Modelling of Groundwater Flow and Contaminant Transport in a Karstic Formation Using Finite Difference Approach

Master Thesis Defense

Submitted By : Jeffrey Fadlallah

Thesis Advisor: Naji Khoury, PhD, PE

Committee Members: Dr. Jacques Harb - Dr. Sophia Ghanimeh
Master Advisor: Dr. Talal Salem

May 12, 2020

OUTLINE

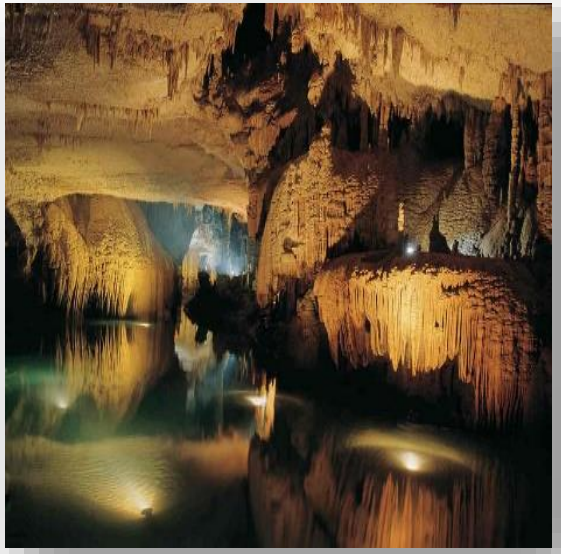
- INTRODUCTION
- PROBLEM STATEMENT
- OBJECTIVES
- PART I: Groundwater Flow Through Karstic Conduits
- PART II: Contaminant Movement Through Karstic Formation
- PART III: Case Study
- PART IV: Groundwater Management Program
- CONCLUSIONS
- PUBLICATIONS

INTRODUCTION

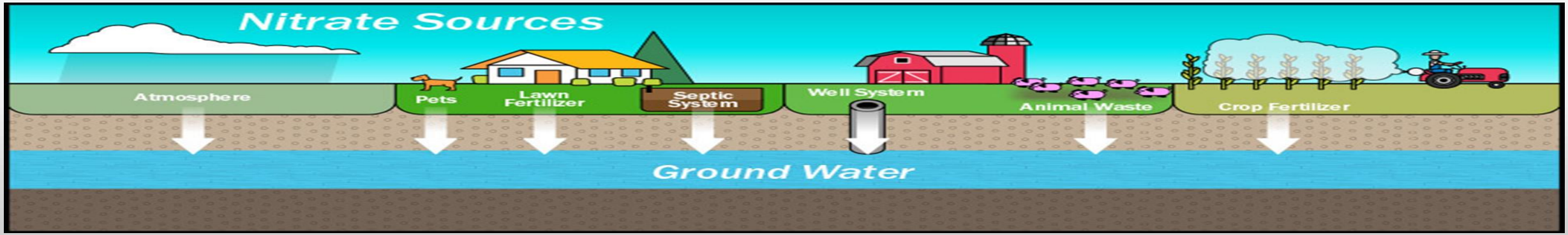
Background and Needs

- Overexploitation of Lebanon's groundwater
- Inadequate national and local governance
- Increased population & Syrian refugees
- Mismanagement of water resources

Karstic Geology



Importance of Snow



PROBLEM STATEMENT

Water scarcity and groundwater contamination in Karstic Formation

OBJECTIVES

1- Experimental testing of Groundwater Hydraulics and Contaminant Movement through a Karstic prototype and comparison with numerical model results

2- Mathematical prediction of contaminant concentration on Karstic prototype

3- Assessing the effect of Geological and Well Characteristics on Contaminant Movement, and validation of field test results through numerical simulation

