many studies (Ahmed 2005; Akiki, T., 2018; Bradford, S., 2005; Bronson, K., 2009; Burton, M., 2007; Dhaka. S., 2016; Dwivedi, D., 2012; Harvey, R., 1991; Hijnen, W., 2006; Huang, L., 2018; Patil, 2013; Gehlar, L., 1992; Gurunadha. R., 1999; Mohrlok, C., 2010; Tufenkji. N., 2006; Wang, P., 2000; Zheng, C., 1999; Zheng, C., 1999) have focused on the assessment of the contaminant flow in porous (sand and gravel) aquifers through the evaluation of fate and transport of chemical and/or bacteriological contaminant in those aquifers using different finite element and/or difference approach. Other studies (Barenblatt, G., 1960; Faulkner, B., 2009; Hill, M., 2008; Gallegos, J., 2013; Karay. G., 2015; Karay. G., 2016; Kuniansky, 2016; Öllős. G., 1960; Reiman, T., 2013; Reiman, T., 2011; Reiman, T., 2009; Saller, S., 2013; Sen, Z., 1995; Sen, Z., 1988; Streltsova, T., 1976; Zogheib, J., 2019) focused on simulating groundwater flow in fractured rocks and karstic aquifers through physical and/or numerical modeling.

The aim of this study is to better understand groundwater flow and contaminant transport in a Karstic formation. For this purpose, a laboratory and numerical model will be generated to simulate water flow and contaminant movement through Karstic conduits. Hydraulic head, contaminant path lines, and concentration variation will be determined experimentally and will be compared to the data generated in the numerical model. Additionally, a regression model will be generated to mathematically predict the contaminant concentration throughout the studied prototype. Further, a case study will be conducted to assess the effect of hydrogeological and well characteristics on groundwater flow and to compare water chemical test results to numerical simulation. Moreover, the assessment of groundwater flow and contaminant movement will be driven forward to develop a water management program aiming to prevent contaminant from reaching certain contaminated well. Protection measures will be generated based on safe abstraction rate and safe setback distance between source of contamination and the well. These protection measures will be used to develop operational procedures tackling pumping regime, sanitation system, and solid waste disposal.

1.4 Format of this Dissertation

Following the introduction presented in Chapter 1, Chapter 2 entitled "*Assessment of Groundwater Flow and Contaminant Transport in a Karstic Formation in Lebanon*" addresses hydraulic head variation and contaminant path lines through karstic conduits. A 2D experimental model was constructed at NDU laboratory replicating karstic conduits. This prototype was used to examine hydraulic head variation for different pumping rates and discharge nodes. Results were compared to numerical ones generated using MODFLOW software. The study also shows the possibility of generating contaminant path lines using MODPATH package. This paper was accepted for presentation at *IWA World Water Congress & Exhibition 2020.*

Chapter 3 entitled "*Tracking of Chemical Contaminant Transport and Concentration Variation through Karstic Formation Using Finite Difference Approach*" presents the core of the study of groundwater movement and contaminant transport through a karstic aquifer. First, experimental hydraulic heads were recorded using vertical piezometers installed at specific nodes throughout the system. Seven trials were tested with different, pumping rate, discharge node, and initial hydraulic head. In order to study contaminant movement, a dyed contaminated water was injected in the system using a submersible pump and samples were collected from specific nodes in order to measure concentration variation in the system. Four trials were tested with different initial contaminant concentration, injection rate, and discharge rate. Additionally, the time required for contaminants to reach the nodes was recorded for each trial. Subsequently, experimental hydraulic heads, contaminant concentration and travel time were compared to numerical results generated using MODFLOW, MT3DMS, MODPATH packages, respectively. Additionally, a statistical analysis was conducted to identify outliers for each experiment. The three approaches showed coherent results despite several recognized errors. Further, a regression analysis was conducted to examine the relationship between experimental input data and the contaminant concentration throughout the prototype. The analysis results in a useful multiple linear regression equation that predicts the contaminant concentration at any node in the system – *Journal paper currently under review*

Chapter 4 entitled "*Using Finite Difference Approach to Model Nitrate Contaminant Transport to a Contaminated Well*" presents a case study of chemical contaminant tracking through karstic aquifer. Samples were collected from a contaminated well in Chadra town. Physical and chemical analysis were conducted on the collected samples. Moreover, nitrate contaminant movement from critical sources of contamination (nearest sources surrounding the well) into the contaminated well was studied. Findings showed that software model results matched chemical testing outcomes to a great extent. Additionally, the paper addressed the effect of three hydrogeological and well characteristics on contaminant path lines. This paper was accepted for presentation at the *2019 Fourth International Conference on Advances in Computational Tools for Engineering Applications (ACTEA)*

Chapter 5 entitled "*Evaluation of Contaminant Transport to Assess and Manage Groundwater Resources Quality in Akkar Region, Lebanon*" focuses on evaluating chemical contaminant transport towards a contaminated well in order to develop groundwater quality management procedures to access safe water. Three wells in Chadra town were modeled with their surroundings and contaminant path lines were produced using MODPATH package. These path lines were used to generate protection measures related to safe well abstraction rate and safe setback distance from source to well, for a specific design period. Based on these measures, a water management program was defined to prevent water contamination and reduce water usage. The program was presented as operational procedures tackling pumping performance, sanitation system practices, and solid waste disposal. This paper is part of a USAID funded project entitled "*Development of a Sustainable Groundwater Quality Management Program for Accessing Safe Water in Lebanon*" under Lebanon Water Project (LWP) | DAI Global LLC.

In Chapter 6, summary of this dissertation and recommendations for future research are presented.

CHAPTER 2

ASSESSMENT OF GROUNDWATER FLOW AND CONTAMINANT TRANSPORT IN A KARSTIC FORMATION IN LEBANON

2.1 Introduction

About half of Lebanon's water supply is groundwater drawn from major aquifers contained in Karstic limestone rock formations (UNDP, 2014) covering about 65% of Lebanon's surface (Abi Rizk J., 2011). These formations allow rainwater and snowmelt, the main sources of groundwater recharge to be rapidly absorbed into the subsurface feeding deep underground layers. Although Lebanon is known for its relatively abundant water resources, several factors make access to potable water difficult: overexploitation of groundwater, historically inadequate national and local governance, increased population, and mismanagement of water resources. Consequently, water scarcity and groundwater contamination mandate the assessment of groundwater flow in Karstic aquifers in order to assess its path through fractured rocks and conduits.

2.2 Hydraulic head

A 2D prototype was constructed to simulate a confined karstic aquifer system using a 300 x 180 cm orthogonal grid with pipes 60 cm long and 0.8 cm in diameter inside a high-level tank. Piezometer outlets were installed at each node to measure hydraulic heads (Figures 2.1and 2.2).

Different discharge nodes with specific discharge rates were tested. Hydraulic heads were measured at each node.

Figure 2.1: Experimental Model - NDU Laboratory

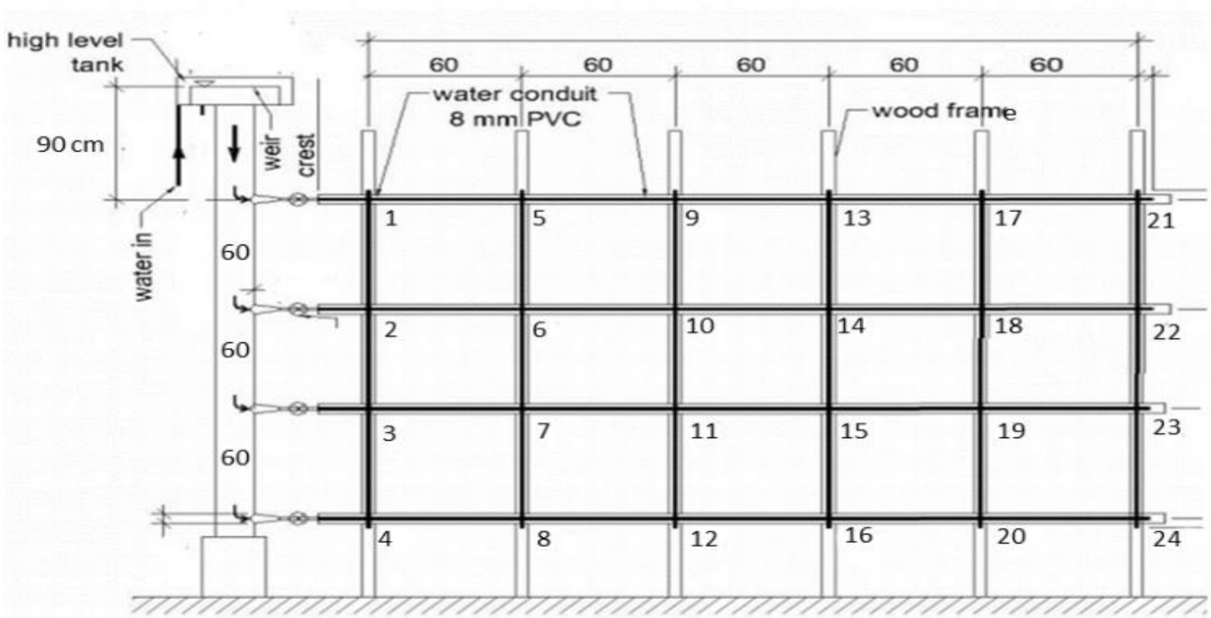

Figure 2.2: Model Schematic

The prototype was modelled on MODFLOW-2005 software. The same discharge rate and initial hydraulic head were used for each discharge node trial. Border layers of the model were set as no-flow boundaries. The simulated hydraulic head of each discharge point (Figure 2.3) was compared to the experimental hydraulic head and the error calculated (Table 2.1).

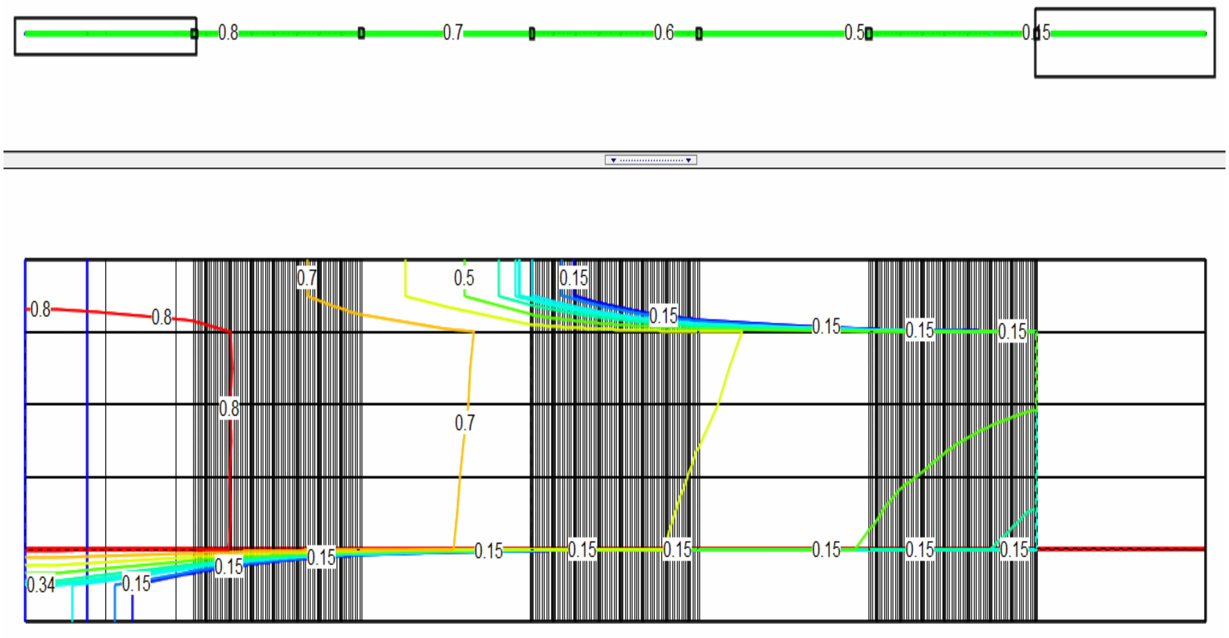

Figure 2.3: MODFLOW 2005 – Discharge Node 24: Variation of Hydraulic Head

Node #	Pumping Rate (m3/min)	Experimental Value (m)	Numerical Value (m)	Error (%)
24	0.00308	0.125	0.15	20
22	0.002625	0.2	0.32	60
21	0.0019	-0.34	-0.3	11.76
19	0.00296	-0.34	-0.32	5.88
12	0.0036	-0.43	-0.5	16.28
11	0.0035	-0.275	-0.5	81.82
1	0.0013	0.15	0.2	33.33

Table 2.1 Experimental and Numerical Head results for Each Discharge Node

Figure 2.4 shows the weighted simulated data versus the weighted observed data. The linear trend of the data from the numerical model (slope = 1) indicates simulated and observed values are close. The numerical and experimental models showed similar results for the hydraulic heads.

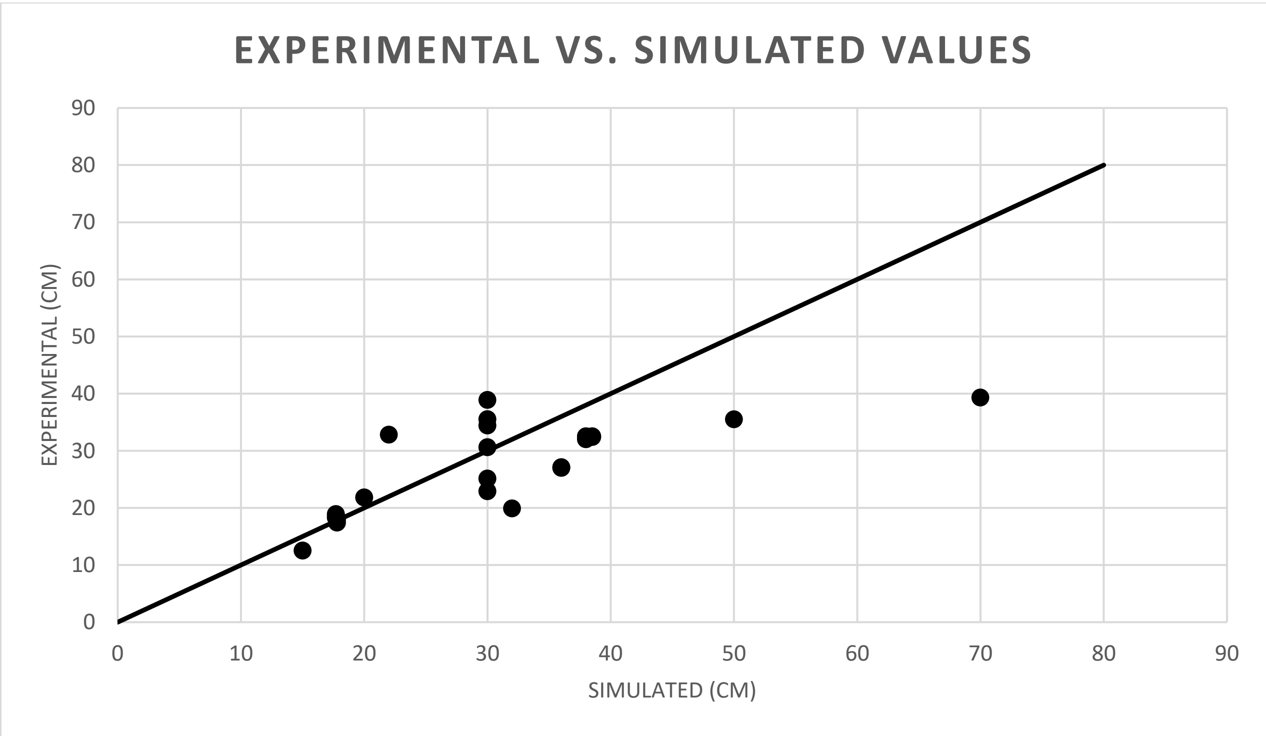

Figure 2.4: Weighted Observed versus Weighted Simulated Head Results

The difference between the hydraulic heads of the laboratory and numerical models can be explained by measurement errors where the water left the over pressured zone. Also, an additional factor that might have contributed to the error is the inaccuracy of water discharge rate measurement.

2.3 Contaminant Path lines

The study also looked at nitrate contaminant transport in karstic formations since nitrates are the result of local on-site sanitation systems and agricultural practices (Argoss, 2001). Dyed contaminated water was injected at a certain injection and discharge rate to determine the contaminant path recorded at specific time period. Figure 2.5 shows the dyed contaminated water reached the red line after 10 seconds. Injected water travelled in the 2nd layer, surpassing the 3rd column grid by 20 cm, towards the discharge node marked with a red circle. The injection rate was $3.14*10^{-5}$ m^3/s, the discharge rate was $2.77*10^{-5}$ m^3/s.

Figure 2.5: Experimental Contaminant Path – IN BLUE

The MODPATH package was used for numeric modelling with the generated flow field from MODFLOW as an input parameter (Pollock D.W., 2012) thereby generating contaminant path lines for the same injection and discharge rates and time interval. Figure 2.6 shows

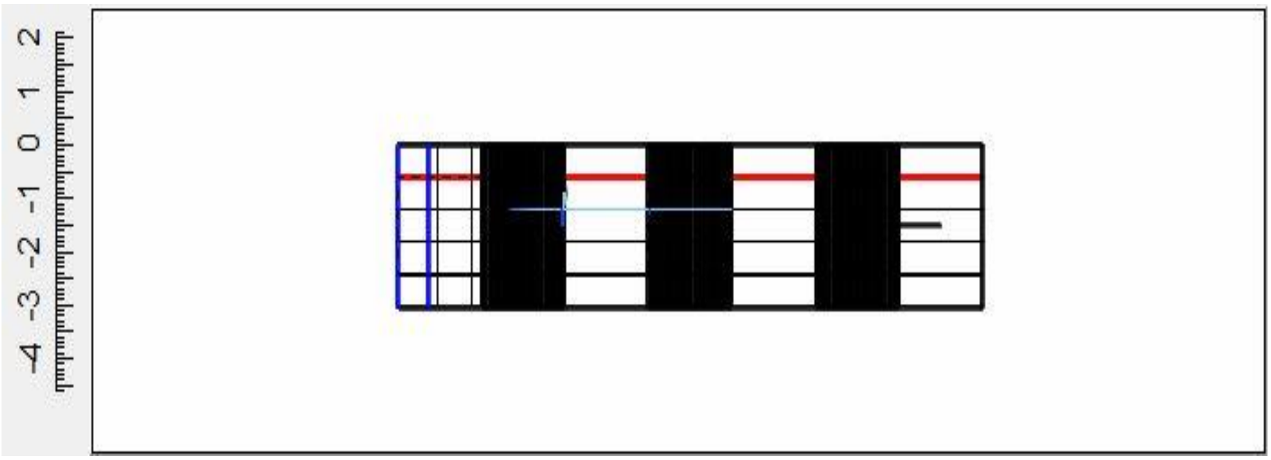

Figure 2.6: Numerical Contaminant Path – IN LIGHT BLUE

contaminated water travelling in the 2nd layer reaching the end of 3rd column grid. Similar behavior was obtained in the numerical and experimental paths with minor differences resulting from inaccurate injection and discharge rate measurement.

2.4 CONCLUSION

This study can serve as a tool to characterize aquifers with Karstic formations. Model results can be used to design new wells or enhance the performance on existing wells. Modelling a karstic aquifer can also help track groundwater contaminant movement. Ongoing studies are being conducted by our research team using the MT3DMS package (Zeng, C., 1999) to determine the variation of contaminant concentration through a karstic aquifer for the same prototype. This study can be used in groundwater resource management to develop remediation measures for existing groundwater pollution and prevent further pollution.

CHAPTER 3

TRACKING OF CHEMICAL CONTAMINANT TRANSPORT AND CONCENTRATION VARIATION THROUGH KARSTIC FORMATION USING FINITE DIFFERENCE APPROACH

3.1 Introduction

About half of Lebanon's water supply is sourced from groundwater, where the major aquifer in Lebanon are contained in Limestone rock formations, Karstic in nature. These latter landforms allow rainwater and snowmelt, the main source of groundwater recharge, to be rapidly absorbed into the subsurface feeding deep underground layers that contain numerous sinkholes. About 65% of Lebanon's surface is covered with carbonates karstic formations.

Although Lebanon is known by its relatively abundant water resources (800mm of rainfall on average), the importance of snow, and the prevalence of a karstic geology, the natural recharge rate of aquifers is estimated at around 500MCM/yr, whereas extraction rates are around 700MCM/yr (UNDP, 2014). Several factors make access to potable water difficult: overexploitation of groundwater, historically inadequate national and local governance, increased population, and mismanagement of water resources. A national study conducted in the 1960s and 70s mapped Lebanon's groundwater resources, showed areas where groundwater resources were decreasing and recommended ongoing studies and assessments to explore new sources and capitalize on existing ones. National and International conflict made it difficult to implement the recommendations leading in turn, to further depletion and contamination of the country's potable water sources. This overexploitation of water resources forms a growing problem especially in Beirut, Tripoli, South Lebanon, and Bekaa (UNHCR, 2018).

Another aspect of the problem is the poor local and national governance. A study led by the UNDP showed that about 55000 to 60000 illegal wells are present in Lebanon, equivalent to 5.6 well per Km^2, almost three times higher than the number of licensed/legal wells (UNDP, 2014). Lebanon is excessively exploiting its aquifer absent any thought for the consequences. Also, this increase use of illegal wells along with poor sanitation systems and solid waste dumpsites led to groundwater contamination from leachate of these latter.

Consequently, water scarcity and groundwater contamination mandate the assessment of groundwater flow in Karstic aquifer in order to tackle all uncertainties of groundwater flow through conduits until reaching the well. Such study will serve as a tool for the design of a newly constructed well and/or improve the performance of an existing well in a Karstic formation. Moreover, understanding groundwater flow will allow tracking of contaminant path lines through the aquifer. The study of contaminant movement can help in generating proactive and remediation measures to prevent groundwater pollution levels.

Additionally, understanding and modeling of flow in karst aquifer will allow evaluation of the effect of hydrogeological and well characteristics on groundwater flow such as hydraulic conductivity, abstraction rate, time period, and so forth.

Many studies (Ahmed 2005; Akiki, T., 2018; Bradford, S., 2005; Bronson, K., 2009; Burton, M., 2007; Dhaka. S., 2016; Dwivedi, D., 2012; Harvey, R., 1991; Hijnen, W., 2006; Huang, L., 2018; Patil, 2013; Gehlar, L., 1992; Gurunadha. R., 1999; Mohrlok, C., 2010; Tufenkji.

N., 2006; Wang, P., 2000; Zheng, C., 1999; Zheng, C., 1999) have focused on the assessment of the contaminant flow in porous (sand and gravel) aquifers through the evaluation of fate and transport of chemical and/or bacteriological contaminant in those aquifers using different finite element and/or difference approach. Other studies (Barenblatt, G., 1960; Faulkner, B., 2009; Hill, M., 2008; Gallegos, J., 2013; Karay. G., 2015; Karay. G., 2016; Kuniansky, 2016; Öllős. G., 1960; Reiman, T., 2013; Reiman, T., 2011; Reiman, T., 2009; Saller, S., 2013; Sen, Z., 1995; Sen, Z., 1988; Streltsova, T., 1976; Zogheib, J., 2019) focused on simulating groundwater flow in fractured rocks and karstic aquifers through physical and/or numerical modeling.

The aim of this study is to better understand groundwater flow and contaminant transport in a Karstic formation. For this purpose, a laboratory and numerical model will be generated to simulate water flow and contaminant movement through Karstic conduits. Contaminant path lines and concentration variation will be determined experimentally and will be compared to the data generated in the numerical model.

3.2 Hypothesis

A finite difference approach can be used to simulate groundwater flow characteristics and contaminant movement in a karstified formation.

3.3 Materials and Methods

3.3.1 Experimental Model Construction

Along with the pores which can be observed among the particles of porous media and in the intact fractured rocks, more discontinuities as fractures, voids, and karst conduits can exists in fractured rocks. Barenblatt et al. introduced the double porosity theory which defines these additional discontinuities as secondary porosity next to the matrix-primary porosity. The flow in the primary porosity is slow, the hydraulic conductivity is low and storativity is quite high; whereas in secondary porosity the water flow might be fast and non-laminar, the hydraulic conductivity is significant higher but the storativity is lower than in matrix porosity (Barenblatt, 1960).

In this study the flow through secondary porosity will be investigated. The flow through matrix porosity and the exchange between the two flows systems will be neglected as the flow in Karstic rock is dominated by conduits.

The prototype that will be built is a vertical 2D model, mounted on a wood frame, as shown in Figure 3.1. An orthogonal grid will be constructed using 60 cm length pipes with $300 \times 180\ cm$ overall size. The diameter of the conduits is $0.8\ cm$. A confined aquifer system will be achieved with a high-level tank. The highest water level in the tank will be above the highest conduit by 90 cm. The water from the high-level tank will flow in a tube that will divide the water among the 4 horizontal conduits. Faucets will be used to control the flow. The model details and dimensions are shown in the schematic in Fig 3.2.

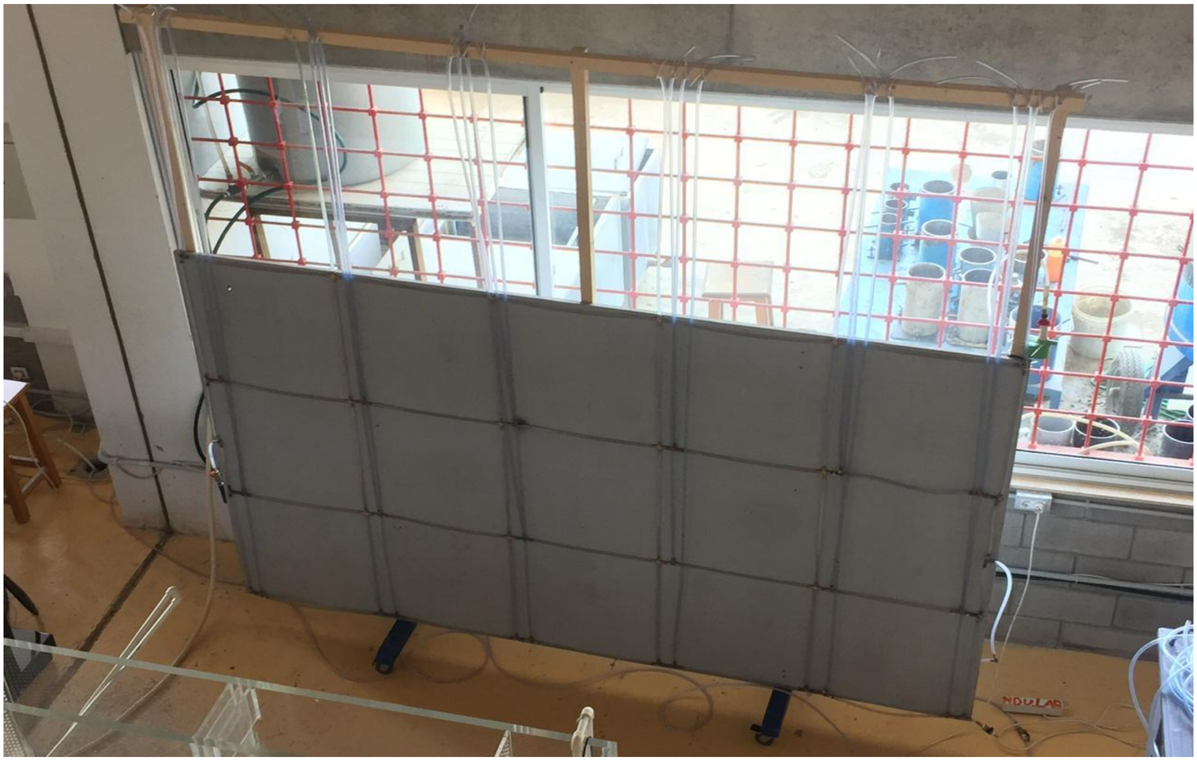

Figure 3.1 Experimental Model at NDU Lab

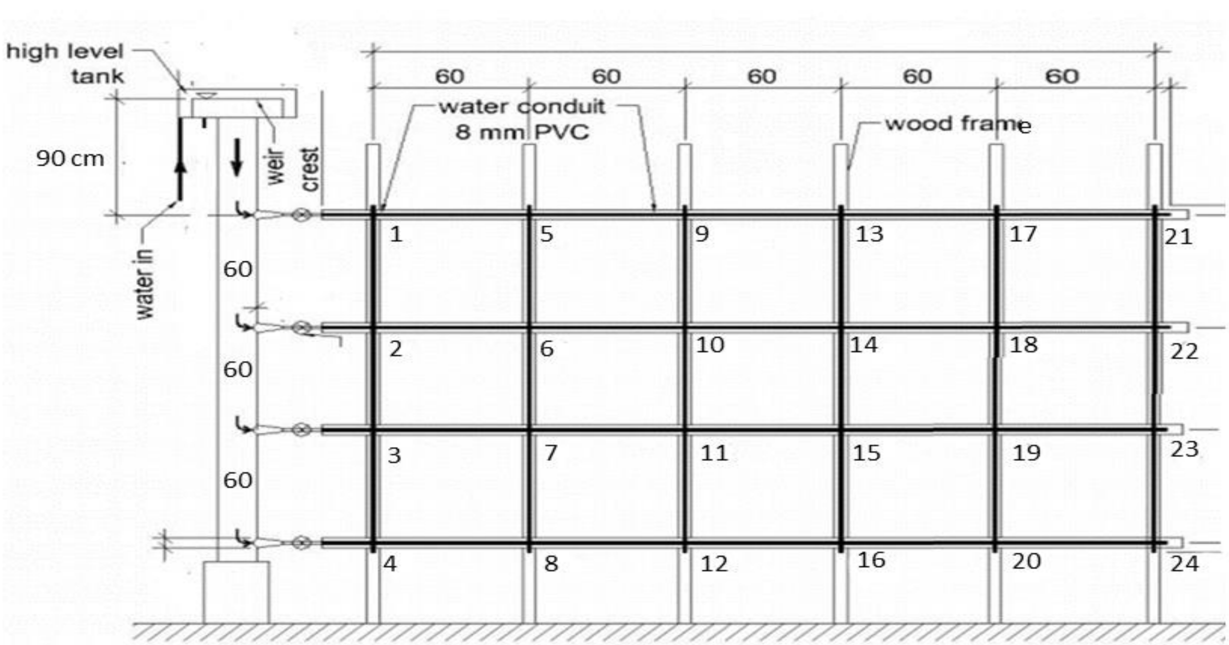

Figure 3.2 Model Schematic and Dimensions

3.3.2 Groundwater Flow Characteristics

Experimental Procedures

Several trials will be performed on different discharge point/nodes. Piezometer-outlets will be installed at each node in order to determine the hydraulic heads. The steps that will be followed for each discharge scenario in order to determine the hydraulic head are as follows:

1- Specify a discharge point/node and run the prototype.
2- Record the initial hydraulic head and Temperature.
3- Collect the water from the discharge point for a known period time in order to calculate the discharge rate.
4- Record final hydraulic head, at the end of the discharge, and calculate the hydraulic head difference.
5- Record hydraulic head at the discharge point/node and all other nodes.

System porosity will be determined by dividing the area of voids (pipes) to the total area of the model/aquifer.

Numerical Model

MODFLOW is a U.S. Geological Survey modular finite-difference flow model that simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. The flow field generated in MODFLOW is used to trace particle path lines using MODPATH and simulate advection, dispersion and chemical reactions of dissolved constituents in groundwater systems using MT3DMS. All three models use ModelMuse as the graphical user interface in order to create input files.

Many groundwater models are developed based on the assumption that Darcy's law governs groundwater flow. In karstic aquifers, turbulent flow is dominant, and when turbulent flow is present, Darcy's law is inapplicable. MODFLOW is a program able to model both, Darcian and Non-Darcian flow within karst aquifers. Flow to wells, areal recharge, evapotranspiration and flow through rivers can be simulated with MODFLOW.

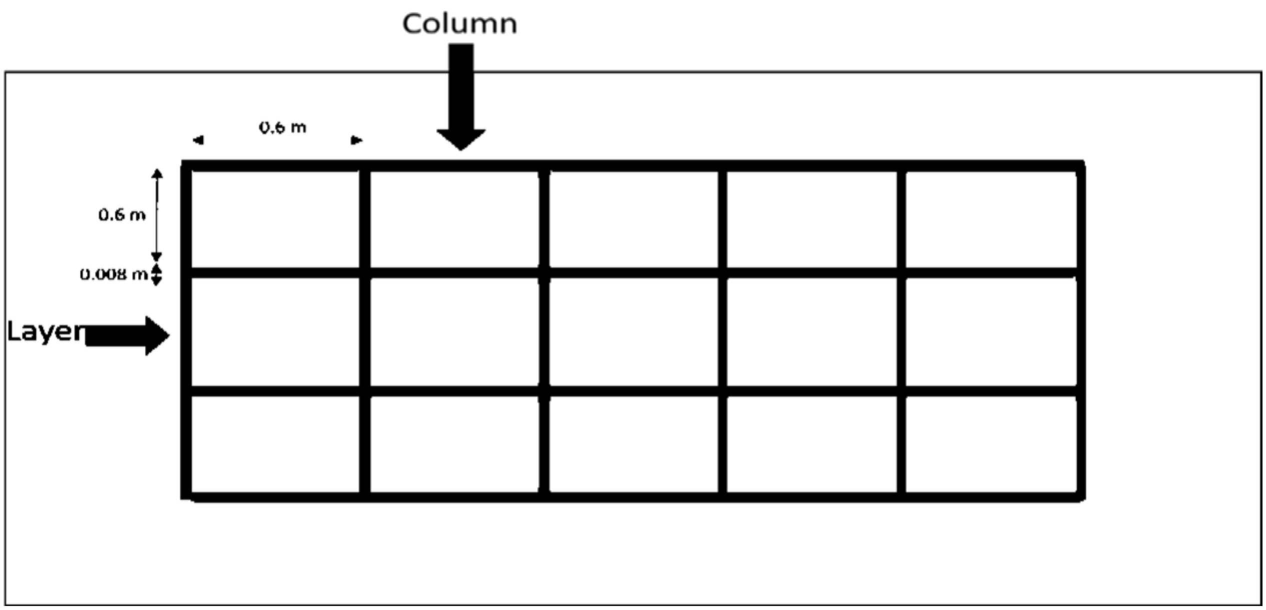

Figure 3.3 Detailed Dimensions - MODFLOW Software

In this study, the prototype system will be built with MODFLOW software. The model will consist on inserting high conductivity flow layers that can switch between laminar and turbulent flow which will be used to duplicate the experimental model.

The prototype consists of 1 row, 5 columns, and 3 layers, whereas the numerical model will be modelled as a 1 row, 7 columns, and 7 layers system. Each layer will have a thickness of

0.6 m, and columns will be also spaced by 0.6 m. Pipe networks (conduits) will be designed as an extra layer of a 0.008m thickness with high conductivity. To sum up, the 7 layers will be distributed as follows: 3 layers of a 0.6 m thickness interstratified with 4 layers of 0.008 m thickness (Figure 3.3). Left and right sides of the analog will beset as no-flow boundaries. The water reservoir will be assumed to have a constant head and will be defined as a boundary all over the layers with a value of 0.9 m.

In order to validate lab results, the prototype will be modeled on MODFLOW with the same discharge rate used in the experiment for each discharge point trial. Subsequently, the simulated hydraulic head of each discharge point, obtained from the software, will be compared to the experimental hydraulic head, and error between both values will be calculated for comparison. As for hydraulic conductivity, several iterations will be performed in order to obtain the value that matches experimental condition.

3.3.3 Contaminant Movement Evaluation

Experimental Procedure

The decision was made to study nitrate contaminant transport in a karstic formation as it represents a chemical contaminant of principal importance that is derived from on-site sanitation systems and agricultural practices (Argoss, 2001). **Though, due to COVID-19 pandemic and corresponding shutdown, laboratory tests were restricted to ammonia compound and additional trials on nitrate were not possible.**

For a certain discharge rate, a dyed contaminated water will be injected, at a certain injection rate, in the experimental model. The time required by the contaminants to reach specific collection points will be recorded. Subsequently, samples will be collected from the collection points at a specific time period. Figure 3.4 shows the injection point along with the 4 collection nodes.

Collected samples concentration along with initial solution will be determined using spectrophotometer and salicylate method for medium range test vials.

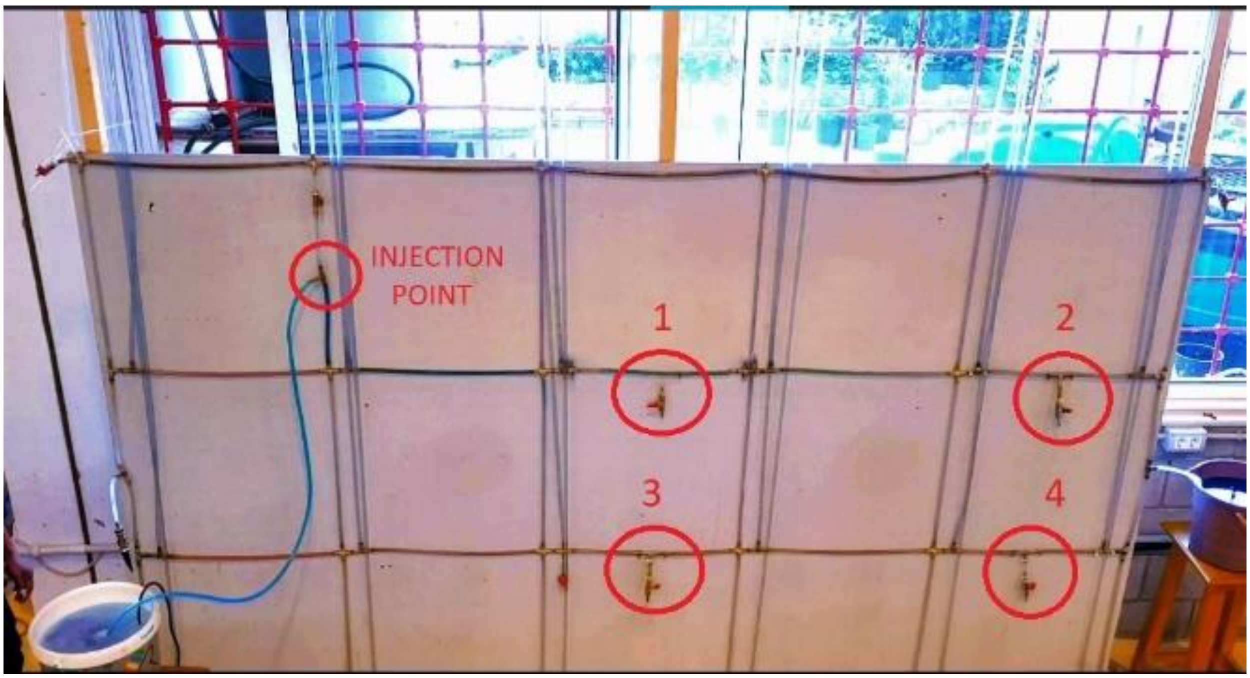

Figure 3.4: Experimental Model – Contaminant movement

The steps that will be followed for each scenario are as follows:

1- Specify a discharge and injection node
2- Record the initial hydraulic head and Temperature.
3- Prepare a dyed contaminated solution and measure its initial concentration using a spectrophotometer.
4- Run the prototype.
5- Record the travel time of dyed contaminated water to reach each collection node.

6- Collect water samples from the collection nodes at specific time period
7- At the end of the experiment, collect water from the discharge point for a known time period in order to calculate the discharge rate.
8- Record the drop in the injection barrel for a specific time period to calculate the injection rate
9- Determine collected samples concentration using the spectrophotometer.

This process will be repeated for different discharge rates, injection rates, and contaminant concentration. The difference between simulated and experimental time will be calculated for comparison and validation.

Numerical Model

MODPATH is a particle-tracking post-processing program also designed by U.S. geological Survey (USGS). Output from steady-state or transient MODFLOW simulations is used in MODPATH to compute paths for imaginary “particles” of water moving through the simulated groundwater system. In addition to computing particles paths, MODPATH computes the times of travel for particles moving through the system.

The Pollock method is implemented in the MODPATH algorithm (Pollock, 2012), which have been officially released as the particle tracking method for MODFLOW. The Pollock Method was first published in 1988 for semi-analytical particle tracking on rectilinear structured grids. The key assumption of the method is that each directional velocity components varies linearly within grid cell in its own coordinate system, which allows an analytical expression to be obtained describing the flow path within an individual grid cell (Pollock, 2012). Given the initial position of the particle as well as the cell geometry and the flows in through the cell faces, the particle coordinate along its path lines within the cell and its travel time can be computed directly without numerical integration. An important application of this method includes tracing particle path lines through any multidimensional flow field that is generated from a block-centered finite-difference groundwater flow model, such as MODFLOW.

MODPATH is currently the fastest particle tracking algorithm available for finite-difference simulations. However, a disadvantage of MODPATH includes its restriction regarding rectilinear structured grids. In 2015, a new extension of MODPATH was developed to handle rectangular unstructured grids (Pollock, 2015). The new extension can sufficiently handle rectangular-based structured grids as well as rectangular-based unstructured grids such as nested grids and quad-based grids.

MT3DMS (Modular Transport, 3-Dimensional, Multi-Species model) is a modular three-dimensional transport model for the simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems (Zheng, 1990). MT3DMS uses a modular structure like the structure utilized by MODFLOW. MT3DMS is used in conjunction with MODFLOW in a two-step flow and transport simulation. In this study, MODFLOW numerical model output will be used along with MODPATH and MT3DMS packages in order to determine the time required by contaminant path lines to reach a certain node and the concentration variation throughout the system. Several collection nodes will be used to collect samples from the system throughout the experiment. Samples will be tested, and contaminant concentration will be determined and compared to numerical ones.

3.4 Results and Discussions

3.4.1 Groundwater Flow Characteristics Results

Experimental Results

Several discharge nodes were studied, and for each node, all hydraulic heads and flow were measured and calculated, respectively. In order to find the discharge rate, a known water volume was collected for a specific time period from the discharge point/node. **Discharge from node 24 will be discussed in detail in the following section.**

During this experiment water temperature was equal 15 degrees Celsius. The initial head before starting the discharge was recorded as 81.5 cm and the head at the end of the discharge was 79 cm. The hydraulic head difference was equal to 2.5 cm. The discharge rate was calculated to be 3080 cm^3/min. Based on these parameters, hydraulic heads were measured and are shown in table 3.1.

Table 3.1 Experimental Results – Discharge at node 24

Node Number	Hydraulic Head (cm)	Node Number	Hydraulic Head (cm)
1	46.5	13	37
2	42.7	14	35.5
3	42.3	15	35.1
4	44	16	32.8
5	41.5	17	32.2
6	39.3	18	28.5
7	38.1	19	27.5
8	38.9	20	15.7
9	38.9	21	26.4
10	38.5	22	25.1
11	37.2	23	21.4
12	37.9	24	12.5

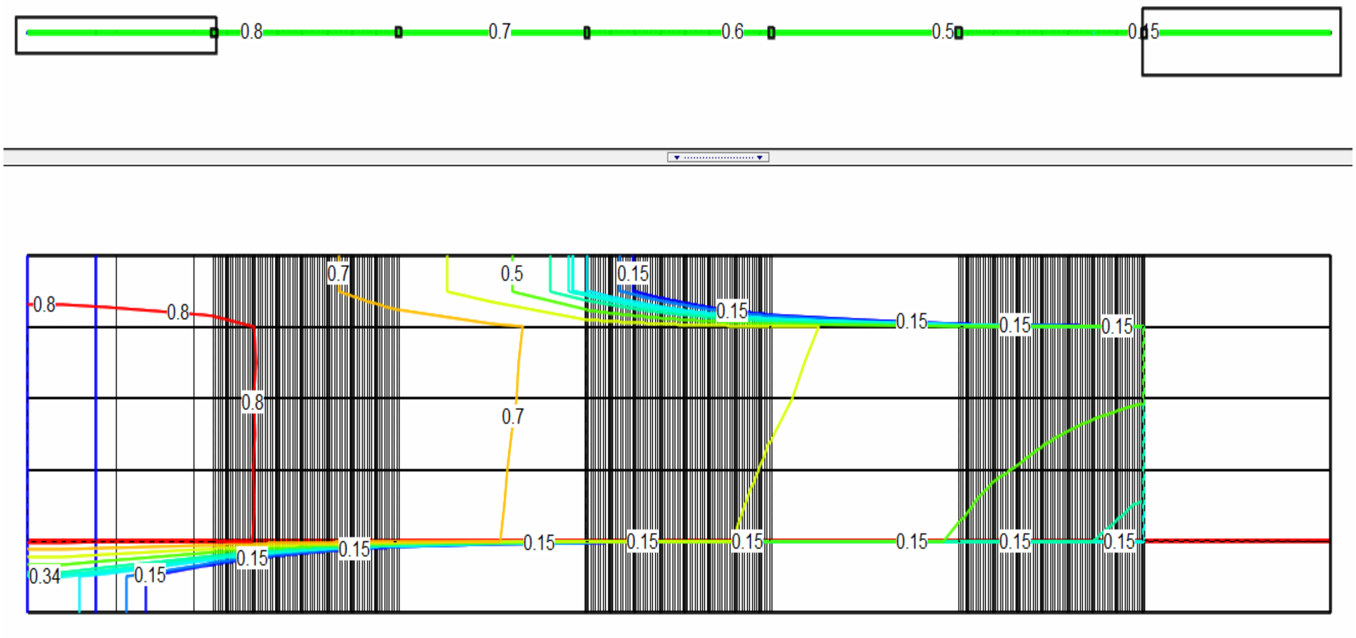

Figure 3.5: MODFLOW – Hydraulic head variation - Discharge at node 24

Numerical Model Results

First, several trials were performed in order to match same hydraulic conductivity of conduits in the experimental model. The hydraulic conductivity K was initial taken as 400 m/s. After many simulations, it was found that the most accurate hydraulic conductivity to be used is within the range 200 m/s and was used for numerical modeling.

The prototype was modeled with an initial hydraulic head of 0.815 m and a discharge rate of 3080 cm^3/min at discharge node 24. The hydraulic head distribution obtained in the software is shown in Figure 3.5. The hydraulic head distribution of the remaining discharge nodes is shown under Appendices.

Identical simulations were done on six other discharge nodes: 22.5, 21, 19, 12, 11, and 1. The experimental hydraulic head and discharge rate for each node were recorded and were used in MODFLOW simulation (Table 3.2). Accordingly, the experimental hydraulic heads at the seven nodes were compared to the simulated ones and the percent error between them was calculated as shown in table 3.3. Additionally, for each tested discharge node, several hydraulic heads were recorded and compared to software simulation results, and all results are shown in table 3.4.

Table 3.2 MODFLOW - Input Hydraulic head and Pumping Rate

Node Number	Pumping Rate (m3/min)	Hydraulic Head (m)
24	0.00308	0.815
22.5	0.002625	0.672
21	0.0019	0.528
19	0.00296	0.5
12	0.0036	0.39
11	0.0035	0.44
1	0.0013	0.28

Table 3.3 Hydraulic Heads- Percent Error between numerical and experimental results

Hydraulic Head at Discharge Node 24			
Node Number	Experimental Head (m)	Simulated Head (m)	Error (%)
24	0.125	0.15	16.67
22	0.2	0.32	37.50
21	-0.34	-0.3	13.33
19	-0.34	-0.32	6.25
12	-0.43	-0.5	14.00
11	-0.275	-0.5	45.00
1	0.15	0.2	25.00

Table 3.4 Hydraulic heads at different nodes – Experimental versus Numerical

Experimental Head (cm)	Simulated Head (cm)	% Error
39.3	70	43.86
38.9	30	29.67
35.5	50	29.00
32.8	22	49.09
25.1	30	16.33
12.5	15	16.67
32.4	38.5	15.84
32.5	38.5	15.58
27.1	36	24.72
27	36	25.00
19.9	32	37.81
21.8	20	9.00
35.5	30	18.33
34.4	30	14.67
32	38	15.79
32.5	38	14.47
22.9	30	23.67
30.6	30	2.00
17.4	17.8	2.25
18	17.8	1.12
18.9	17.7	6.78
18.7	17.7	5.65
18.3	17.7	3.39
18.3	17.7	3.39

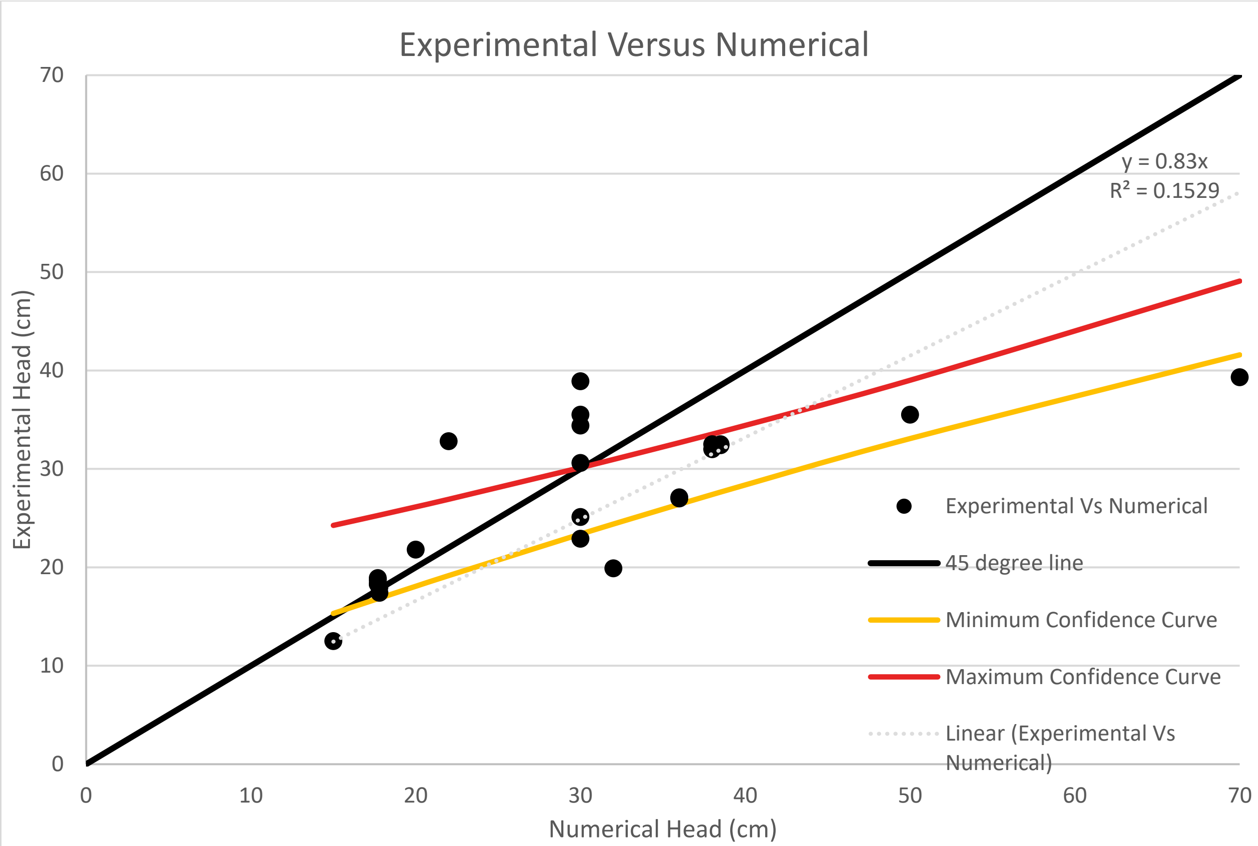

Figure 3.6: Weighted Experimental Vs Weighted Numerical

Additionally, a graph was generated showing the weighted simulated data versus weighted experimental data as shown in Figure 3.6. The linear trend of the data (with slope of 1) indicates that the simulated values are close to the observed values in the numerical model. Additionally, 95% confidence intervals were generated and presented as minimum and maximum curves in Figure 3.6. This signifies that the true mean of 95% of the experimental heads is likely to be within these two curves. All 7 values beyond the two curves are considered as outliers.