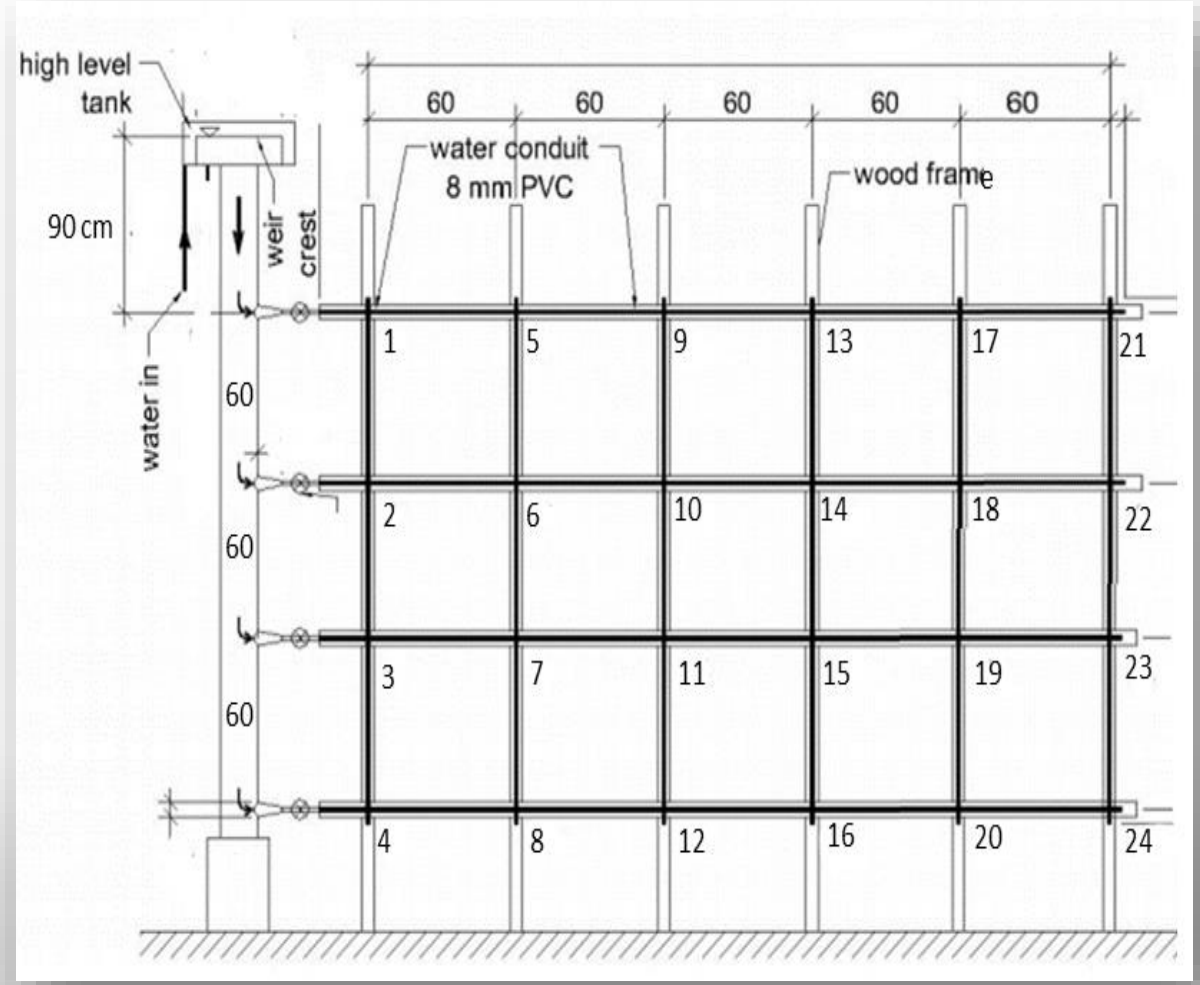
4- Development of Guidelines to prevent groundwater contamination