The difference between laboratory and numerical hydraulic heads are directly related to the inaccuracy of head measurements, where the water left the over pressured zone. Also, an additional factor that might have contributed to the error is the inaccuracy of water discharge measurement.

3.4.2 CONTAMINANT MOVEMENT EVALUATION RESULTS

Experimental Results

Four trials were conducted each with different initial contaminant concentration, discharge rate, and injection rate. The input parameters for all trials are summarized in the table 3.5 below.

Table 3.5 Contaminant Movement – Input Data

Input Data	Trial 1	Trial 2	Trial 3	Trial 4
Contaminated Water - Initial Concentration (mg/L)	23.20	11.80	36.30	16.50
Recharge Point Initial Concentration (mg/L)	0.00	0.20	0.00	0.00
Discharge Rate (m3/s)	1.77E-05	1.03E-05	1.13E-05	9.00E-06
Injection Rate (m3/s)	4.09E-05	2.93E-05	1.26E-05	1.47E-05
Initial Hydraulic Head (m)	0.3	0.5	0.5	0.5
Temperature ©	-	-	16.5	16

i. Concentration Variation

As previously stated, four collection points were set in the prototype to collect water samples at specific time period. For each trial, two collection period were adopted (either 60s & 120s or 120s & 180s) and the collected samples were placed in enumerated beakers as shown in Figure 3.7 below.

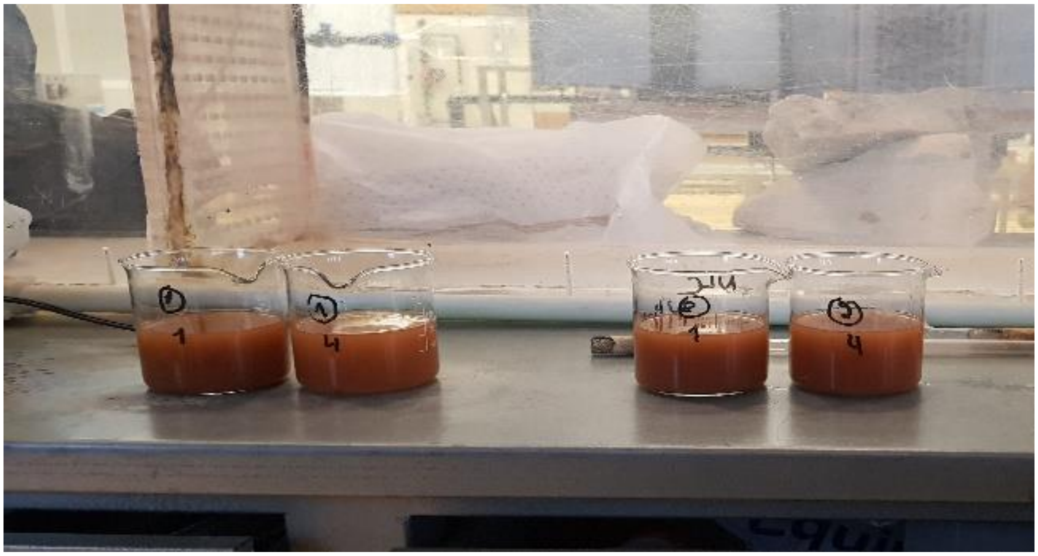

Figure 3.7: Collected Samples – Node 1& 4- Time period 60s & 120s

Subsequently, collected samples were tested for ammonia concentration using the spectrophotometer and medium range ammonia vials. Figure 3.8 shows trial 4 ammonia concentration for the sample collected from node 4 at 120s.

Figure 3.8: Collected Samples – Node 4 – Time period =120s – Ammonia Concentration = 7.8mg/L

The same process was applied for the remaining collection nodes for the 4 trials and all results are summarized in table 3.6 below.

Table 3.6 Contaminant Concentration – Experimental Results

Trial #	Time Period (s)	Node #	Experimental Results (mg/L)
1	60	1	12.5
		4	10.9
	120	1	14.7
		4	12.8
2	60	1	7.6
		2	4.3
		3	3.2
		4	5.3
	120	1	7.5
		2	3.7
		3	3.2
		4	4.9
3	60	1	18.7
		4	6.7
	120	1	19.9
		4	11.4
4	120	1	10.5
		4	7.8
	180	1	10.8
		4	9.4

ii. Contaminant Path lines

In order to track contaminant movement, the time required by the injected solution to reach the collection nodes was recorded. Figure 3.9 shows an example of the path taken by contaminated solution from injection point to node #1. For trials 2, 3, and 4 the travel time of contaminants was recorded and summarized in table 3.7.

rate.

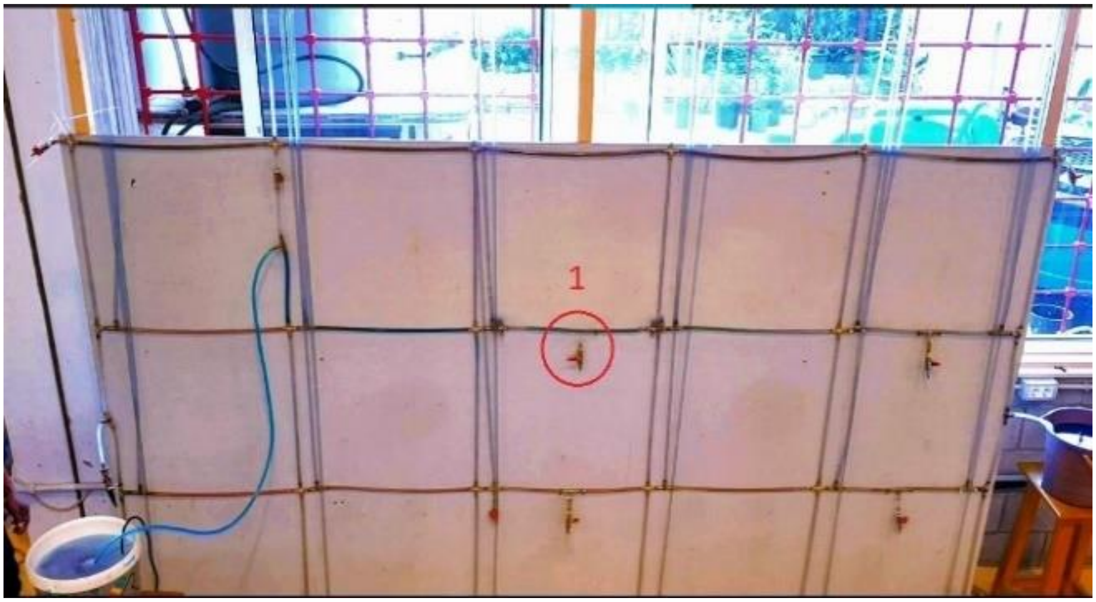

Figure 3.9: Contaminant path line from source to node #1

Table 3.7 Contaminant Path line – Experimental Results

Trial #	Node #	Experimental Time (s)
2	1	3.37
	2	6.27
	3	-
	4	-
3	1	20.36
	2	-
	3	-
	4	51.93
4	1	10.32
	2	-
	3	15.40
	4	36.53

It should be noted that the number of nodes reached by injected solution depends on the path taken by this latter through the prototype. The path pattern depends on the injection rate and discharge rate.

Numerical Model Results

i. Concentration Variation

For each trial, the prototype was modeled with the input data shown in table 9. Based on the generated flow field in MODFLOW, MT3DMS package was used to generate the concentration variation throughout the whole system and specifically at collection nodes.

For each trial and time period, the concentration at each collection point was recorded. Figure 3.10 shows contaminant concentration variation throughout the prototype for trial 3 and at time period = 120s. The same process was repeated for all trials and numerical results were recorded. These latter were compared to experimental ones as shown in table 3.8. The contaminant concentration variation for the remaining trials are shown under Appendices.

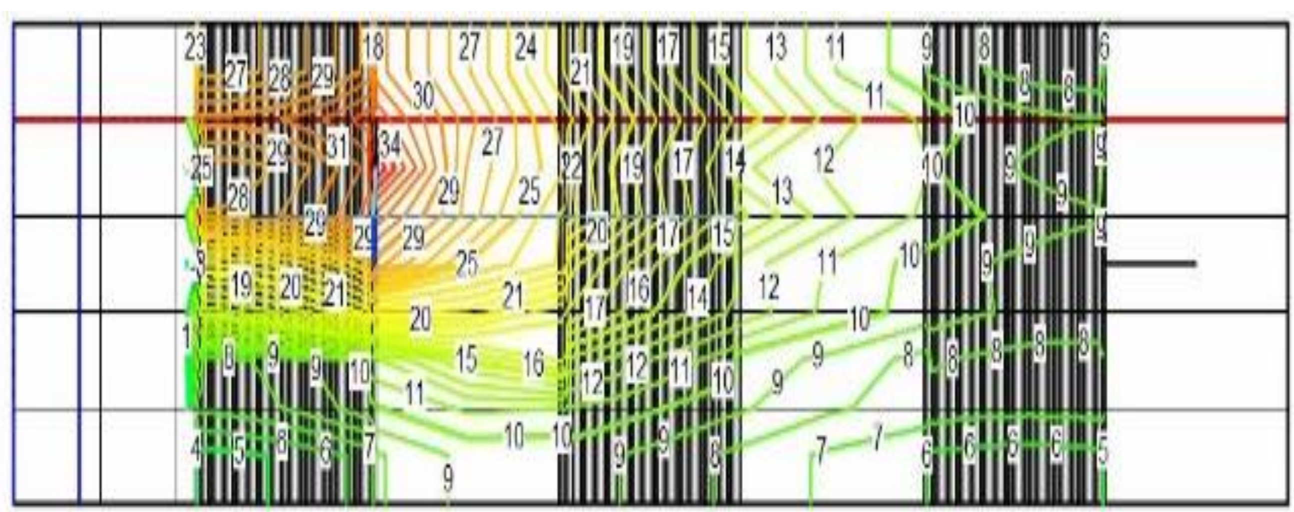

Figure 3.10 Concentration Variation – Trial 3 – Time Period = 120s

Table 3.8: Contaminant Concentration – Experimental Vs Numerical Results

Experimental Results (mg/L)	Numerical Results (mg/L)
12.5	12.60
10.9	5.40
14.7	16.00
12.8	10.40
7.6	5.80
4.3	1.90
3.2	5.20
5.3	1.40
7.5	7.30
3.7	3.80
3.2	6.80
4.9	3.70
18.7	14.30
6.7	4.40
19.9	18.90
11.4	8.90
10.5	8.90
7.8	4.2
10.8	10.6
9.4	6.4

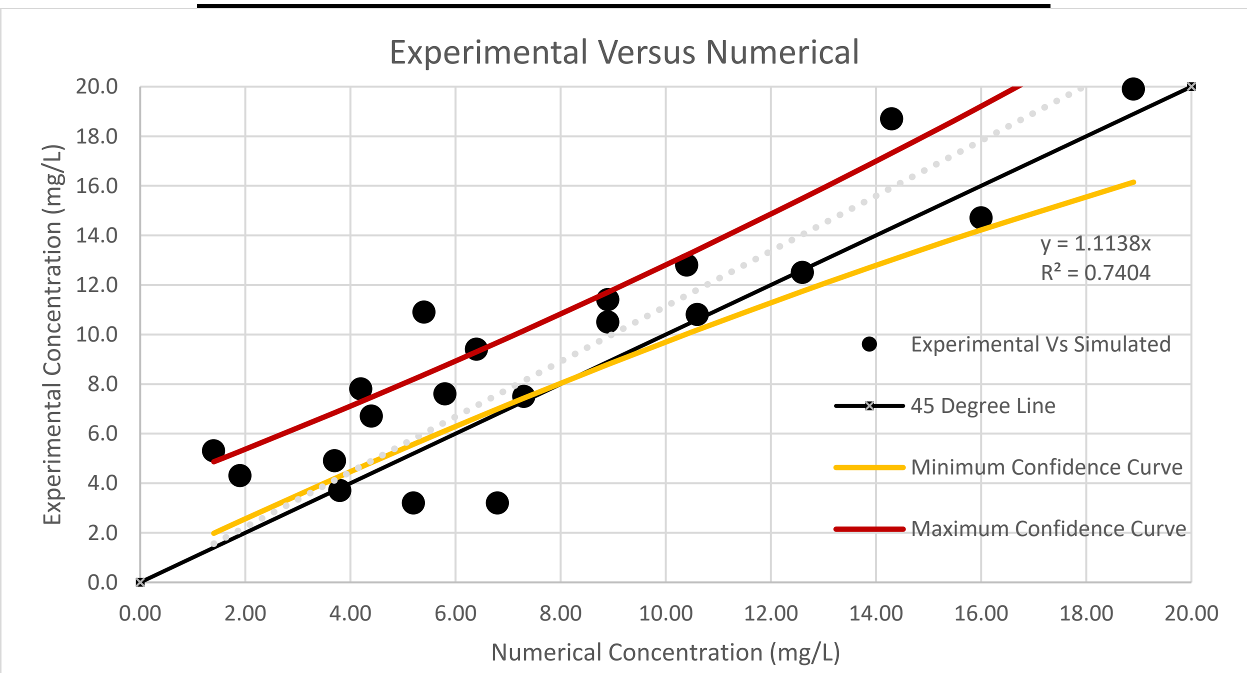

Figure 3.11 Weighted Experimental vs Weighted Numerical

Additionally, a graph was generated showing the weighted simulated data versus weighted experimental data as shown in Figure 3.11. 95% confidence intervals were generated, and minimum & maximum curves were produced as shown in Figure 3.11 (red curves). This signifies that the true mean of 95% of the experimental concentrations is likely to be within these two curves. Accordingly, points beyond the two curves were considered as outliers. It should be noted that experimental values are mostly greater than numerical values for each trial. This explains why the two curves are shifted beyond the 45 degrees line. Though, points located on this line and outside the confidence curves cannot be considered as outlier. In conclusion, numerical results largely reflect experimental ones, and 4 out of 20 trials (beyond red curves) are considered as outliers. The linear trend of the data (with slope of 1) indicates that the simulated values are close to the observed values in the numerical model.

Additional variables introduced into the experiment imposed more errors into the experiment resulting in this difference between experimental and numerical results. Potential errors that occurred during the experiment are the following:

1- Inaccuracy of discharge and injection rate measurements
2- Inaccuracy in sample's collection time: approximately five seconds were required to collect water samples at collection nodes. Therefore, the specified time periods differed by this lag time.
3- Instrumental error: the error in the measuring instrument to determine sample's concentration.

ii. Contaminant Path lines

The flow field generated in MODFLOW was used to generate path lines using MODPATH package. For each trial, the time required by contaminants to reach specific nodes was recorded. Figure 3.12 shows contaminant path lines, in blue, for trial #3 passing through nodes 1 and 4. Moreover, simulated travel time were compared to experimental ones, and the percent error were calculated as shown in table 3.9.

Table 3.9: Contaminant Travel Time – Experimental versus Numerical Results

Node #	Experimental Time (s)	Simulated Time (s)
1	3.37	5.5
2	6.27	6.5
1	20.36	20
4	51.93	54
1	10.32	15
3	15.40	40
4	36.53	51

Figure 3.12: Trial #3 – Simulated Contaminant Path Line (in light blue)

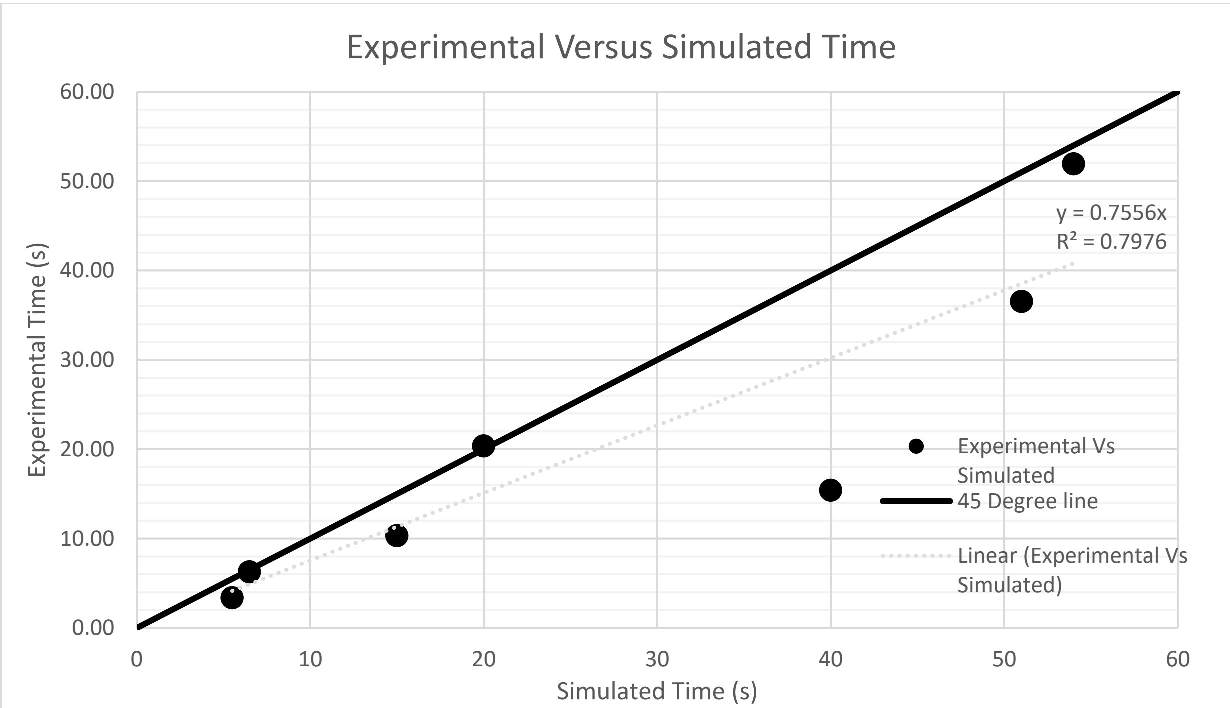

Figure 3.13 Contaminant Travel Time - Weighted Experimental vs Weighted Numerical

Additionally, a graph was generated showing the weighted simulated data versus weighted experimental data as shown in Figure 3.13. The linear trend of the data (with slope of 1) indicates that the simulated values are close to the observed values in the numerical model.

In addition to the previously stated errors, new variables were present in this experiment and errors where mainly human ones:

1- Inaccurate tracking of contaminant movement: especially with rapid movement of dyed water throughout the prototype

2- Inaccurate travel time recording: a lag time between the arrival of dyed water to a certain node and time recording.

Mathematical Method

Additional analysis was conducted on contaminant concentration experimental results in order to mathematically predict contaminant concentration at a certain node. All experiment trials were investigated and the input variables along with contaminant concentration at corresponding node were summarized in table 3.10 below.

Table 3.10: Contaminant Concentration Calculation - Input Variables

	Discharge Rate (m3/hr)	Initial Contaminant Concentration (mg/L)	Time Period (hr)	Injection Rate (m3/hr)	Horizontal Distance X from injection point (m)	Vertical Distance Y from Injection point (m)	Contaminant Concentration at Node X
NODE 1	0.0636	23.2	0.01667	0.14712	0.9	-0.3	12.5
	0.0636	23.2	0.03333	0.14710	0.9	-0.3	14.7
	0.0372	11.8	0.01667	0.10562	0.9	-0.3	7.6
	0.0372	11.8	0.03333	0.10560	0.9	-0.3	7.5
	0.0408	36.3	0.01667	0.04527	0.9	-0.3	18.7
	0.0408	36.3	0.03333	0.04530	0.9	-0.3	19.9
	0.0324	16.5	0.03333	0.05281	0.9	-0.3	10.5
	0.0324	16.5	0.05000	0.05280	2.1	-0.9	9.4
NODE 2	0.0372	11.8	0.01667	0.10562	2.1	-0.3	4.3
	0.0372	11.8	0.03333	0.10560	2.1	-0.3	3.7
NODE 4	0.0636	23.2	0.01667	0.14712	2.1	-0.9	10.9
	0.0636	23.2	0.03333	0.14710	2.1	-0.9	12.8
	0.0372	11.8	0.01667	0.10562	2.1	-0.9	5.3
	0.0372	11.8	0.03333	0.10560	2.1	-0.9	4.9
	0.0408	36.3	0.01667	0.04527	2.1	-0.9	6.7
	0.0408	36.3	0.03333	0.04530	2.1	-0.9	11.4
	0.0324	16.5	0.03333	0.05281	2.1	-0.9	7.8
	0.0324	16.5	0.05000	0.05280	2.1	-0.9	9.4
NODE 3	0.0372	11.8	0.01667	0.10562	0.9	-0.9	3.2
	0.0372	11.8	0.03333	0.10560	0.9	-0.9	3.2

Additionally, graphs were generated to better visualize the effect of the variation of each input variable on contaminant concentration at node x as shown in figures 3.14 to 3.19.

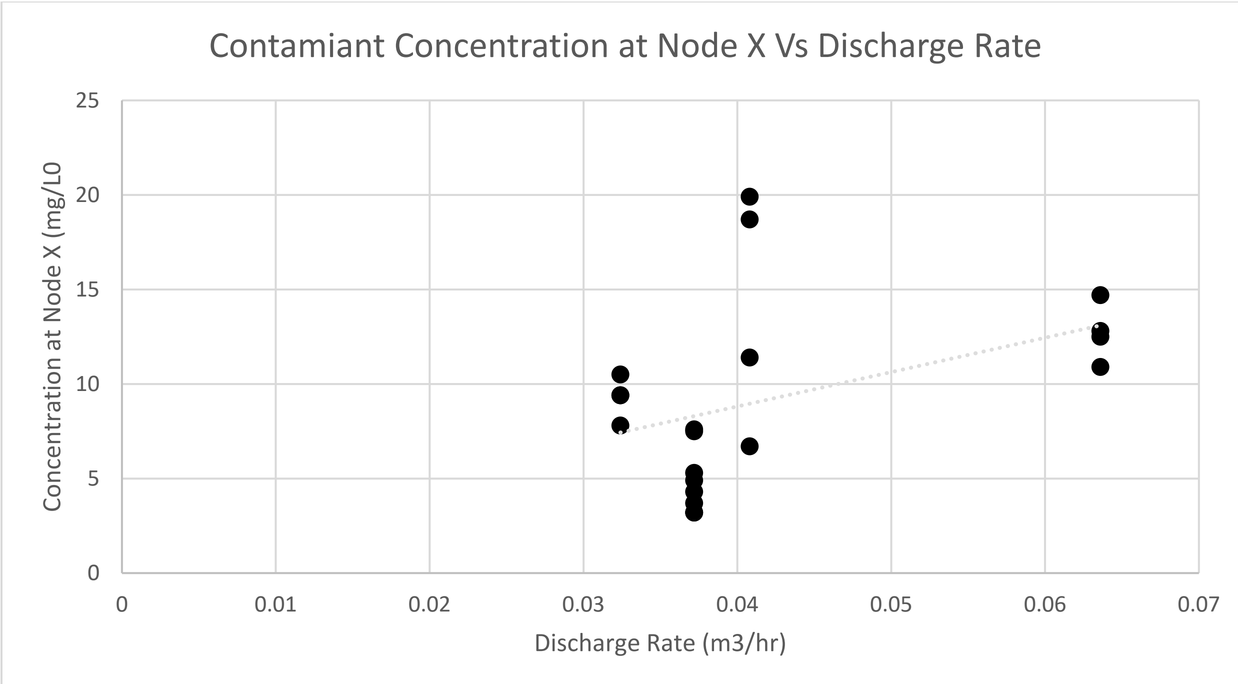

Figure 3.14 Contaminant Concentration at node x versus Discharge rate

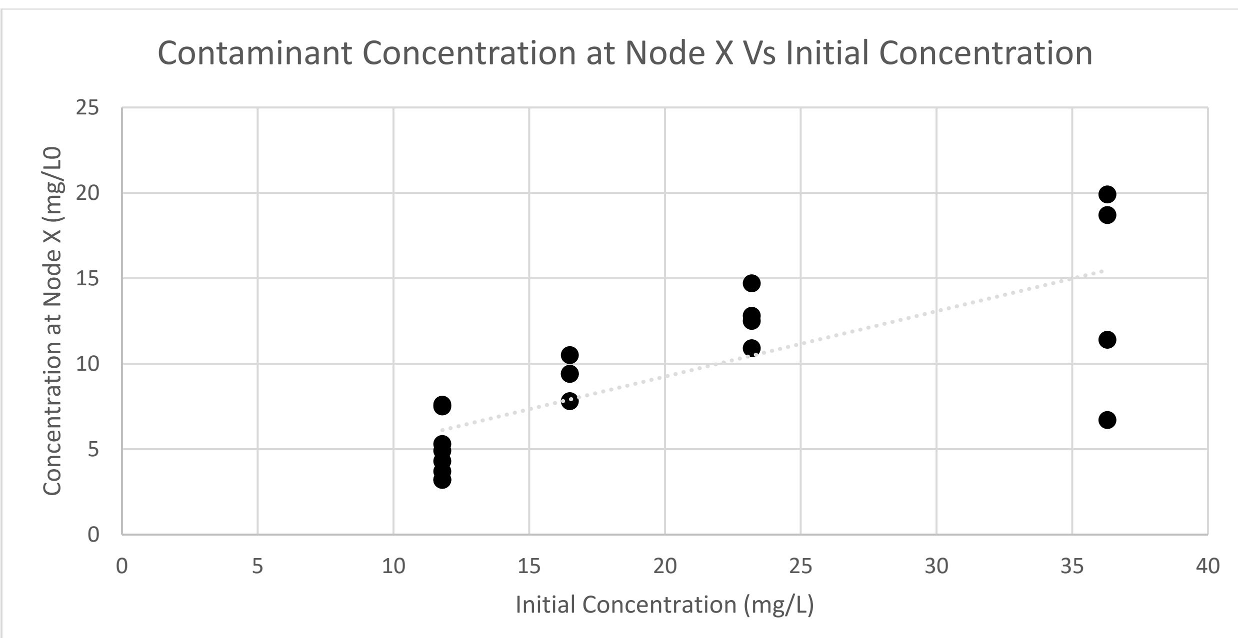

Figure 3.15 Contaminant Concentration at node x versus Initial Contaminant Concentration

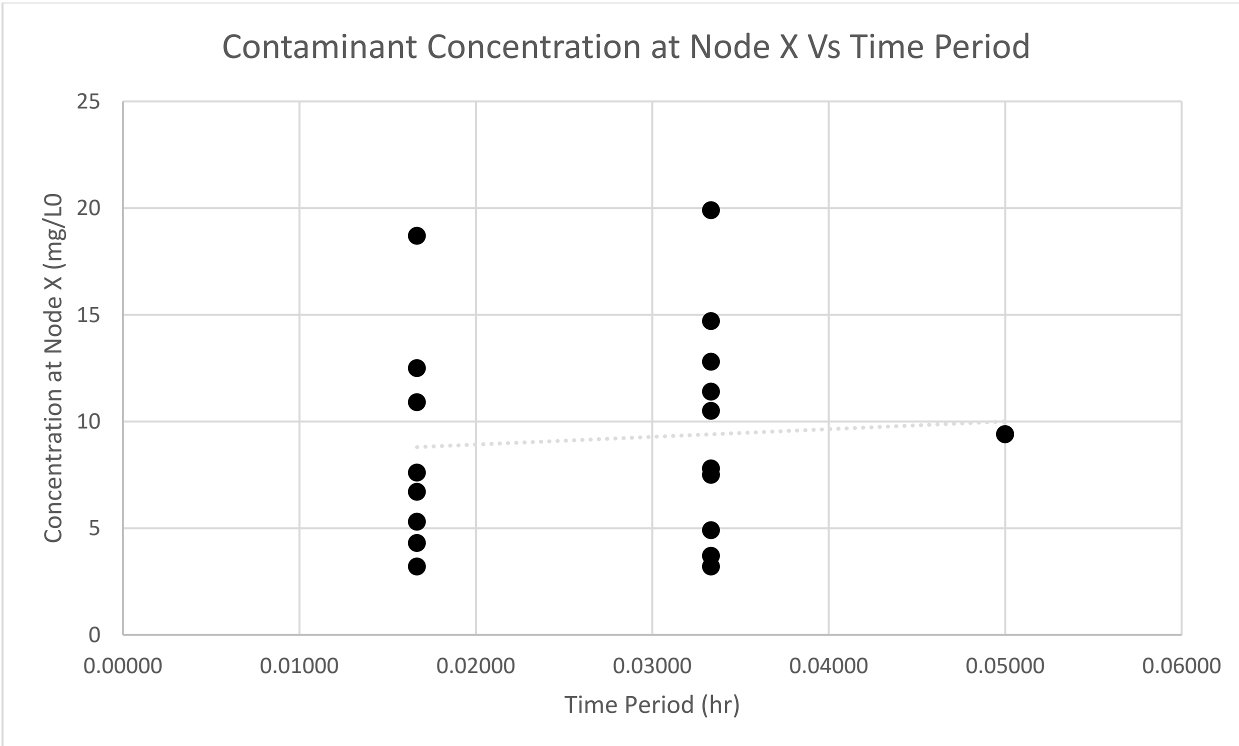

Figure 3.16: Contaminant Concentration at node x versus Time Period

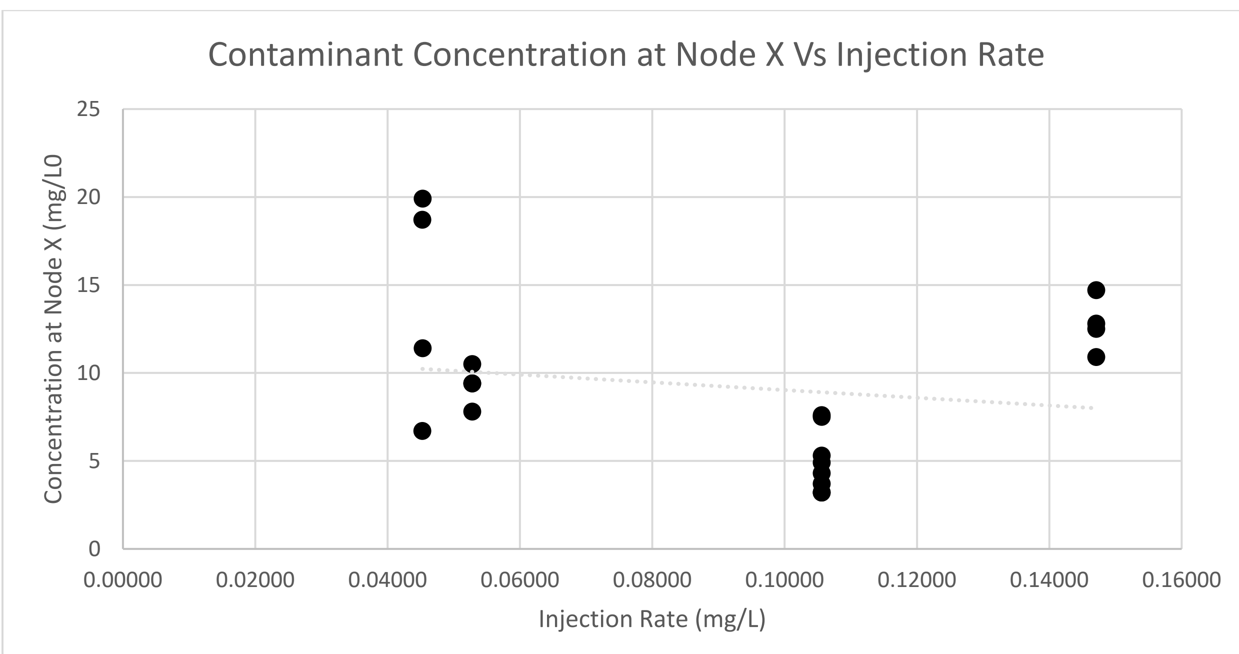

Figure 3.17: Contaminant Concentration at node x versus Contaminant Injection Rate

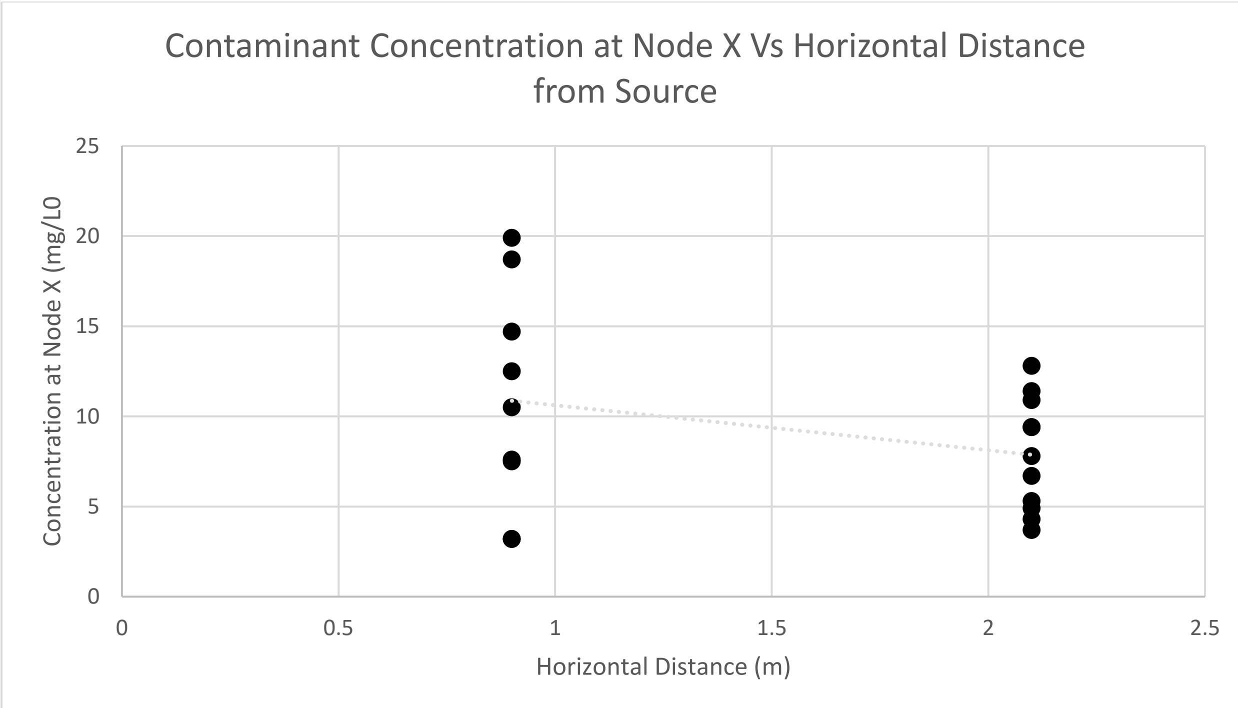

Figure 3.18: Contaminant Concentration at node x versus Horizontal Distance from Injection Point

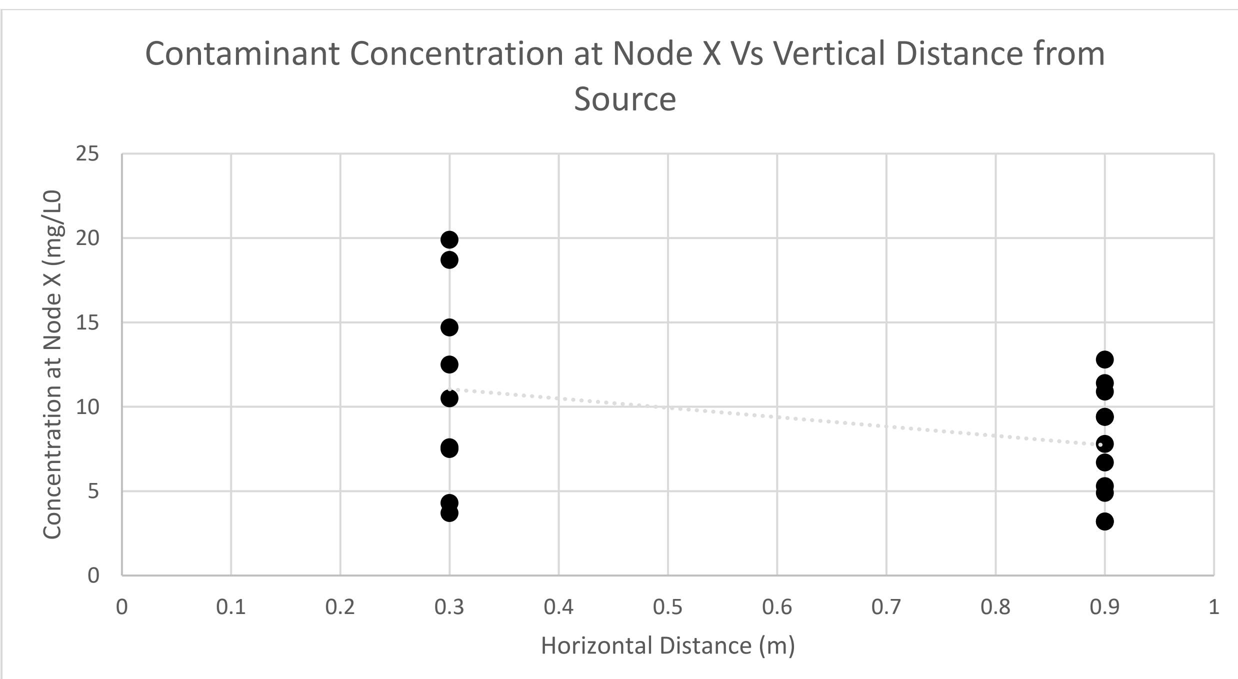

Figure 3.19: Contaminant Concentration at node x versus Vertical Distance from Injection Point

Based on generated graphs in figure 3.14 to 3.19, a relationship, not a well pronounced one, do exist between input variables and contaminant concentrations. These latter showed a proportional relationship with discharge rate, initial contaminant concentration, and experiment time period as concentration increases with the increase of these variables. On the other hand, contaminant concentration at a certain node showed an inversely proportional relationship with injection rate, horizontal distance, and vertical distance as concentration decreases with the increase of these variables.

Additionally, the least squares method was used to generate a regression equation that best fits the experimental data. A multiple linear regression equation was generated using LINEST function in excel using the six input variables. The regression equation is polynomial of the following form:

$$y = a1x1 + a2x2 + a3x3 + a4x4 + a5x5 + a6x6 + a7$$

y: contaminant concentration at Node #
x1: Discharge rate (m^3/hr)
x2: Initial Contaminant Concentration (mg/L)
x3: Time Period (hr)
x4: Injection Rate (m^3/hr)
x5: Horizontal distance from injection point (m)
x6: Vertical distance from injection point (m)
a1, a2, a3, a4, a5, a6: Variables slopes
a7: Intercept

The regression equation was generated with all slopes and intercept as shown below:

$$y = 471x1 + 0.017x2 + 82.6x3 - 117.5x4 - 1.48x5 + 4.3x6 + 2.38$$

Subsequently, the predicted y values were calculated using LINEST function and a graph was generated to compare predicted concentrations to experimental ones. The predicted values along with the graph are shown in table 3.11 and figure 3.20, respectively.

Table 3.11: Contaminant Concentration at Node X – Predicted Versus Experimental Values

Experimental Concentration at node X (mg/L)	Predicted Concentration at node X (mg/L)
12.50	14.22
14.70	15.60
7.60	6.46
7.50	7.83
18.70	15.67
19.90	17.04
10.50	11.86
9.40	8.87
4.30	4.67
3.70	6.05
10.90	9.85
12.80	11.23
5.30	2.09
4.90	3.47
6.70	11.31
11.40	12.68
7.80	7.49
9.40	8.87
3.20	3.87
3.20	5.25

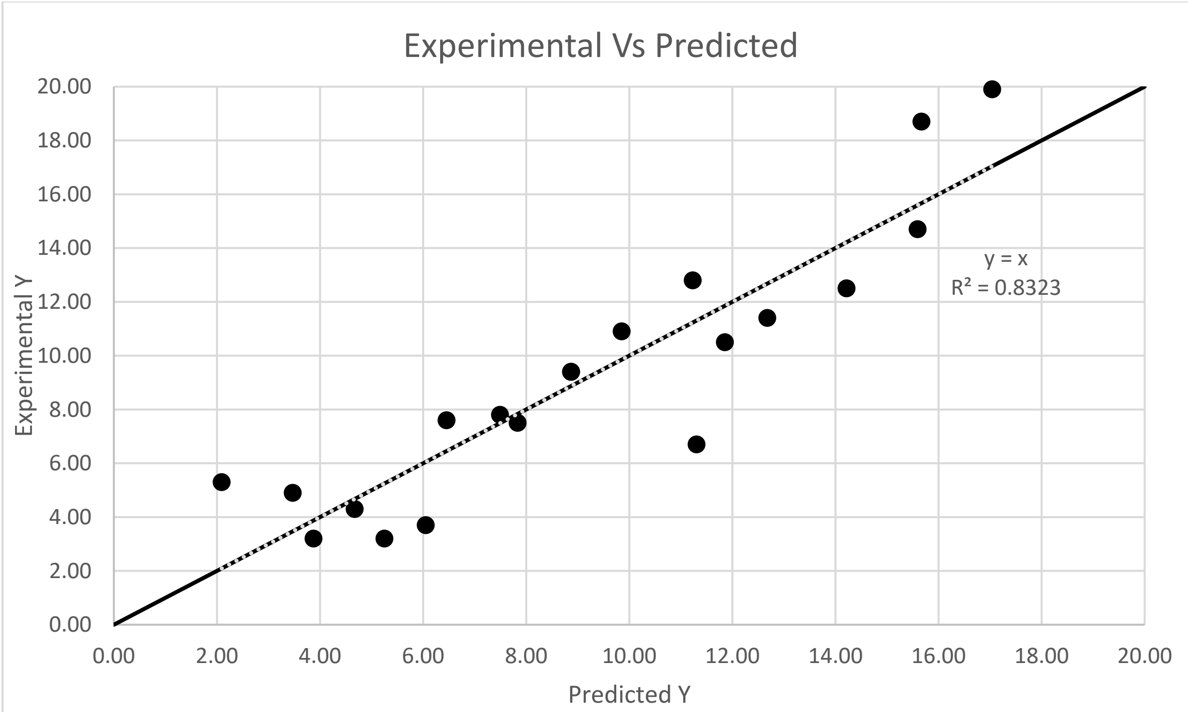

Figure 3.20: Contaminant Concentration at node x – Experimental Versus Predicted Values

As can be seen in figure 3.20, a linear trend was generated and gave an equation that exactly fits the 45-degree line with y = x. This shows that the predicted data are very close to experimental data, and the obtained regression equation can be used to mathematically predict the contaminant concentration at any node with a high level of accuracy.

Additional statistical analysis was conducted in order to test the significance of the obtained regression model. In other words, to check the appropriateness of the regression equation in predicting the assessed Y value. First, regression statistics were generated using LINEST function and are summarized in table 3.12 below:

Table 3.12: Regression Statistics

Regression Statistics	
Coefficient of Determination R^2	0.832339
F statistic	10.75623
Regression sum of squares	367.8539
St. error for Y Estimate	2.387437
Degree of freedom	13
Residual sum of squares	74.09814

The coefficient of determination R^2 indicates that around 83% of our dependent variables (contaminant concentration at node X) are explained by the independent variables (input data), which is a good fit. This is also shown by the small value of standard error for Y estimate that indicates the precision of the regression analysis. The regression sum of squares is already used in the calculation of R^2 value. As for the residual sum of squares, the smaller its value compared to total sum of squares, the better the regression model. This is the case here as the residual sum of squares is even way below the regression sum of squares. The remaining parameters (F-Value & Degree of freedom) will be used in the succeeding analysis.

An additional analysis, the F-Test, was conducted in order to test the significance of the regression model. Test results are shown in table 3.13 below:

Table 3.13: F-test Results

F-Test Results	
F-value	10.75623
Alpha	0.05
v1	6
v2	13
Probability of a higher F value	0.000212
F-critical (based on the table)	2.93

The F-value was previously obtained using LINEST function. Alpha value represents the probability of wrong decision, meaning that there is a 5% probability of erroneously concluding that there is a relationship. V1 and V2 represents the numerator and denominator degrees of freedom, respectively. These two are used to calculate the probability of a higher F-value. The F-critical represents the critical level of F-value below which the regression equation becomes not useful in predicting the assessed Y value. F-critical is determined based on V1 and V2 from published F-distribution tables (Six Sigma Materials 2020). The probability of higher F-value was calculated using FDIST function in excel.

Test results show that the F-value is beyond F-critical (10.76>2.93). Therefore, the regression equation is useful in predicting the assessed value of contaminant concentration at a certain node X. This was also concluded by the very small probability obtained (0.000212<0.05 statistically accepted).

Ultimately, the obtained regression equation can be used to predict the contaminant concentration at any of the model nodes with an acceptable level of accuracy, without the need for experimental trials. Moreover, this tool can be upgraded to field studies, and contaminant concentration can be determined at any location, knowing the source of contamination and abstraction point characteristics.

3.5 Conclusion

In this paper, an experimental prototype replicating karstic conduits was constructed at NDU laboratory in order to assess groundwater flow and contaminant transport. The model was then built using a finite difference software with same input parameters, and a flow field was generated

First, seven trials were conducted to calculate hydraulic heads at specific nodes. Each trial having a specific pumping rate and discharge node. The same prototype was modeled using MODFLOW software and numerical heads were generated and compared to experimental ones. Additionally, 95% confidence intervals were generated in order to identify outliers.

Then, an injection point was introduced to the prototype to inject dyed contaminated solution and evaluate the concentration variation throughout the system. In order to achieve that, four trials were conducted, each with specific initial contaminant concentration, injection rate, discharge rate, and hydraulic head. Samples were collected from four nodes at a specific time period and the concentration of each sample was measured using a spectrophotometer. On the other hand, the flow field generated using MODFLOW was used to track contaminant concentration using MT3DMS package and numerical concentrations for each trial were generated. Consequently, results were compared, and 95% confidence intervals were generated to evaluate the efficacy of our experiment and identify potential outliers.

Further, identification of contaminant path lines and travel time to reach certain nodes were conducted concurrently on three out of the four trials. Along with experimental results, the flow field generated in MODFLOW was used to generate contaminant path lines and evaluate the time of travel using MODPATH package. Accordingly, numerical results were compared to experimental ones.

Additional analysis was conducted on contaminant concentration experimental data to mathematically predict contaminant concentration at any node in the prototype. The least square method was used to generate a regression equation that best fits experimental data. Regression statistics and F-test were conducted to validate the efficiency of the regression model.

The results of the study show that experimental prototype results reflect numerical simulations to a great extent. The difference in values is expected and accounted for by the multiple variables in each experiment that imposed several errors. These latter were mainly human related to injection and discharge rates measurement, time recording, sample collection, and contaminant tracking. Also, experimental errors were presented mainly in concentration measuring instrument.

Additionally, the generated regression model is useful in predicting assessed contaminant concentration at any node throughout the prototype. This powerful can help in investigating additional trials without the need for conducting laboratory experiments. Also, this mechanism can be applied to field studies and help in predicting the contaminant concentration at any location and prevent potential groundwater contamination.

Evaluation of groundwater movement and contaminant transport in karstic conduits and rock fractures is essential. This type of aquifers constitutes a major underground water basin, yet it is highly susceptible to contamination due to conduits connecting the most vulnerable location of the karst area, that are endangered by point source pollution. Consequently, such study will serve as a tool to better understand underground hydraulics and contaminant movement through these conduits and fractures. This will help in generating protection measures to prevent point source pollution from reaching a certain abstraction point. Also, in managing water quantity by enhancing the performance of a certain abstraction point.

CHAPTER 4

USING FINITE DIFFERENCE APPROACH TO MODEL NITRATE CONTAMINANT TRANSPORT TO A CONTAMINATED WELL

4.1 INTRODUCTION

Although Lebanon's geography and climate would seem to provide adequate renewable water resources, several factors make access to potable water difficult: overexploitation of groundwater, historically inadequate national and local governance, increased population, and mismanagement of water resources. A national study conducted in 2014 showed areas where groundwater resources were decreasing and recommended ongoing studies to explore new sources and capitalize on existing ones. National and international conflict made it difficult to implement the recommendations leading in turn, to further depletion and contamination of the country's potable water sources.

One of these crises, the Syrian conflict, contributed to Lebanon's groundwater access and management problems through the sudden influx of refugees fleeing to neighboring countries. As of January 2018, approximately 25% of Lebanon's population were Syrian refugees. The influx of refugees has resulted in depletion of water resources and increased use of illegal wells and poorly built pit latrines which, in turn contributes to groundwater contamination. It also puts a significant strain on Lebanon's water resources and contributes to health problems in remote communities.

Previous studies were conducted on detecting and modeling general groundwater contaminants using finite difference method. Other studies focused on uncertainties in nitrate-transport in groundwater using spatial and temporal variabilities.

Also, there are no studies, to the author's knowledge, that have been conducted to model contaminant transport in groundwater to a pumping well. Therefore, the aim of this study is to use MODFLOW software to model nitrate contaminant transport to a contaminated well in Akkar, a remote area in Lebanon, in order to understand the flow of contaminants towards the well and validate field data.

MODFLOW is the U.S. Geological Survey modular finite-difference flow model that simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of both. The flow field generated in MODFLOW is used to trace particle path lines using MODPATH and simulate advection, dispersion and chemical reactions of dissolved constituents in groundwater systems using MT3DMS. All three models use ModelMuse as the graphical user interface in order to create input files.

The results of this study will help in the management of groundwater and in creating proactive and remediation measures for local communities and authorities to reduce groundwater water pollution levels.

4.2 METHODOLOGY

4.2.1 LAB TESTING

Groundwater contamination has many sources including pollutants entering the water table from sewage or corroded casings. Frequent testing is crucial to determine which contaminants are present and at what levels. It is also important to determine the source of contaminants and rate of contaminant flow to prevent further contamination and develop remediation programs.

Water samples were collected from Akkar public wells on February 9, 2019. The sample studied in this paper is from Chadra El Seha. Physical (i.e., turbidity, total suspended solids, total dissolved solids) and chemical (i.e., pH, ammonia, and nitrate) tests were conducted. The decision was made to study nitrate transport and concentration variation using MODFLOW software as the chemical contaminant of principal importance that is derived from on-site sanitation is nitrate.

The town’s water supply is provided by the public well in Chadra El Seha. Our research team, in collaboration with the municipality of Chadra, collected water samples. Samples were preserved in sterile plastic bags and immediately placed in a lightproof, insulated box containing icepacks with water to ensure rapid cooling. An analysis lab report is shown in Table 4.1.

Table 4.1 Lab Testing Results - Chadra El Seha Well

Parameter	Unit	Test Results	Standards (WHO)	Methods
Physical and Chemical Properties				
pH	Pt. Co scale	8.02	6.5-8.5	Electrometric
Turbidity	NTU	0.9	5	Turbidity
Nitrate	mg/l	20.54	10	Colorimetric
TDS	mg/l	258.33	1500	Evaporation
Ammonia	mg/l	0.0457	0.2	Colorimetric

Examination of the testing report reveals the ammonia concentration is below the accepted levels whereas nitrates exceed accepted levels. The TDS level is 258.33 mg/l, which is below the limit. The pH shows water from this well is most likely alkaline indicating a low probability of heavy metal or chemical contamination.

4.2.2 MODFLOW MODEL

The Chadra El Seha well and its surroundings (e.g., nearest 5 houses or sources of contaminants surrounding the well) was modeled with MODFLOW 2005. Nitrate was selected for modeling of contaminant transport to the well. The geological characteristics of Chadra were extracted from a groundwater study previously conducted in the Akkar area by NDU's research team. The study showed that C4 formations, Sanine limestone (alternating dolomitic limestone and limestone) exists in this area. MODFLOW 2005 was used to generate a 100x100m grid. Two soil layers, thickness of 95 and 50m respectively, were modeled with the aquifer in the second layer. Due to the lack of data, an average wastewater effluent concentration of 40mg/L was considered in reference to Pennsylvania Department of Environmental Protection (PADEP). The input parameters used for modeling are summarized in Table 4.2 below.

Table 4.2 MODFLOW Input Parameters

Input parameters for Nitrate-N transport modeling	
Parameter	**Value**
Number of Layers	2
Layer Thickness (m)	95 and 50
Hydraulic Conductivity k (m/s)	0.0001
Porosity n	0.25
Initial Nitrate Concentration (mg/L)	40
Longitudinal Dispersivity (m)	10
Well Abstraction rate (m3/s) *	-0.003

Well Depth (m)*	130
Initial Head (m)*	80

**Chadra Municipality*

A parametric study was conducted by changing the variables to determine their effect on the contaminant path toward the well. The studied variables were porosity, time period, and well abstraction rate. Particle tracking and nitrate concentration variation were generated using MODPATH, and MT3DMS respectively.

Using the data in Table 4.2, the system was modeled for a 5-year period, equivalent to the actual operation period of the Chadra El Seha well. Results were compared to lab results obtained from field tests for validation.

Figure 4.1: Model Grid

4.2 PRESENTATION AND DISCUSSION OF RESULTS

4.2.1 EFFECT OF POROSITY, TIME, AND ABSTRACTION RATE ON CONTAMINANT PATH

The results of three variables investigated (i.e., porosity, time period, and abstraction rate) are summarized in Table 4.3.

Table 4.3 Summary of the effect of porosity, time and abstraction rate on contaminant path

Parametric Study						
Time (month)	**Abstraction Rate (m3/s)**	**Porosity n**	**Contaminant Source**	**Distance from well (m)**	**Contaminant Path (m)**	**Remaining distance to well (m)**
1	0.003	0.5	Source 1	12	4.60	7.40
			Source 2	18	6.50	11.50
			Source 3	20	1.50	18.50
			Source 4	30	11.30	18.70
			Source 5	20	4.40	15.60
		0.3	Source 1	12	8.30	3.70
			Source 2	18	9.50	8.50
			Source 3	20	2.60	17.40
			Source 4	30	13.40	16.60
			Source 5	20	5.50	14.50
		0.25	Source 1	12	10.30	1.70
			Source 2	18	10.20	7.83
			Source 3	20	5.00	15.00
			Source 4	30	14.10	15.90
			Source 5	20	6.70	13.30
3	0.003	0.25	Source 1	12	12.00	0.00
			Source 2	18	18.00	0.00
			Source 3	20	20.00	0.00
			Source 4	30	29.80	0.20
			Source 5	20	19.60	0.40
6	0.003	0.25	Source 1	12	12.00	0.00
			Source 2	18	18.00	0.00
			Source 3	20	20.00	0.00
			Source 4	30	30.00	0.00
			Source 5	20	20.00	0.00
	0.0015		Source 1	12	12.00	0.00
			Source 2	18	18.00	0.00
			Source 3	20	20.00	0.00
			Source 4	30	29.80	0.20
			Source 5	20	19.20	0.80
	0.00075		Source 1	12	12.00	0.00
			Source 2	18	11.00	7.00
			Source 3	20	11.20	8.80
			Source 4	30	17.80	12.20
			Source 5	20	10.50	9.50

The study started by changing the porosity of the formation where a contaminant was injected at a fixed time period of one month. The contaminant's path was measured using the measure tool in Model Muse. Distance versus porosity was plotted for each house/source.

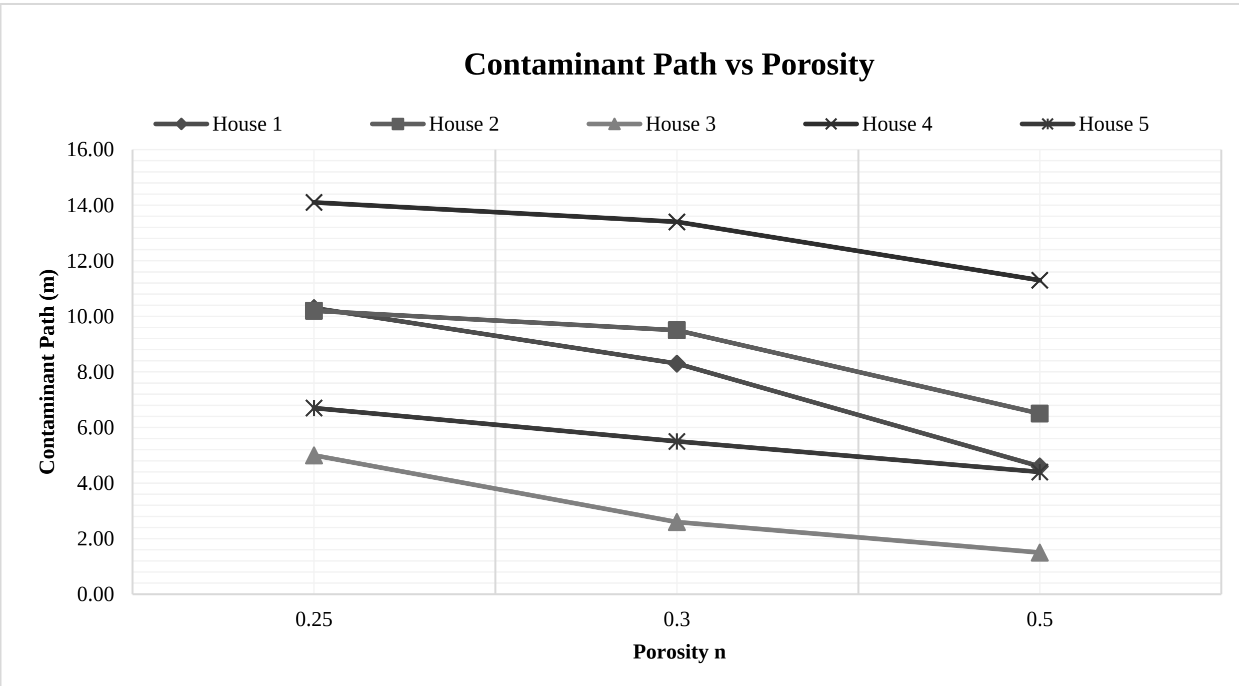

Figure 4.2: Variation of Contaminant Path with Porosity

As shown in Figure 4.2, the distance from source to well (contaminant path) is inversely proportional to porosity since when porosity increases the distance traveled by the particles decreases.

Three modeling periods were investigated: 1 month, 3 months, and 6 months. With all other variables fixed, the results showed that as time increased contaminant path also increased, reaching the well from three out of five sources for a 3-month period and from all five sources in a 6-month modeling period (refer to Table 4.3).

Three abstraction rates were considered: -0.00075 m3/s, -0.0015 m3/s, and -0.003 m3/s. Contaminants were injected at a fixed rate of 40mg/L for 6 months with porosity equal to 0.25. Results showed that as the abstraction rate increased the contaminant path increased reaching the well from one, three, and five sources out of five for the lowest to highest abstraction rate, respectively (refer to Table 3).

Figures 4.3, 4.4, and 4.5 show the path line, generated using MODPATH, traveled by contaminants from the source to the well for the three abstraction rates. The path lines get closer and reach the well as the abstraction rate increases.

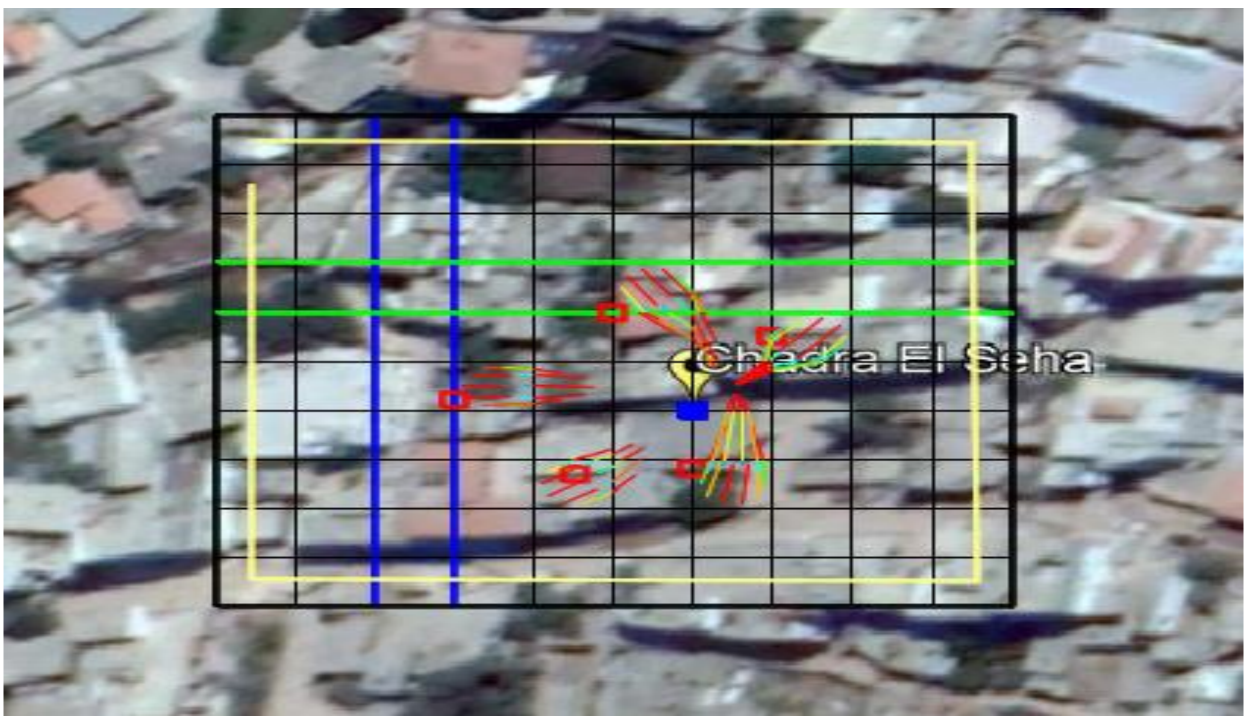

Figure 4.3: Contaminant Path – Abstraction rate = 0.00075m^3/s

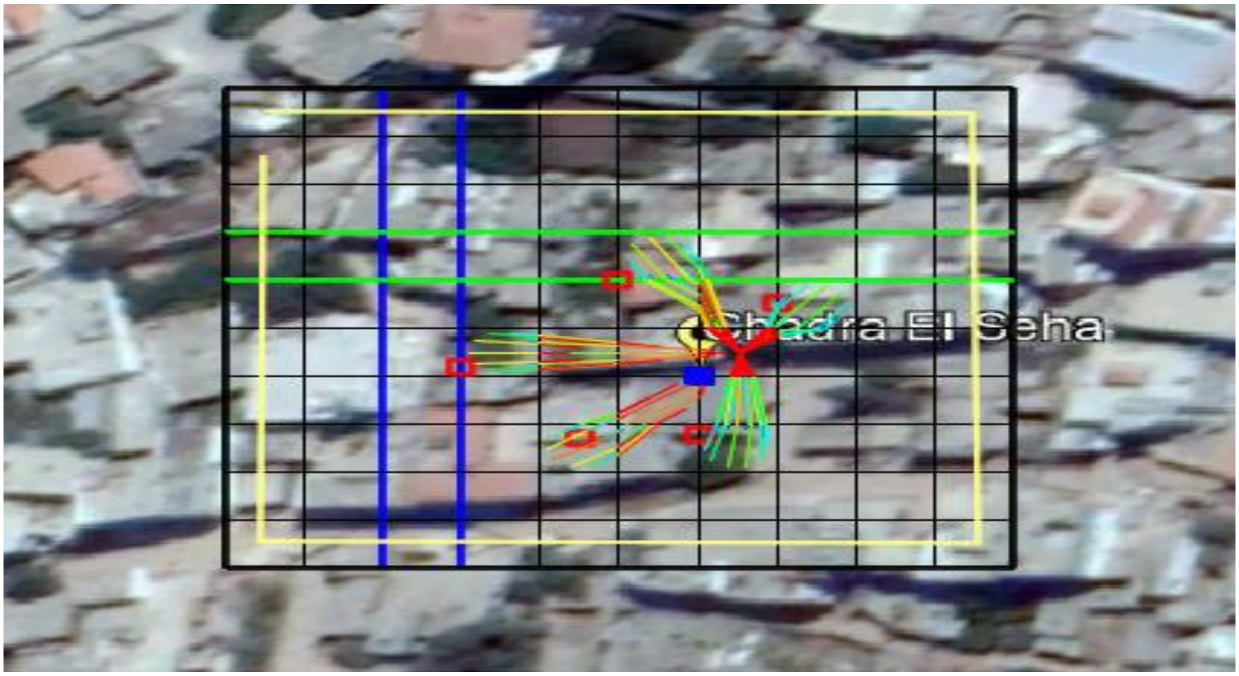

Figure 4.4: Contaminant Path – Abstraction rate = 0.0015m³/s

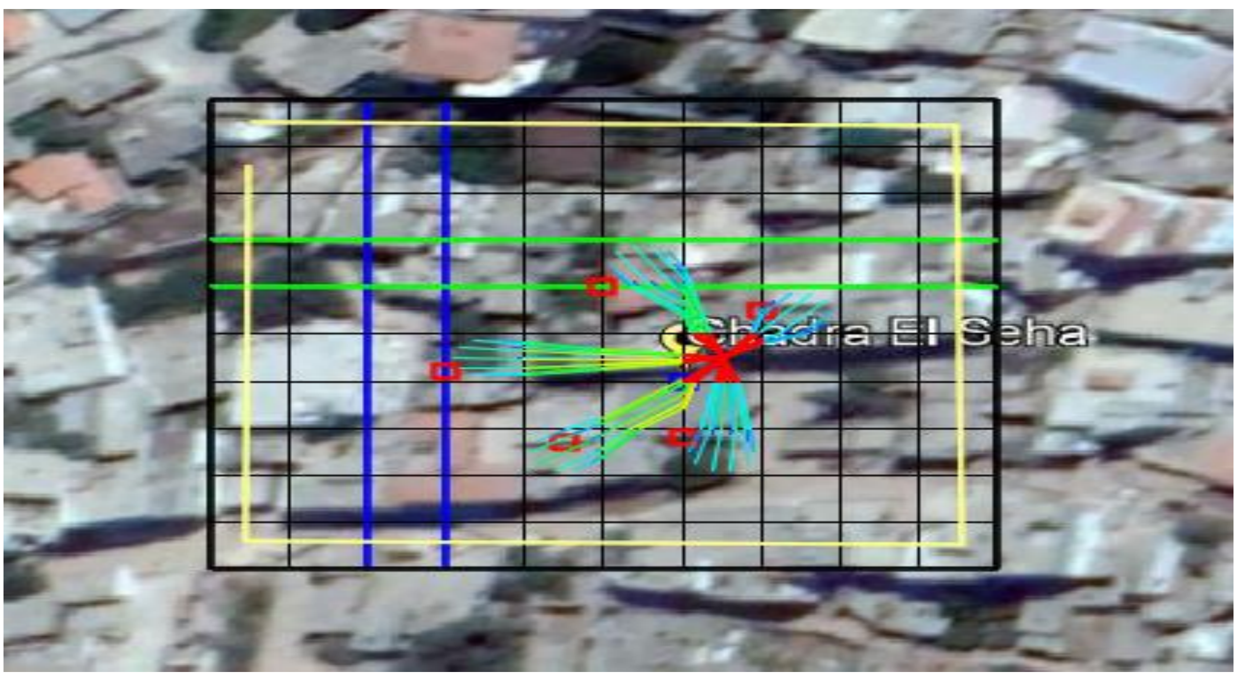

Figure 4.5: Contaminant Path – Abstraction rate = 0.003m³/s

4.2.2 COMPARISON BETWEEN LAB TESTING AND MODFLOW RESULTS

The water sample collected from the Chadra El Seha well showed an average nitrate concentration equal to 20.54 mg/L. In order to validate this result, the well was modeled with its surroundings on MODFLOW for a period of 5 years, the length of time the well has been in operation. Using MT3DMS, the variation of nitrate concentration was generated resulting in a value of 25mg/L after five years (Figure 4.6).

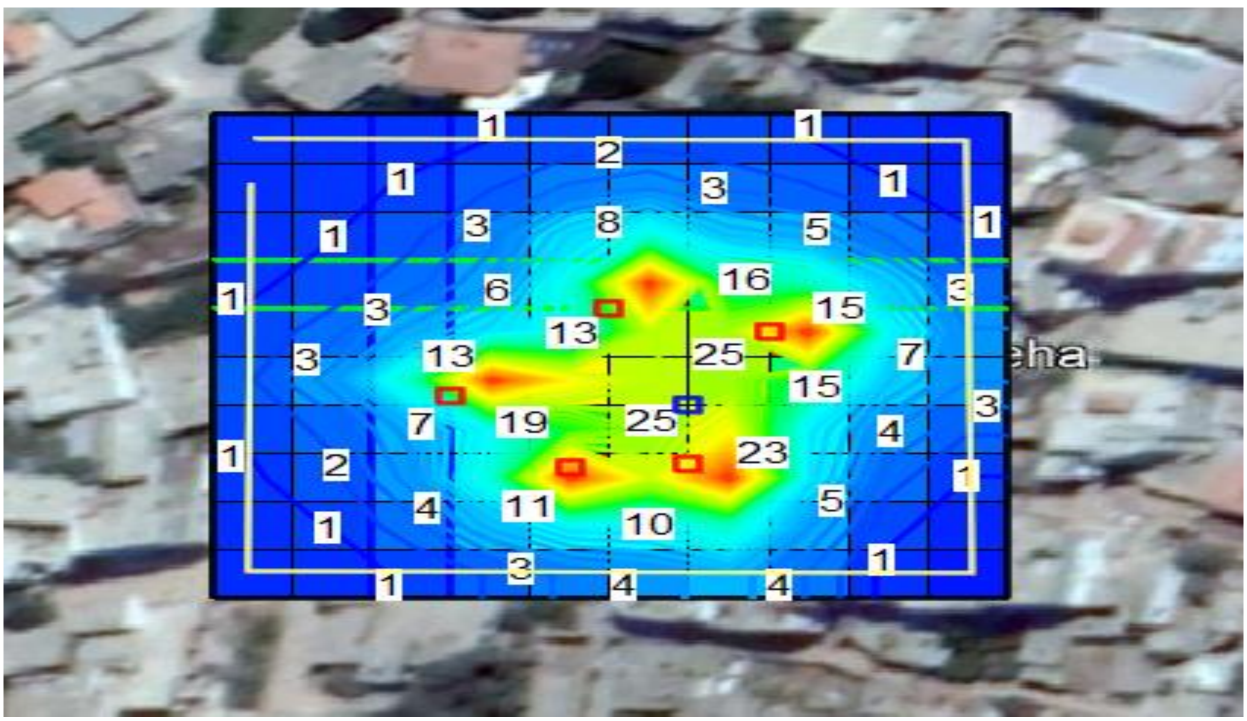

Figure 4.6: Variation of Nitrate Concentration – Time period = 5years

Although a small difference exists between the two concentrations, the numerical model and lab testing show similar results of nitrate contaminant transport.

4.4 CONCLUSION

This paper shows the use of a finite difference approach to model nitrate contaminant transport in a contaminated well and to study the effects of different parameters on the distance traveled by contaminants from the source to the pumping well. The parametric study was conducted and the effect of each variable on the contaminant path was investigated using MODFLOW, MODPATH and MT3DMS.

The effect of porosity on the contaminant path was studied by increasing the porosity from 0.25 to 0.5. The results showed an inversely proportional relationship between porosity and contaminant path due to the advection, dispersion and chemical retardation mechanisms that govern contaminant transport in groundwater. As porosity increases, contaminants mixing and reaction with porous material increases meaning contaminants are more dispersed and move slower while passing through large pores, leading to relatively shorter paths. The other two variables, time period and abstraction rate, gave logical results as contaminants are given enough time to reach the well or a faster pace, respectively.

Finally, nitrate-transport modeling reflected the actual field/lab results largely. The difference between concentrations can be explained by several assumptions made on hydrogeological and transport properties such as hydraulic conductivity, porosity, dispersion, advection, and retardation coefficients as well as on all other coefficients that may present uncertainties

CHAPTER 5

EVALUATION OF CONTAMINANT TRANSPORT TO ASSESS AND MANAGE GROUNDWATER RESOURCES QUALITY IN AKKAR REGION, LEBANON

5.1 INTRODUCTION

About half of Lebanon's water supply is sourced from groundwater, where the major aquifer in Lebanon are contained in Limestone rock formations, Karstic in nature (UNDP, 2014). These latter landforms allow rainwater and snowmelt, the main source of groundwater recharge, to be rapidly absorbed into the subsurface feeding deep underground layers that contain numerous sinkholes. About 65% of Lebanon's surface is covered with carbonates karstic formations (Abi Rizk, J., 2011).

Although Lebanon is known by its relatively abundant water resources (800mm of rainfall on average), the importance of snow, and the prevalence of a karstic geology; the natural recharge rate of aquifers is estimated at around 500MCM/yr, whereas extraction rates are around 700MCM/yr (UNDP, 2014). Several factors make access to potable water difficult: overexploitation of groundwater, historically inadequate national and local governance, increased population, and mismanagement of water resources. A national study conducted showed areas where groundwater resources were decreasing and recommended ongoing studies to explore new sources and capitalize on existing ones. National and international conflict made it difficult to implement the recommendations leading in turn, to further depletion and contamination of the country's potable water sources. One of these crises, the Syrian conflict, contributed to Lebanon's groundwater access and management problems through the sudden influx of refugees fleeing to neighboring countries (LME, 2014). As of January 2018, approximately 25% of Lebanon's population were Syrian refugees (UNHCR, 2018). This influx has resulted in depletion of water resources and increased use of illegal wells and poorly built pit latrines. This has added to Lebanon's long-standing problems with groundwater contamination. It has also put a significant strain on Lebanon's water resources and contributed to health problems in remote communities.

Consequently, this study aims to model chemical contaminant transport to three contaminated wells in Akkar area, specifically Chadra town, in Lebanon to understand the flow of contaminants in the subsurface towards the well. Results of numerical modeling will help determine safe abstraction rate for each well and safe setback distances for pit latrines and/or solid waste disposal sites. Subsequently, guidelines on pumping regime, sanitation system, and solid waste disposal will be developed based on numerical model results.

5.2 Materials and Methods

5.2.1 Data Characterization

The study was conducted on three wells: Chadra El Seha, Chadra El Madraseh, Chadra El Nahr. All wells are in "Akkar" district, an administrative division of "Akkar Governorate" at approximately 450 m above sea level and at 150 km from Beirut (Figure 5.1).

Figure 5.1: Wells Location

Based on the geological map of Akkar area, and specifically for Chadra town, C4 Sanine formation does prevail and defined as Pale gray, fractured fine and thick bedded limestone and marly limestone (Figure 5.2). This formation is widely exposed and highly karstified and considered one of the major water towers in Lebanon. Groundwater is stored and transmitted to this aquifer by fractures and conduits. C4 formation is covered by upper Miocene (mcg) formation that consists of conglomerates, sandy, silty, and marl deposits. Also, Pliocene (PI) which is mostly volcanic rocks with marl and conglomerate (UNDP, 2014). Both formation act as an aquiclude above the C4 formation.

Soil properties were retrieved from geological map, literature review, and previous studies conducted on Akkar area (Akiki, T., 2018). The soil properties summarized in Table 5.1 were considered for this study:

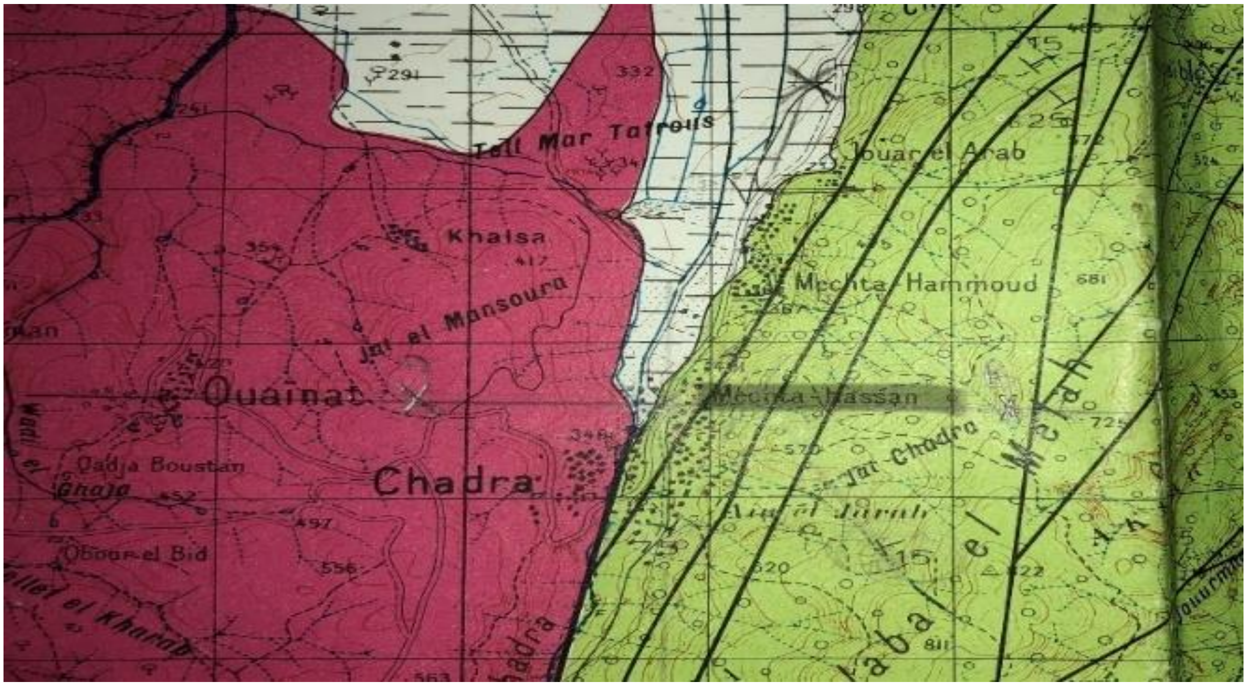

Figure 5.2: Geological Map of Chadra

Table 5.1 Soil Properties.

Soil Properties	
Parameter	**Value**
Number of Layers	2
Layer Thickness (m)	95 & 50
Hydraulic Conductivity k (m/s)	0.0001
Porosity n	0.25
Longitudinal Dispersivity (m)	10

5.2.2 Field Visits

Two field visits were conducted, February 9, 2019 and May 18, 2019, to collect water samples and gather information for each well. Our research team, in collaboration with municipalities, collected water samples. Samples were preserved in sterile plastic bags and immediately placed in a lightproof, insulated box containing icepacks with water to ensure rapid cooling. In the second site visit, a fully housed mobile laboratory was used, and physical and microbiological testing were conducted on site.

As for well characteristics, a well inspection form was prepared and filled out based on the information provided by the Municipality and North Lebanon Water Establishment NLWE representatives. Table 5.2 shows a completed well inspection form for Chadra El Seha well. The two other wells inspection form are shown in Appendices.

Table 5.2 Well Inspection Form - Chadra El Seha

WELL INSPECTION FORM			
GPS Coordinates	Lat: 34.61973 Long: 36.32328	Well #	Chadra #2
City/Town	Chadra	Drilling Date	N/A
Kaza	Akkar	Inspection Date	9/2/2019
Measurement Point Elevation (m)	377	Well type	Public
Usage	Drinking	Chadra El Seha	
WELL & PUMP CHARACTERISTICS			
Well Diameter (m)	N/A	Year of Pump Installation	2006
Well Depth (m)	130	Pump Type	Caprari - E6X406
Casing Length (m)	N/A	Depth of Pump (m)	130
Screen Position (m)	N/A	Pump Power (HP)	25
Pumping Time per day (hr)	11	Highest Pumping Season	Summer
Aquifer Type	C4-C5	Permeability K (m/s)	N/A
Initial Piezometric Level (m)	80	Transmissivity T (m2/s)	N/A
Discharge Rate (m3/day)	276.5	Storativity S	N/A
WELL PERFORMANCE TEST			
# of steps / Discharge Rate (m3/hr) / Duration (hr)	N/A	N/A	N/A
Well Efficiency		N/A	
Additional Remarks: - Contaminated Well and Chlorine treated - Septic tanks under houses - Wastewater piping system exists but not working			

5.2.3 Water Testing

Groundwater contamination has many sources including pollutants entering the water table from sewage or corroded casings. Frequent testing is crucial to determine which contaminants are present and at what levels. Physical (i.e., Temperature, pH, Turbidity, Conductivity, and Total Dissolved Solids TDS) chemical (i.e., Ammonia, Nitrate) and bacteriological (i.e., E-Coli and Other Microorganisms) tests were conducted. Samples from 1st site visit were tested at Notre Dame University environmental laboratory, whereas samples from 2nd site visit were tested both on site and at university lab.

Results from both site visits were compared for validation and correction. All test results and WHO drinking water standards are presented in Table 5.3 and Table 5.4, respectively.

Table 5.3 Water Test Results.

		Site Visit #1			Site Visit #2					
		Testing Date: 11-2-2019 (LAB)			Testing Date: 19-5-2019 (ON SITE)			Testing Date: 21-5-2019 (LAB)		
TEST TYPE	WELL	Chadra El Seha	Chadra El Madraseh	Chadra El Nahr	Chadra El Seha	Chadra El Madraseh	Chadra El Nahr	Chadra El Seha	Chadra El Madraseh	Chadra El Nahr
PHYSICAL	Temperature (ºC)	NA	NA	NA	21	19.83	24.5	18	18	18.5
	pH	8.02	7.56	8.09	NA	NA	NA	7.57	8.01	7.89
	TDS (mg/L)	258	NA	143	294	NA	253	287	247	238
	Turbidity (NTU)	0.91	0.72	1.89	NA	NA	NA	0.18	0	0.62
	Condutivity (µS/cm)	621	508	447	586	NA	514	519	449	444
BACTERIOLOGICAL	E-Coli (CFU/100mL)	NA	NA	NA	NA	NA	-	-	-	-
	Other Microorganisms (CFU/100ml)	NA	NA	NA	NA	NA	-	-	-	-
CHEMICAL	Nitrate (mg/L)	20.54	UR	UR	NA	NA	NA	NA	NA	NA
	Ammonia (mg/L)	0.0457	0.3163	UR	NA	NA	NA	NA	NA	NA

NA: Not Available/ No test

UR: Under Range

Table 5.4 WHO Water Standards

Properties	Parameter	Unit	Standards (WHO)
Physical	pH	Pt. Co scale	6.5-8.5
	Turbidity	NTU	5
	TDS	mg/l	1000
	Conductivity	µS/cm	300
Chemical	Nitrate	mg/l	10
	Ammonia	mg/l	1.5

For Physical properties, all water samples from the three wells met WHO standards except for Electrical Conductivity (Value beyond WHO acceptable limit).

For Chemical properties, all water samples from the three wells met WHO standards except for Nitrate in Chadra El Seha well (20.54 mg/L > 10 mg/L). For Bacteriological properties, all water samples from the three wells met WHO standard.

It should be noted that the focus of this study will be on chemical contaminants only. Bacteriological analysis is beyond the scope of this research and will not be covered.

5.2.4 Software Modelling

MODFLOW is a U.S. Geological Survey modular finite-difference flow model that simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow to wells, areal recharge, evapotranspiration and flow through rivers can be simulated with MODFLOW

(MODFLOW, 2005). The flow field generated in MODFLOW is used to trace particle path lines using MODPATH. The two models use ModelMuse as the graphical user interface in order to create input files.

MODPATH is a particle-tracking post-processing program also designed by U.S. geological Survey (USGS). Output from steady-state or transient MODFLOW simulations is used in MODPATH to compute paths for imaginary "particles" of water moving through the simulated groundwater system. In addition to computing particles paths, MODPATH computes the times of travel for particles moving through the system. The Pollock method is implemented in the MODPATH algorithm (Pollock, 2012), which have been officially released as the particle tracking method for MODFLOW. The Pollock Method was first published in 1988 for semi-analytical particle tracking on rectilinear structured grids. The key assumption of the method is that each directional velocity components varies linearly within grid cell in its own coordinate system, which allows an analytical expression to be obtained describing the flow path within an individual grid cell (Pollock, 2012). Given the initial position of the particle as well as the cell geometry and the flows in through the cell faces, the particle coordinate along its path lines within the cell and its travel time can be computed directly without numerical integration. An important application of this method includes tracing particle path lines through any multidimensional flow field that is generated from a block-centered finite-difference groundwater flow model, such as MODFLOW. MODPATH is currently the fastest particle tracking algorithm available for finite- difference simulations.

In this study, each well and its surroundings (i.e., nearest sources of contaminants surrounding the well) was modeled with MODFLOW 2005. Results from MODFLOW were used to trace particles using MODPATH. The decision was made to study nitrate contaminant transport to the well as it represents a chemical contaminant of principal importance that is derived from on-site sanitation systems and agricultural practices (Argoss, 2001).

Figure 5.3: Chadra El Seha well grid - MODFLOW

For Chadra El Seha well software simulation, a 100x100m grid was generated using MODFLOW 2005 (Figure 5.3). This size was adopted to cover well surroundings and to not deteriorate model performance, in terms of hydrological processes, with a very large grid at the same time (DKSY Klaas *et al*., 2017). Subsequently, two soil layers, thickness of 95 and 50m respectively, were modeled with the confined aquifer being in the second layer. Due to the lack of data, an average wastewater effluent concentration of 40mg/L was considered in reference to Pennsylvania Department of Environmental Protection (PADEP). This value corresponds to the average nitrate concentration of wastewater flowing out of sewer systems. The input parameters used for modeling are summarized in Table 5.5 below:

Table 5.5 Input Parameters for MODFLOW Software - Chadra El Seha Well

Input Parameters for Nitrate-N Contaminant Transport Modeling	
Parameter	**Value**
Number of Layers	2
Layer Thickness (m)	95 and 50
Hydraulic Conductivity k (m/s)	1.00E-04
Porosity n	0.25
Initial Nitrate Concentration (mg/L)	40
Longitudinal Dispersivity (m)	10
Well Abstraction rate (m3/s)	-1.47E-03
Source Injection rate (m3/s)	1.157E-05
Well Depth (m)	130
Initial Piezometric Head (m)	80

Consequently, flow produced in MODFLOW was used to generate contaminant path lines using MODPATH package. These path lines were assessed in order to generate protection measures as will be shown in the following section. Figure 5.4 and Figure 5.5 below show the travel of contaminants from the five sources/house to the well.

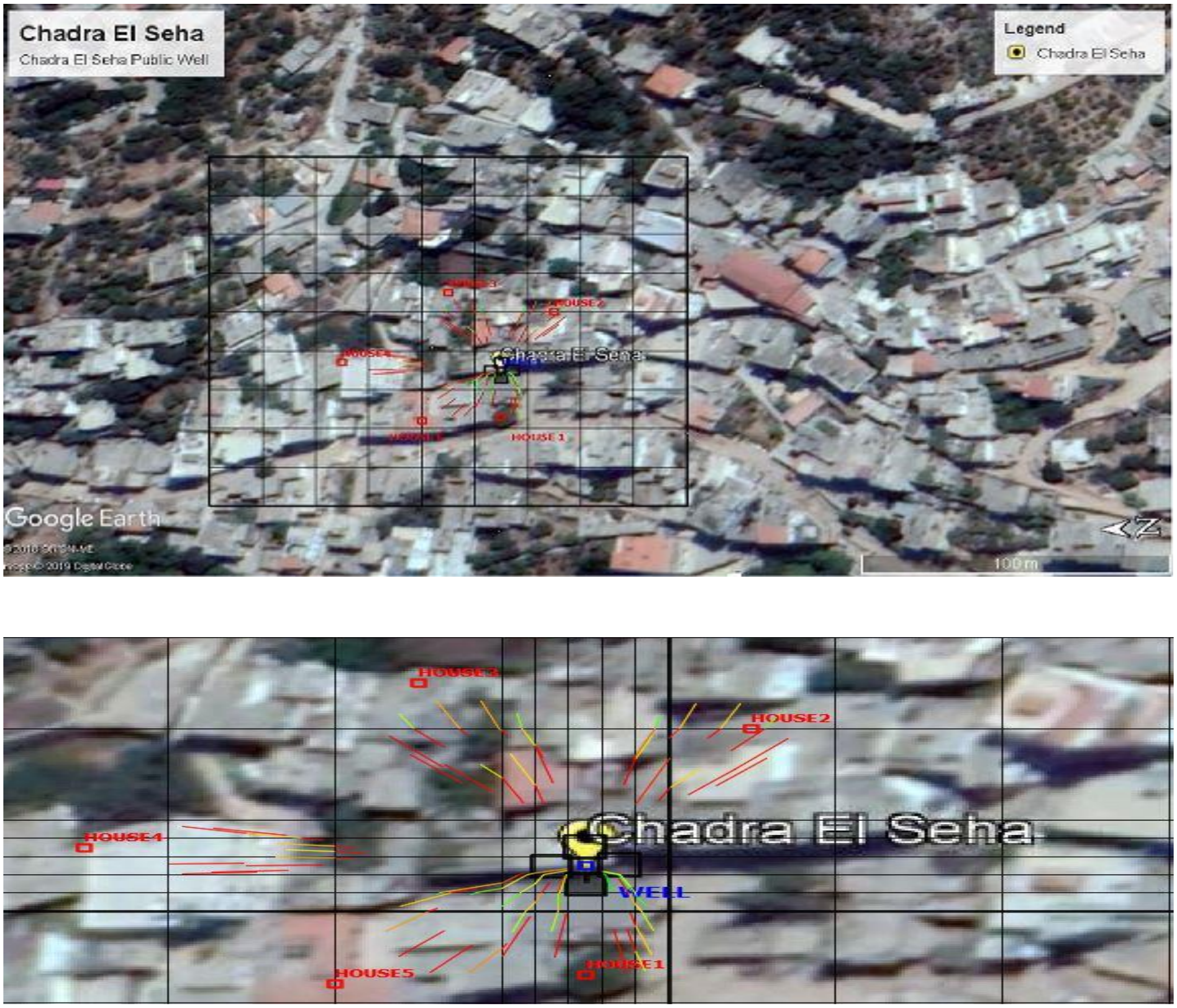

Figure 5.4: Chadra El Seha Well – Contaminant path 2D

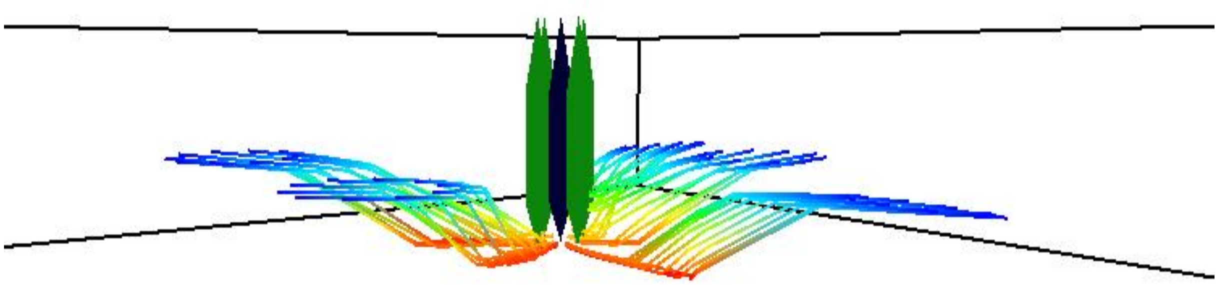

Figure 5.5: Chadra El Seha Well – Contaminant path 3D

Similarly, the remaining two wells were modeled in the same manner with different input parameters and grid size. For Chadra El Madraseh well, input parameters, contaminant path in 2D, and 3D are shown in Table 5.6, figure 5.6, and figure 5.7, respectively.

Table 5.6 Input Parameters for MODFLOW Modelling - Chadra El Madraseh Well

Input Parameters for Nitrate-N Contaminant Transport Modeling	
Parameter	**Value**
Number of Layers	2
Layer Thickness (m)	95 and 50
Hydraulic Conductivity k (m/s)	1.00E-04
Porosity n	0.25
Initial Nitrate Concentration (mg/L)	40
Longitudinal Dispersivity (m)	10
Well Abstraction rate (m3/s)	-1.60E-03
Source Injection rate (m3/s)	1.157E-05*
Well Depth (m)	110
Initial Piezometric Head (m)	80

**For School with 224 students - Well Abstraction rate :1.55E-04*

Figure 5.6: Chadra El Madrase Well – Contaminant Path 2D

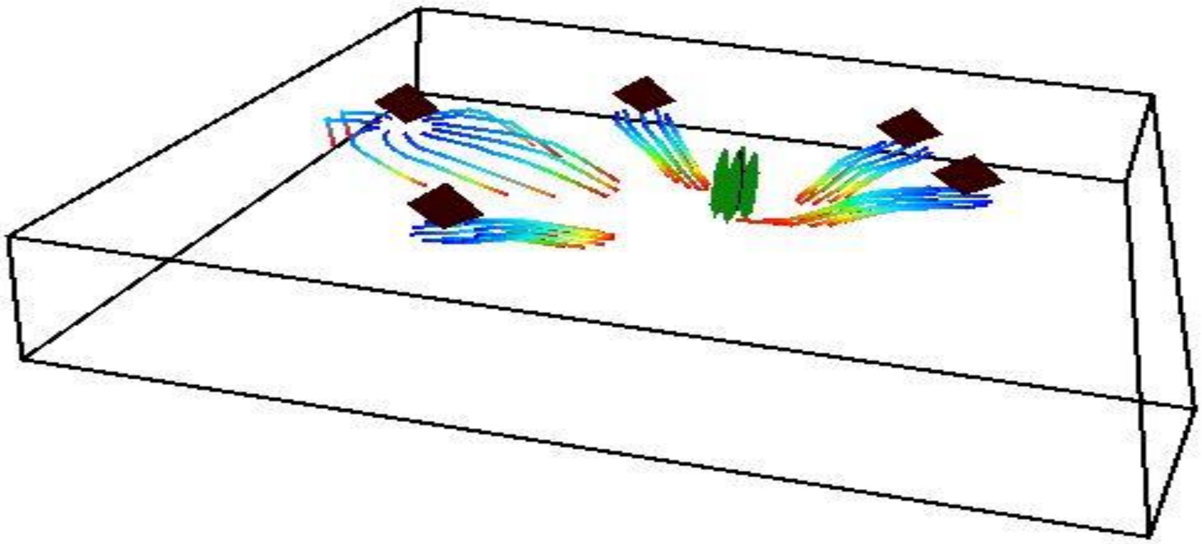

Figure 5.7: Chadra El Madrase Well – Contaminant Path 3D

For Chadra El Nahr well, input parameters, contaminant path in 2D, and 3D are shown in Table 5.7, Figure 5.8, and figure 5.9, respectively.

Table 5.7 Input Parameters for MODFLOW Modelling - Chadra El Nahr Well

Input Parameters for Nitrate-N Contaminant Transport Modeling	
Parameter	**Value**
Number of Layers	2
Layer Thickness (m)	95 and 300
Hydraulic Conductivity k (m/s)	1.00E-04
Porosity n	0.25
Initial Nitrate Concentration (mg/L)	40
Longitudinal Dispersivity (m)	10
Well Abstraction rate (m3/s)	-9.00E-03
Source Injection rate (m3/s)	1.157E-05
Well Depth (m)	350
Initial Piezometric Head (m)	80

Figure 5.8: Chadra El Nahr Well – Contaminant Path 2D

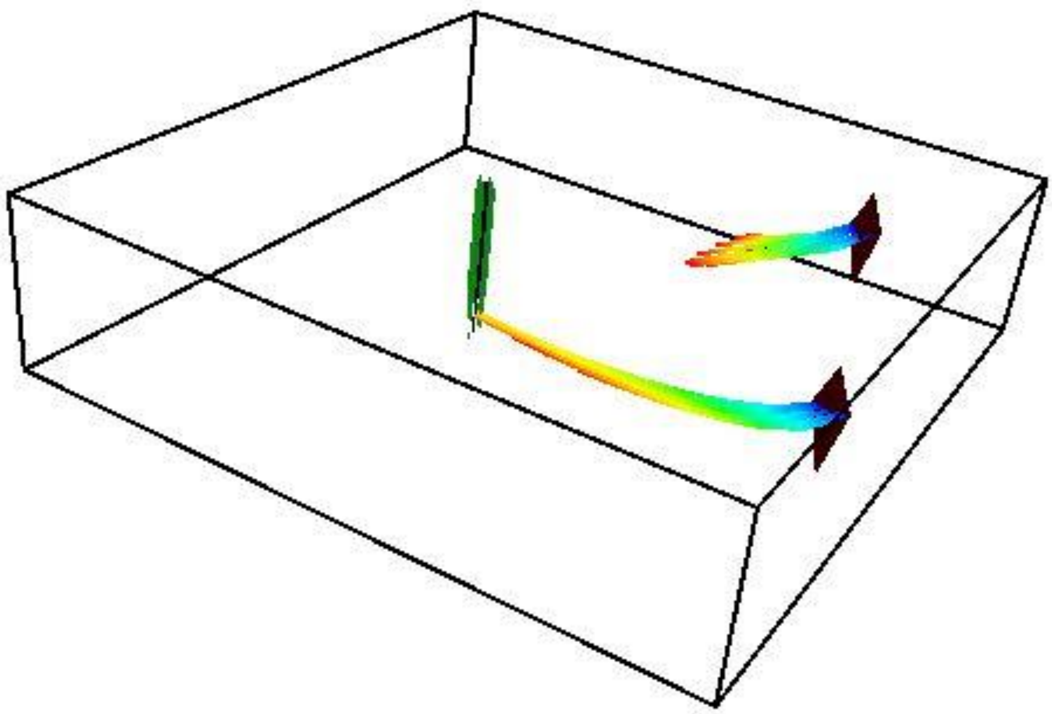

Figure 5.9: Chadra El Nahr Well – Contaminant Path 3D

5.3 RESULTS AND DISCUSSION

5.3.1 PROTECTION MEASURES

Based on numerical model results, three protection measures were generated and are summarized as follows:

1- Pumping Regime:

Determining a safe abstraction rate for a design period of 5 years based on travel of contaminants from critical/closest source to well.

2- Sanitation System:

Determining a safe setback distance, from sanitation system source to well, based on actual abstraction rate and a design period of 5 years.

3- Solid Waste Disposal:

Determining a safe setback distance, from solid waste disposal source to well, based on actual abstraction rate and a design period of 5 years.

Two factors were considered to define the design period of protection measures:

-Lead Time Factor: enough period is needed for initiation of protection measures and implementation of the proposed guidelines in the next chapter. In other words, the transitional phase from current situation towards adopting proposed solutions requires enough time period.

-Tolerable Outcome: longer design period will result in more conservative results in terms of safe abstraction rate and setback distance. Consequently, this will affect the water supply and the whole model will face social rejection.

For Chadra town, protection measures are summarized in Table 5.8 below:

Table 5.8: Protection Measures - Chadra Town

# PM	Variable			Protection Measure
PM1	Well	Distance to Critical Source - m	Time Period - year (day)	Safe Abstraction Rate - m3/d
	Chadra El Seha	12	5 (1825)	63.1
	Chadra El Madrase	28		110.6
	Chadra El Nahr	105		2004.5
PM2/3	Well	Actual Abstraction Rate - m3/d	Time Period - year (day)	Safe Setback Distance - m
	Chadra El Seha	127	5 (1825)	26
	Chadra El Madrase	138.25		50
	Chadra El Nahr	777.6		75

Table 5.9: Travel Time to well – Chadra Town.

Well	Variables		Result
	Actual Abstraction Rate - m3/d	Distance to Critical Source - m	Time for Contaminant to Reach the Well - year (day)
Chadra El Seha	127	12	2.41 (880)
Chadra El Madrase	138.25	28	4.014 (1465)
Chadra El Nahr	777.6	105	12.795 (4670)

As can be seen in Table 5.9, one safe setback distance was generated for sanitation system and solid waste disposal (i.e. PM2 & 3). The only difference between these latter is in the initial contaminant concentration; wastewater effluent nitrate concentration is assumed to be 40 mg/L whereas the average nitrate concentration of untreated solid waste leachate is estimated to be 75mg/L. Despite this difference, contaminant travel time and path lines trajectory are identical for both concentrations. This point was proven through software simulation.

For the protection measures, based on critical source distance in PM1, the actual abstraction rate for Chadra El Seha well is beyond the safe rate (63.1 > 127 m^3/d) for a design period of 5 years. This explains why the safe setback distance obtained for PM2/3 is greater than the actual distance (26> 12 m). Similarly, for Chadra El Madrase well, the actual abstraction rate is beyond the safe rate (138.25 > 110.6 m3/d) for a design period of 5 years. This explains why the safe setback distance obtained for PM2/3 is greater than the actual distance (50> 28 m). On the other hand, for Chadra El Nahr well, the actual abstraction rate is below the safe rate (2004.5 > 777.6 m3/d) for a design period of 5 years. This shows that the well is safe and explains why the safe setback distance obtained for PM2/3 is below the actual distance of the critical source (75< 105 m).

Furthermore, an additional analysis of software findings was performed showing the time needed by contaminants to reach the well from the critical source based on the actual abstraction rate (Table 5.7). For Chadra El Seha and Chadra El Madrase wells, table 7 shows that based on the current practice contaminants will need 2.41 and 4 years respectively to reach the well from the closest source. Accordingly, either a decrease in abstraction rate or an increase in the setback distance would guarantee an increase in the time for contaminant to reach the well. Therefore, both wells are considered unsafe for a design period of 5 years. On the other hand, based on the current practice in Chadra El Seha well, contaminants will need 12.8 years to reach the well from the closest source. Therefore, a design period of 5 years is considered safe.

5.3.2 Operational procedures

Based on protection measures developed in the previous section a water management program will be defined. This latter will be presented as operational procedures tackling pumping performance, sanitation system practices, and solid waste disposal. These procedures will provide solutions related to water consumption and contamination.

Pumping Regime

Based on the protection measures results, some wells are considered safe in terms of chemical contaminant for a design period of 5 years, while others are not. Therefore, pumping alternation should be introduced to control contaminant travel for a specific design period.

Considering Chadra town, actual abstraction rate for Chadra El Seha and Chadra El Madraseh should be reduced in order to meet protection measure criteria, as shown in protection measures section, whereas abstraction rate for Chadra El Nahr well can be increased. The scenario to be followed is illustrated in Table 5.10.

Table 5.10. Actual vs Pump Alternation Cases

	Pumping Rate (m3/d)			
Case	Chadra El Seha	Chadra El Madrase	Chadra El Nahr	Total Rate
Actual Case	127	138.25	777.6	1042.85
Pump Alternation Case	63.1	110.6	869.15	1042.85

Based on Table 5.8, abstraction rate of Chadra El Nahr well must be increased by around 95 m^3/d to overcome the reduction in the two other wells.

It should be noted that the yield of Chadra El Nahr well should be taken into consideration to determine whether this increase is possible or not. Moreover, this procedure is applicable for a design period of 5 years.

Next step that should be considered after controlling water quality is to adopt a technique to control water quantity. In order to achieve that, a water metering system must be introduced by water authorities to measure the volume of water used by residential and commercial buildings. The water metering strategy is complemented by a tariff system. This technique is already implemented in some Lebanese cities. Although there are no specific water tariff regulations in the Lebanese text laws, text law 221/2002 mentions the elements to be considered in the pricing of water: ***"Water establishments will be in charge each within its region and competence of putting tariffs for potable, irrigation and wastewater taking into consideration social, and general economic constraints" (par.1 section b of article 4).*** (Melki, 2014). In order to validate the efficiency of such solution, a study performed in California by Tanverakul and Lee (2015) on the impact of metering on residential water use showed that unmetered residences used more water than comparable metered residences by an average of 22.67% in 3 cities. Also, after implementing the water metering system for a six-month period, the average monthly water consumption decreased within the newly metered residences by 17%.

Sanitation system

As per municipalities, a sewage collection system is being currently built in Akkar. In the meantime, citizens are building their own sanitation systems of pit latrines and septic tanks. Sanitation systems are one of the leading causes of groundwater contamination in Lebanon (Houri and Jeblawi, 2007). That is due to the lack of local governance and regulations that organize the construction of these systems, in addition to the absence of any supervision to monitor private systems. Septic tanks are mostly used in areas where no sewage collection systems are available. When not properly maintained and cleaned, septic tanks pose a great danger on the surrounding ground water. That is why, emptying of septic tanks/pit latrines should be regularly performed.

The frequency of emptying tanks or latrines is determined based on:

- Loading rate
- Performance of septic tanks
- Local rules and regulations

Furthermore, a proper design of septic tanks should be followed. Newly constructed septic tanks should conform with the approved design of the Ministry of Environment shown in the following schematic (Figure 5.10).

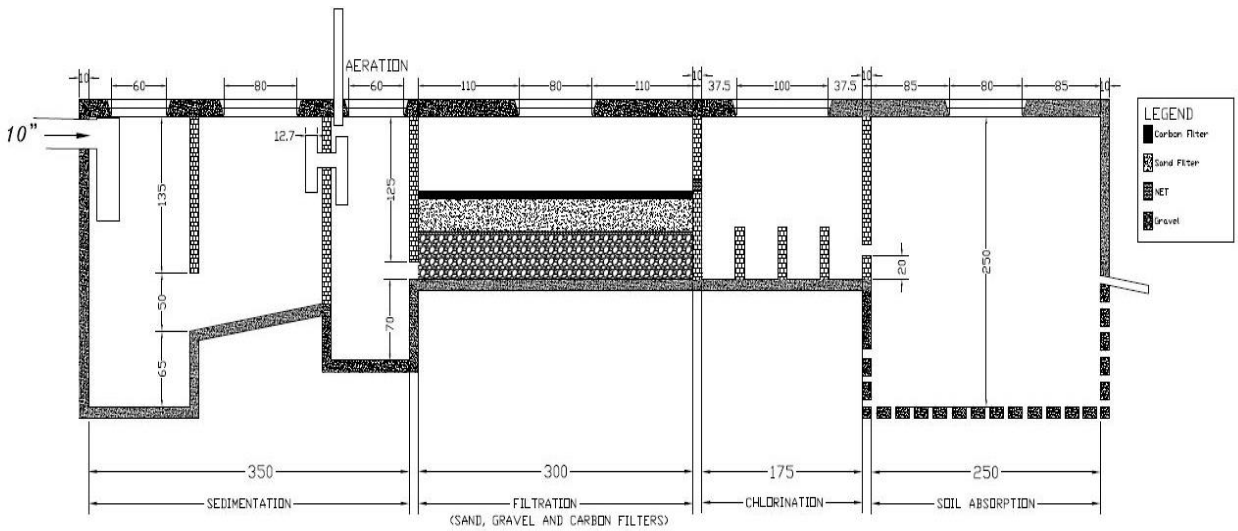

Figure 5.10: Proper Septic Tank Design

Lastly, routine operation and maintenance (O&M) of the on-site sanitation system (OSS) is extremely critical to ensure safe and efficient sludge and management practices. In general, communities tend to underestimate the importance of proper OSS design and O&M and tend to neglect them, especially in poor areas due to the lack of money. However, local authorities should increase the community awareness by educating and informing property owners about the importance of the proper functioning and maintenance requirements of these systems and encourage regularly cleaning.

The on-site O&M responsibilities of sanitation infrastructure (private) for which property owners are responsible include:

- Repair and maintenance of toilets, septic tanks, soak pit and piping
- Clearing pipe blocks
- Identification and repair of cracks
- Getting fecal sludge emptied from private or municipal vacuum emptier at an interval of 2-3 years or as per local regulations.

Solid waste disposal

Solid waste disposal is also one of the leading causes of groundwater contamination especially due to the leachate, which is the liquid generated from solid waste decomposition. If not collected or treated, leachate can migrate from the point of generation and contaminants soil, groundwater, and surface water (ISWA, 2016).

The key to solid waste management is at source. Therefore, the most critical aspect of the solid waste disposal is the community awareness and engagement. This can be achieved through sorting the waste at every source. Sorting is done to segregate the waste into different categories based on their type and if they are recyclable or not:

- Dry recyclables
- Construction and demolition waste
- Biodegradable waste or organic waste
- Bulky waste (too large to be accepted by regular collection)
- Hazardous waste

- Mixed MSW (often referred to as comingled waste)

Although it is the most important, as it will make the whole process easier, waste sorting systems should be initiated and controlled by local authorities. Finally, sorting at the source is meaningless if the other sorting stages are not respected:

- At municipal bins
- At transfer stations or centralized sorting facilities
- At waste processing sites (pre and post sorting)
- At landfills

Another technique for solid waste disposal is “dumpsite relocation/rotation”. This method is usually applicable for waste removal from a specific dumpsite to another waste handling facilities to take the waste, specifically a new sanitary landfill (ISWA, 2016). In this study the same concept is proposed, however moving from one dumpsite location to a safer one as a short-term solution. The site selection process is usually one of the most critical steps in the waste management cycle. Social, economic, and environmental impact should be considered to come up with an appropriate location. Therefore, direct public involvement, economic impact in the surroundings, and detailed well, geological, and hydrogeological characteristics should be considered.

Considering Chadra town, dumpsite location should be far enough from residential and commercial units in order to be socially and economically accepted. These two criteria comply also with well and hydrogeological characteristics as both Chadra El Seha and Chadra El Madraseh are located in the center of the town and are considered unsafe in terms of groundwater contamination from solid waste leachate. On the other hand, Chadra El Nahr well is located far away from town's center and is hydro-geologically safe, as previously mentioned in protection measures section.

Therefore, a five-year design period should be considered as a transitional phase leading to dumpsite closure and upgrading into controlled sanitary landfill. Closure by upgrading of an open dumpsite includes the use of low permeability cap and a topsoil layer over the existing waste mass which can then be vegetated. For Chadra Town, and based on 5 years design period, a potential location can be at a certain site, considering also geographical features, beyond the red circle shown in Figure 5.11.

Figure 5.11: Potential Dumpsite Location

By that, selecting a suitable location for waste disposal would accelerate the transition to a controlled sanitary landfill with proper liner. This technique will require continuous monitoring and assessment of the site.

5.4 Conclusion

The aim of this study is to assess current groundwater contamination and develop guidelines to increase water security in a remote area of Lebanon, specifically Akkar area. In order to achieve that, 3 wells were selected for the study; Chadra El Seha, Chadra El Madraseh, and Chadra El Nahr well.

As a first step, two site visits, in February and May, were conducted to collect water samples from wells for testing. Physical, chemical, and bacteriological analysis were conducted on site and at NDU laboratory. All wells did not meet electrical conductivity standards for drinking water. For Chemical analysis, Chadra El Seha well showed out of range value of nitrate concentration.

Secondly, all wells were modeled using MODFLOW 2005 and flow fields were generated. These latter were used to generate contaminant path lines, specifically for nitrate contaminant, using MODPATH package. Subsequently, protection measures were generated, for a design period of five years, based on contaminant path lines. These measures were based on a safe well abstraction rate and safe setback distance. Results showed that Chadra El Nahr well is safe for a design period of 5 years, whereas the common practices for Chadra El Seha and Chadra El Madraseh wells need to be adjusted in order to meet protection measures criteria for the 5 years period.

Accordingly, a water management program was developed aiming toward reducing water consumption and pollution. This program was presented as operational procedures for pumping regime, sanitation system, and solid waste disposal. For pumping regime, pump/well alternation and water metering system were proposed to control water quality and quantity respectively. For sanitation system, desludging, proper septic tank design, and operation and maintenance program were proposed to extensively reduce wastewater leaching into the ground. For solid waste disposal, waste sorting and dumpsite relocation were suggested to reduce the amount of solid waste and prevent their leachate from reaching the well, respectively.

This study relates to groundwater resource management in several ways. First, the followed methodology is applicable for the study of possible water well or improvement in performance of an existing well at any geological setting. In addition to hydrological features and well parameters, the effect of well surroundings on groundwater contamination is considered to ensure access to clean water. Additionally, generated remediation measures are used to develop a list of guidelines for promoting water safety and security at the local level:

1- Pump/well abstraction rate alternation.
2- Water metering system.
3- Sanitary surveillance program.
4- Regular emptying of septic tanks.
5- Comprehensive solid waste sorting.
6- Dumpsite relocation.

Community outreach is a key point in this study. Community members must understand the importance of safe water practices and help, along with local authorities, to put these actions in place. Finally, this plan of action, while developed for a specific remote area, can serve as templates for other areas in Lebanon and around the world.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

6.1 Summary

Lebanon is naturally reach in water resources including surface water, groundwater, and springs owing to heavy rainfall and snowfall in winter season and the prevalence of Karstic geology. Though, overexploitation and mismanagement of water resources along with poor sanitation practices have led to water shortage and groundwater contamination. Consequently, there is a need to assess the groundwater flow and contaminant transport in Karstic aquifers in order to have a better understanding of groundwater movement through conduits and help create management plans to access safe water.

In this study, fast flow regime or flow through karstic conduits will be investigated as it governs groundwater flow in karstic formation. A 2D experimental prototype was constructed with 300x180cm overall size and conduit diameter of 8 mm. A confined aquifer was achieved with a high-level tank, and the flow through the 6 vertical and 4 horizontal conduits was controlled by faucets. All system nodes were equipped with vertical piezometers to measure hydraulic head.

In the first experiment, seven trials were performed, with different pumping rate and discharge node, in order to determine the variation in hydraulic heads throughout the system. For each trial, hydraulic head were recorded at a specific time period and for specific nodes.

Subsequently, the prototype was modeled on MODFLOW software and conduits were replicated by inserting high conductivity flow layers with 8 mm thickness that can switch between laminar and turbulent flow duplicating the flow through karstic conduits. Several iterations were performed in order to obtain the hydraulic conductivity (200 m/s) that matches experimental condition. Consequently, flow field was generated for each trial and the hydraulic heads at each node were recorded. Experimental and numerical results were compared, and a linear trend was generated. Additionally, 95% confidence curves were generated to assess the efficacy of the experiment, and 7 out of 24 outcomes were considered as outliers.

In the second experiment, Ammonia contaminant concentration variation throughout the prototype conduits was assessed. The system was equipped with a submersible pump to inject a dyed contaminated water at a certain injection point and four collection nodes to collect water samples. Four trials were performed with different initial contaminant concentration, injection rate, discharge rate, and hydraulic head. Samples were collected from the collection nodes at two time periods (60s & 120s, or 120s & 180s). Subsequently, collected samples were tested for ammonia concentration using the spectrophotometer and medium range ammonia vials. On the other hand, the prototype was modelled on MODFLOW with the same input data for each trial. Based on the flow field generated in MODFLOW, MT3DMS package was used in order to determine the contaminant concentration variation throughout the prototype and specifically at collection nodes. Consequently, experimental and simulated concentration were compared, and linear trend was generated (R^2 =0.74). Similarly, 95% confidence curves were generated to assess the efficacy of the experiment, and 4 out of 20 outcomes were considered as outliers.

Further, identification of contaminant path lines and travel time to reach collection nodes were concurrently investigated on three out of the four trials of experiment 2. Besides that, the flow field generated on MODFLOW was used along with MODPATH package to numerical determine the travel time for the contaminant to reach the collection nodes. Experimental and numerical times were compared, and a linear trend line was generated (R^2=0.79).

Errors were encountered in the three experiments and were mainly human ones related to inaccuracy of head, discharge rate, and injection rate measurements; lag time in collecting water samples and travel time recording; inaccurate tracking of contaminant movement. Also, instrumental errors affected experimental results especially in the concentration measuring device.

Additional analysis was conducted on experimental results in order to mathematically predict contaminant concentration at ant node of the prototype. A regression analysis was conducted and a multiple linear regression equation, with six variables, that best fits the experimental data was developed. Additionally, regression statistics were generated and showed a good coefficient of determination R^2=0.83. Also, the regression model significance was validated through the F-test that showed an F-value much higher than F-critical (10.76>2.93), and a very low probability of higher F-value (0.0002). As a result, the regression equation was proved to be useful in predicting the assessed value of contaminant concentration at any node. This equation can be used to predict contaminant concentration without the need to conduct experimental trials. Also, this model can be replicated to an actual field case to predict contaminant concentration and prevent possible water contamination.

Additionally, a case study was conducted to assess chemical contaminant transport to a contaminated public well in Northern Akkar area, specifically Chadra village. In order to achieve that, water samples were collected from Chadra El Seha well. Physical (i.e., turbidity, total suspended solids, total dissolved solids) and chemical (i.e., pH, ammonia, and nitrate) tests were conducted on the water samples at NDU laboratory. Results showed that nitrate concentration level exceeded WHO standards (20.54 mg/l > 10mg/l). Subsequently, the well and its surroundings (e.g., nearest 5 houses or sources of contaminants surrounding the well) were modeled with MODFLOW 2005. The well and geological characteristics were extracted from groundwater study previously conducted in the Akkar area by NDU's research team and from literature. The flow field generated in MODFLOW was used along with MODPATH and MT3DMS to determine contaminant path lines and concentration variation from source to well, respectively.

As a first step, a parametric study was conducted by changing certain variables to determine their effect on the contaminant path toward the well. The studied variables were porosity, time period, and well abstraction rate. Results showed that by increasing the porosity from 0.25 to 0.5, the contaminant travel distance decreased. This inversely proportional relationship between porosity and contaminant path is mainly due to the advection, dispersion and chemical retardation mechanisms that govern contaminant transport in groundwater. As porosity increases, contaminants are more dispersed and move slower while passing through large pores, leading to relatively shorter paths. Time period and well abstraction rate showed a proportional relationship with contaminant travel distance. As time period increased from 1 to 6 month and abstraction rate increased from 0.00075 to 0.003 m^3/s, contaminant path increased. Both results are logical as contaminants are given enough time to reach the well or a faster pace, respectively.

The second step in the study was to validate laboratory testing results. Therefore, MT3DMS package was used to determine the variation of nitrate concentration from source to well at a 5 years period. This latter representing the time the well has been in operation. Subsequently, nitrate concentration at the well level was determined and was equal to 25 mg/l. Consequently, nitrate-transport modeling reflected the actual field/lab results to a large extent despite several assumptions made on hydrogeological and chemical transport properties.

Finally, the assessment of chemical contaminant transport to a contaminated well was taken to the next level, and software results were used to generate groundwater management guidelines to prevent water contamination and reduce water usage. In order to achieve that, three wells were selected for the study all located in Northern Akkar area, specifically Chadra village: Chadra El Seha, Chadra El Madraseh, and Chadra El Nahr. Two site visits were conducted to collect water samples from wells for testing. Physical, chemical and bacteriological analysis were conducted both on site using a movable laboratory and at NDU laboratory. As a result, Chadra El Seha well showed out of range value of nitrate concentration. Subsequently, all wells were modelled with their surrounding using MODFLOW software and MODPATH package to generate nitrate contaminant path lines. These latter were used to generate protection measures, for a design period of 5 years, related to safe well abstraction rate and safe setback distance from point source to well. Results showed that Chadra El Nahr well is safe for a design period of 5 years, whereas current practices in Chadra El Madrase and Chadra El Seha must be adjusted in order to meet protection measures criteria for 5 years period. Then, water management guidelines were generated, based on protection measures, and were presented as operational procedures for pumping regime (pump/well alternation, water metering system) sanitation system (Sanitary surveillance program, desludging), and solid waste disposal (solid waste sorting, and dumpsite relocation).

Ultimately, understanding groundwater hydraulics and contaminant movement in karstic aquifers is a key factor to implement safe water practices. Though, community outreach will always be the focal point in every study in understanding the importance of water safety and to work together along with authorities in putting these studies and plans in action.

6.2 Recommendations

Based on the observations from this study, the following recommendations are made for future studies:

1- Groundwater flow and contaminant movement were experimentally investigated on one specific prototype porosity. Therefore, future studies are recommended to evaluate the effect of porosity on hydraulic head, contaminant concentration variation, and contaminant travel time. Also, to find a correlation between porosity and the studied variables by introducing different pipe size into the prototype. This relationship can then be upgraded into field studies to investigate karstic formation with its complex conduit network. This exercise is currently being conducted with NDU undergraduate senior group under Dr. Khoury's supervision.

2- The flow through low-conductive rock matrix and water infiltration into soil (primary porosity), as well as the exchange between slow flow components (primary) and fast flow components (secondary) were not addressed in this study. It is recommended that future test introduce soil materials into the current prototype and evaluate contaminant transport and groundwater movement.

3- The study of contaminant transport was supposed to be done on both nitrate and ammonia. However, due to the ongoing global pandemic, it was no longer feasible to conduct trials on nitrate and experimental studies were only restricted to ammonia, whereas case studies investigated nitrate contaminant transport from point source to well. Therefore, it is necessary to conduct experimental trials on nitrate and compare the behavior of each chemical compound on contaminant transport. Also, future studies should assess bacteriological contaminant performance as it poses major effect on the human health and environment

4- The study of hydraulic head and contaminant concentration variation, as well as contaminant travel time throughout the system were conducted on a two-dimensional, fully saturated, and confined karstic aquifer with equally spaced conduit rows and columns. A future study is recommended to include more sophisticated three-dimensional karst system with coupled saturated and unsaturated flow and alternating fast and slow flow regimes (as previously stated). Such model will include all effects that should be considered to replicate groundwater flow through different compartments passing from soil-epikarstic zone, vadose zone, to the phreatic zone.

5- Contaminant path lines generated in this study for sanitation system and solid waste disposal measures showed identical results in terms of safe setback distance. This was mainly due to the limited data on leachate properties and loading rate. Future studies are recommended to evaluate the difference between point and nonpoint source of contamination in terms of contaminant type, loading rate, and transport mechanism. Additionally, the same concept can be applied on tracking of residual agricultural contaminants derived from fertilizers to limit groundwater pollution and promote safe agricultural practices

6- The groundwater management plan methodology focused on contaminant transport from source to a contaminated well. Future studies are recommended to upgrade this methodology to predict the impact of underground contaminant transport on surface water bodies.

APPENDICES

1- MODFLOW - Hydraulic Head Variation

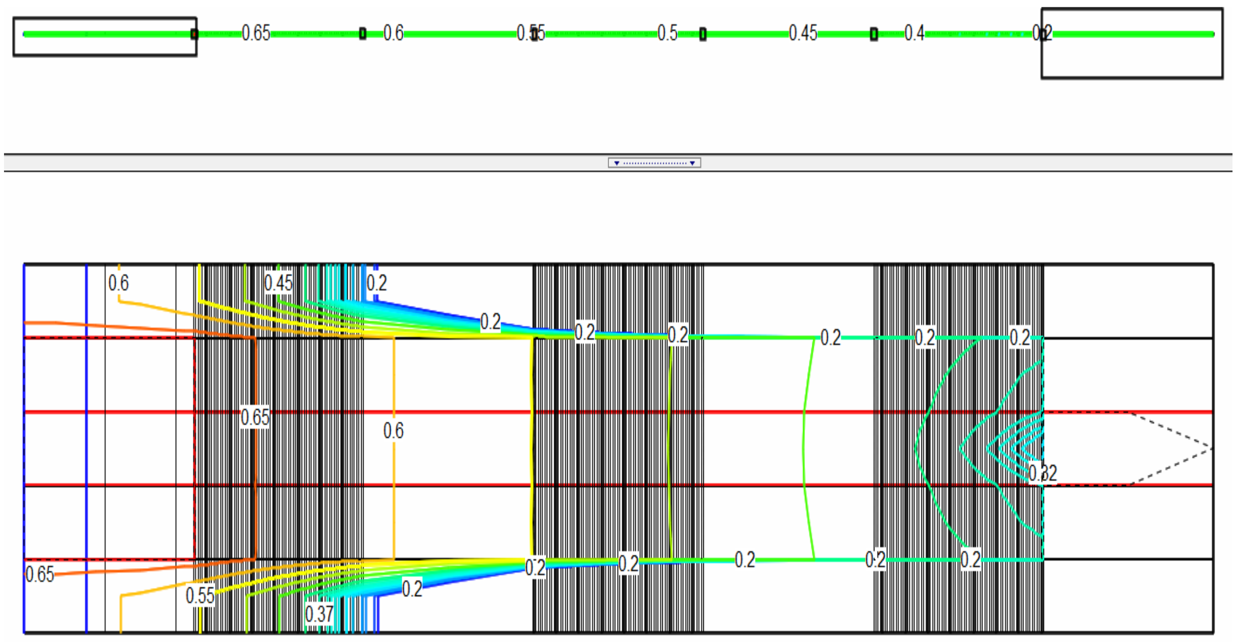

Figure 3.21: MODFLOW – Hydraulic Head Distribution – Discharge Node 22.5

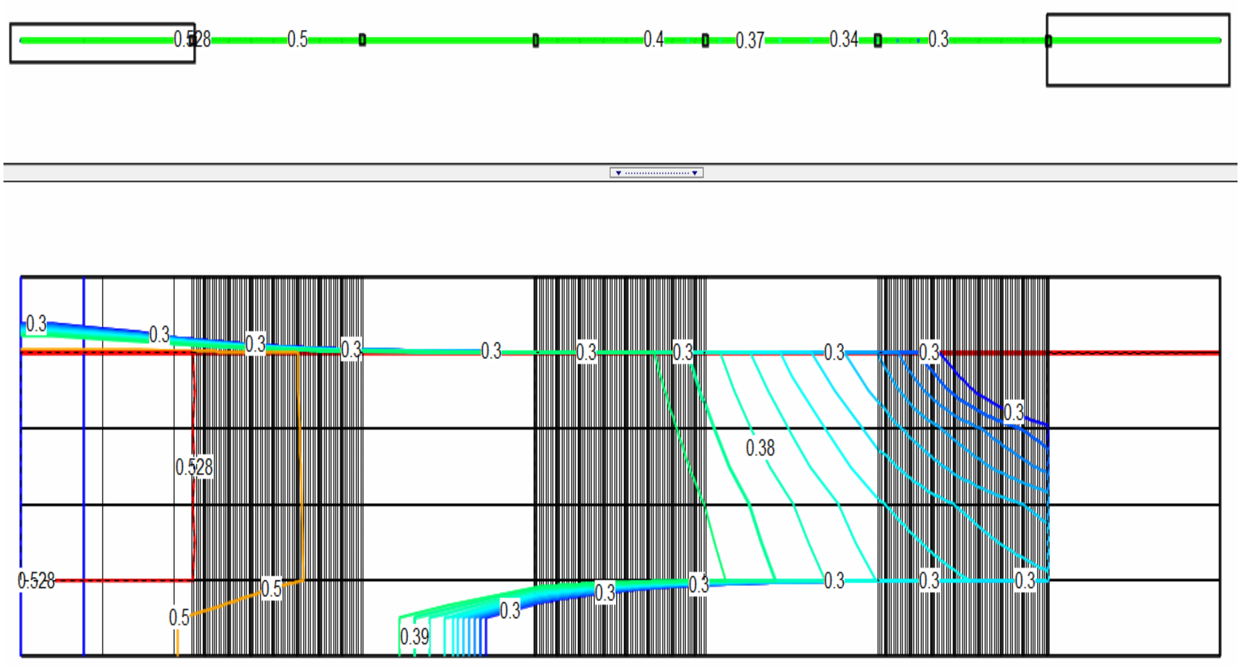

Figure 3.22: MODFLOW – Hydraulic Head Distribution – Discharge Node 21

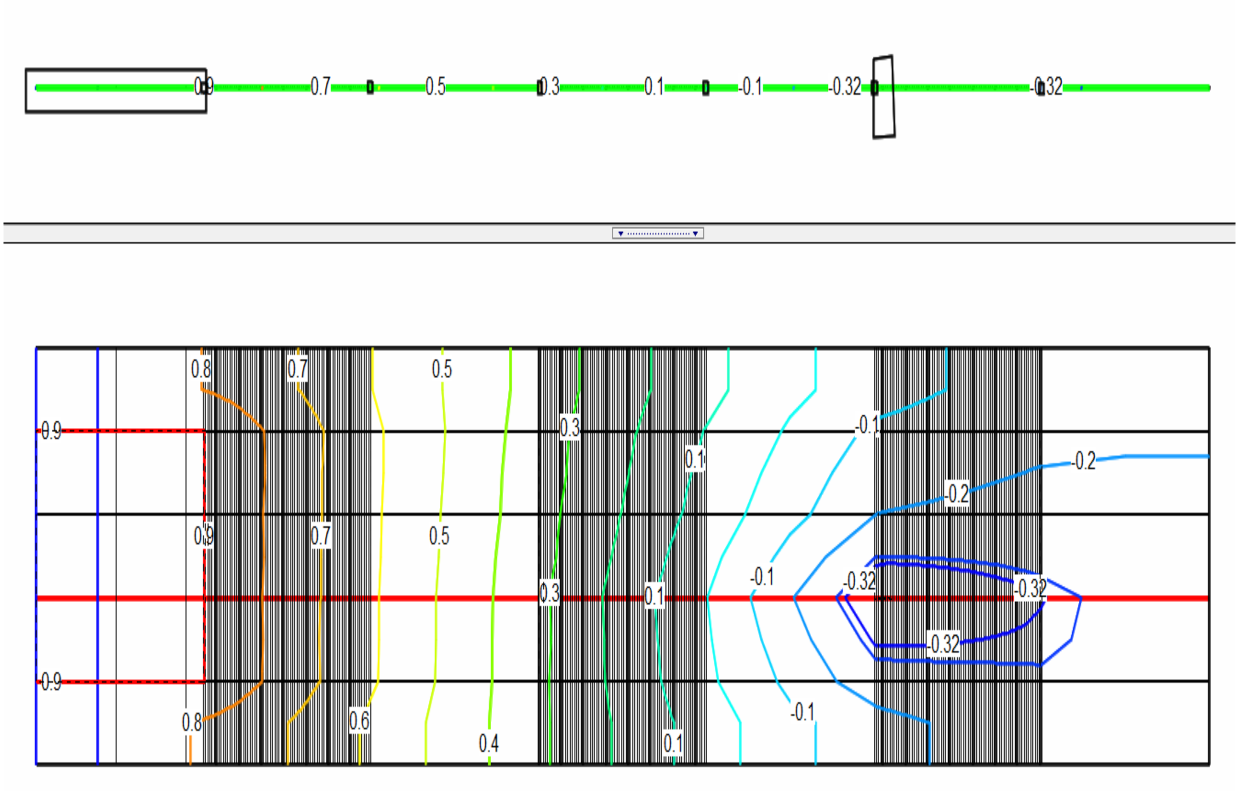

Figure 3.23: MODFLOW – Hydraulic Head Distribution – Discharge Node 19

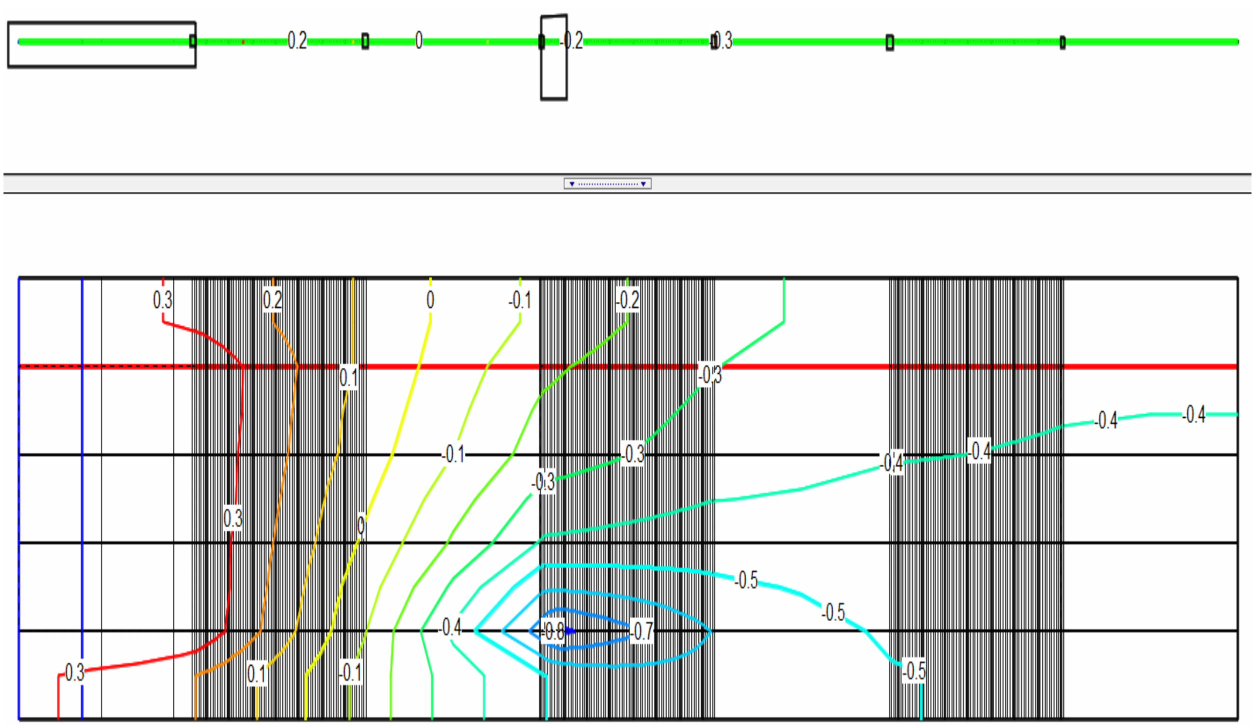

Figure 3.24: MODFLOW – Hydraulic Head Distribution – Discharge Node 12

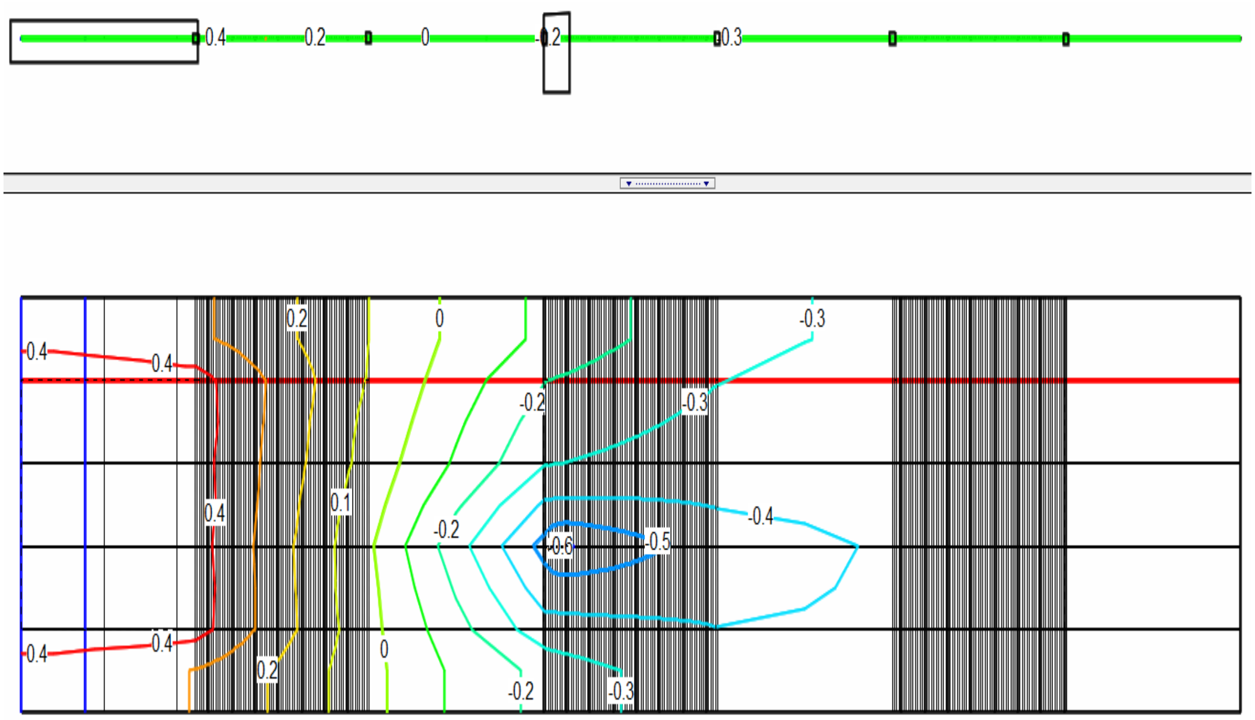

Figure 3.25: MODFLOW – Hydraulic Head Distribution – Discharge Node 11

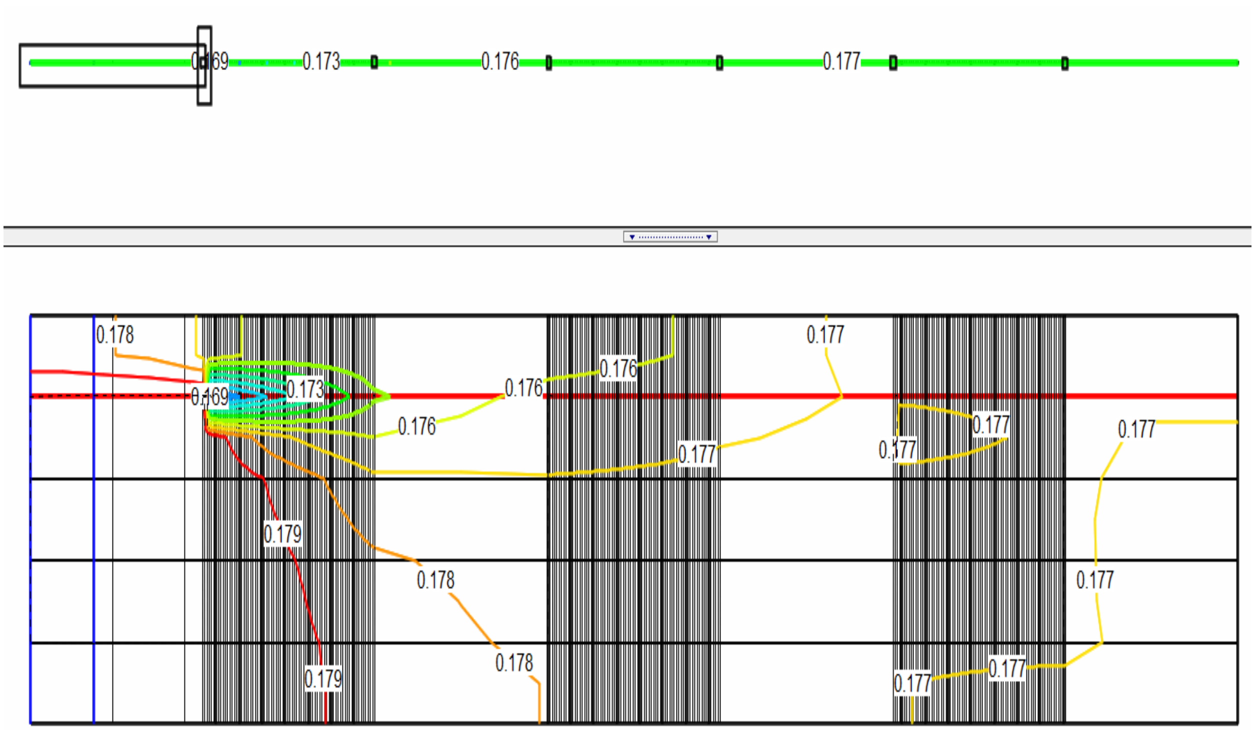

Figure 3.26: MODFLOW – Hydraulic Head Distribution – Discharge Node 1

2- MT3DMS – Contaminant Concentration Variation

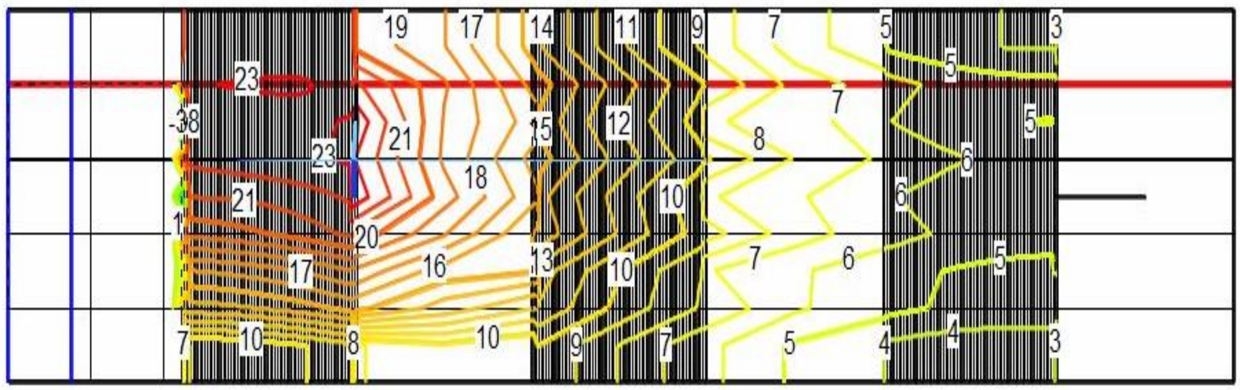

Figure 3.27: Concentration Variation – Trial 1 – Time Period = 60s

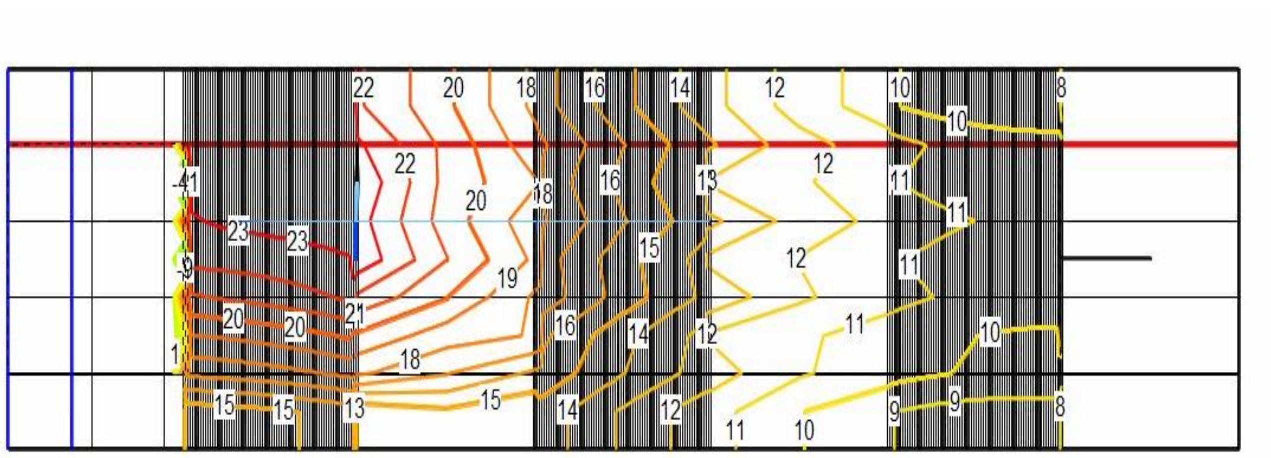

Figure 3.28: Concentration Variation – Trial 1 – Time Period = 120s

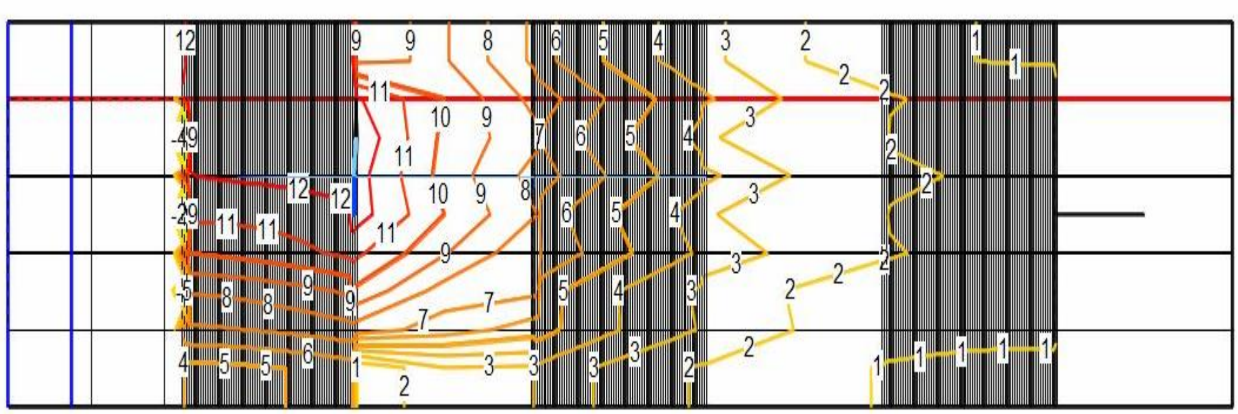

Figure 3.29: Concentration Variation – Trial 2 – Time Period = 60s

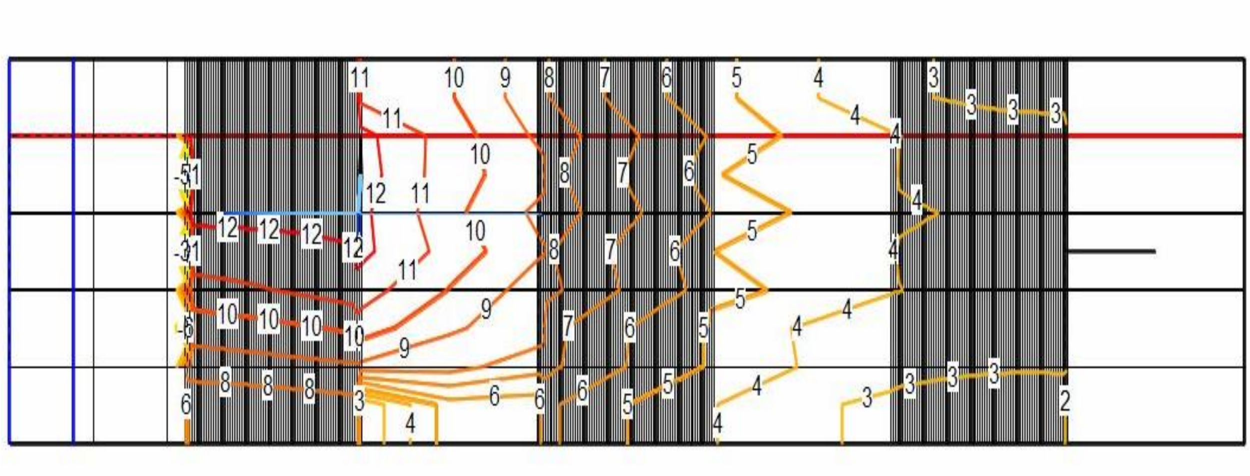

Figure 3.30: Concentration Variation – Trial 2 – Time Period = 120s

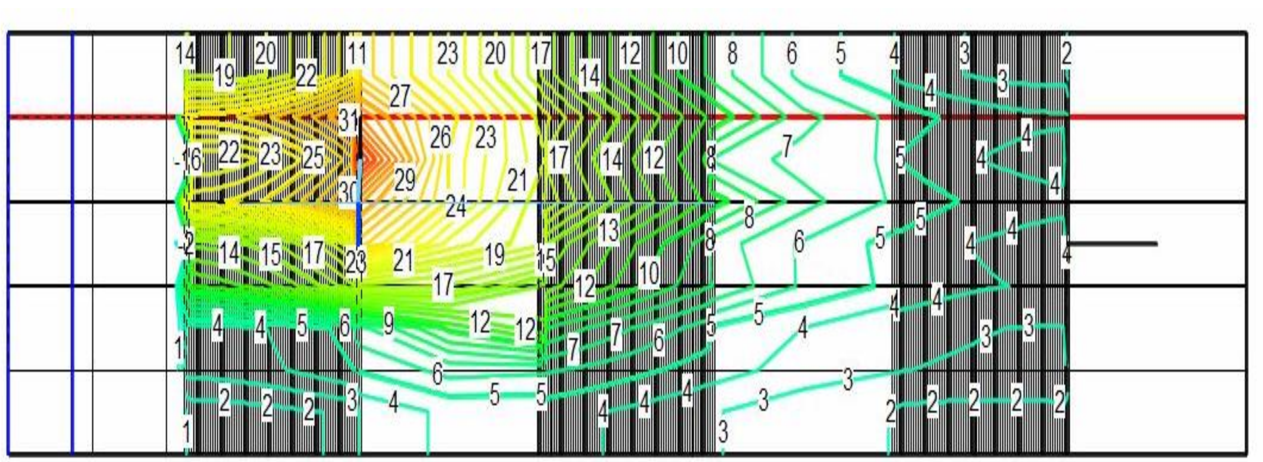

Figure 3.31: Concentration Variation – Trial 3 – Time Period = 60s

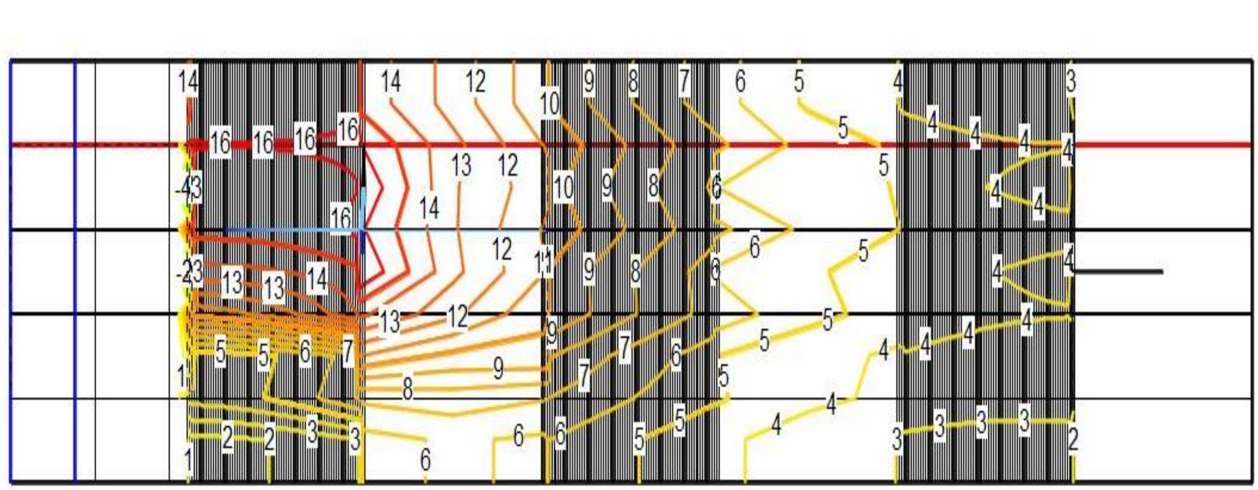

Figure 3.32: Concentration Variation – Trial 4 – Time Period = 120s

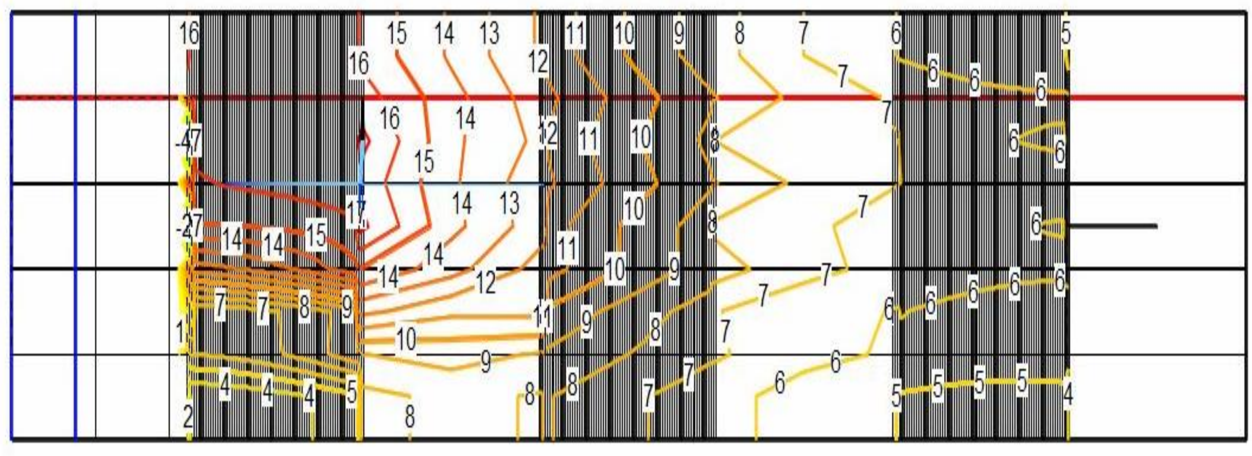

Figure 3.33: Concentration Variation – Trial 4 – Time Period = 180s

3- WELL INSPECTION FORMS

Table 5.11: Well Inspection Form – Chadra El Madraseh

WELL INSPECTION FORM			
GPS Coordinates	**Lat: 34.61702 / Long: 36.32218**	Well #	**Chadra #1**
City/Town	**Chadra**	Drilling Date	**N/A**
Kaza	**Akkar**	Inspection Date	**9/2/2019**
Measurement Point Elevation (m)	**369**	Well type	**Public**
Usage	**Drinking**	**Chadra El Madraseh**	
WELL & PUMP CHARACTERISTICS			
Well Diameter (m)	**N/A**	Year of Pump Installation	**1995**
Well Depth (m)	**135**	Pump Type	**Caprari**
Casing Length (m)	**N/A**	Depth of Pump (m)	**110**
Screen Position (m)	**N/A**	Pump Power (HP)	**25**
Pumping Time per day (hr)	**12**	Highest Pumping Season	**Summer**
Aquifer Type	**N/A**	Permeability K (m/s)	**N/A**
Initial Piezometric Level (m)	**80**	Transmissivity T (m2/s)	**N/A**
Discharge Rate (m3/day)	**276.5**	Storativity S	**N/A**
WELL PERFORMANCE TEST			
# of steps / Discharge Rate (m3/hr) / Duration (hr)	**N/A**	**N/A**	**N/A**
Well Efficiency	**N/A**		

Additional Remarks:

- Chlorine Injected Well

Table 5.12: Well Inspection Form – Chadra El Nahr

WELL INSPECTION FORM			
GPS Coordinates	**Lat: 34.6145 / Long: 36.32084**	Well #	**Chadra #3**
City/Town	**Chadra**	Drilling Date	**N/A**
Kaza	**Akkar**	Inspection Date	**9/2/2019**
Measurement Point Elevation (m)	**N/A**	Well type	**Public**
Usage	**Drinking**	**Chadra El Nahr**	
WELL & PUMP CHARACTERISTICS			
Well Diameter (m)	**N/A**	Year of Pump Installation	**N/A**
Well Depth (m)	**350**	Pump Type	**N/A**
Casing Length (m)	**N/A**	Depth of Pump (m)	**N/A**
Screen Position (m)	**N/A**	Pump Power (HP)	**N/A**
Pumping Time per day (hr)	**N/A**	Highest Pumping Season	**Summer**
Aquifer Type	**N/A**	Permeability K (m/s)	**N/A**
Initial Piezometric Level (m)	**80**	Transmissivity T (m2/s)	**N/A**
Discharge Rate (m3/day)	**777.6**	Storativity S	**N/A**
WELL PERFORMANCE TEST			
# of steps / Discharge Rate (m3/hr) / Duration (hr)	**N/A**	**N/A**	**N/A**
Well Efficiency	**N/A**		

Additional Remarks:

- Well not contaminated

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