Hydraulic Head Variation

PART I: GROUNDWATER FLOW THROUGH KARSTIC CONDUITS

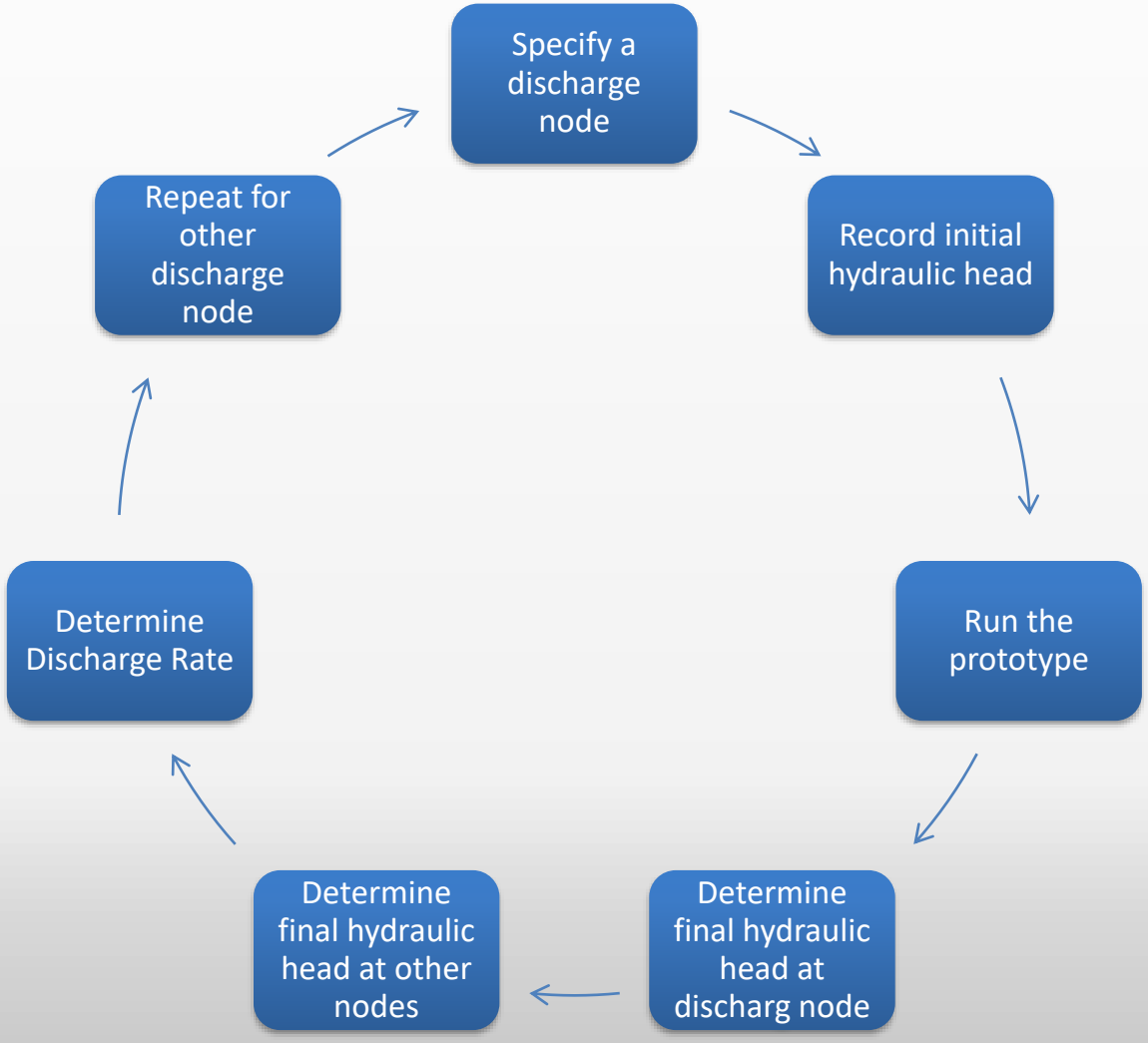
EXPERIMENTAL PROCEDURE

Model Construction



EXPERIMENTAL PROCEDURE

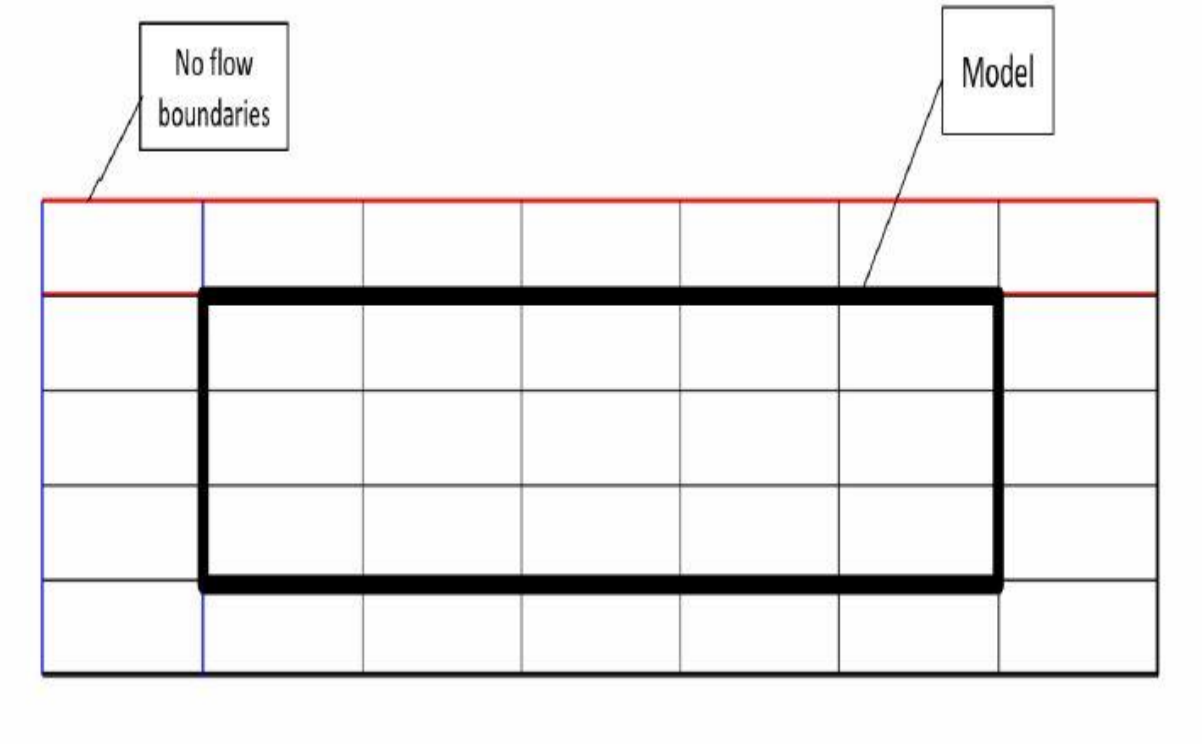
Hydraulic Head Experimental Steps



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

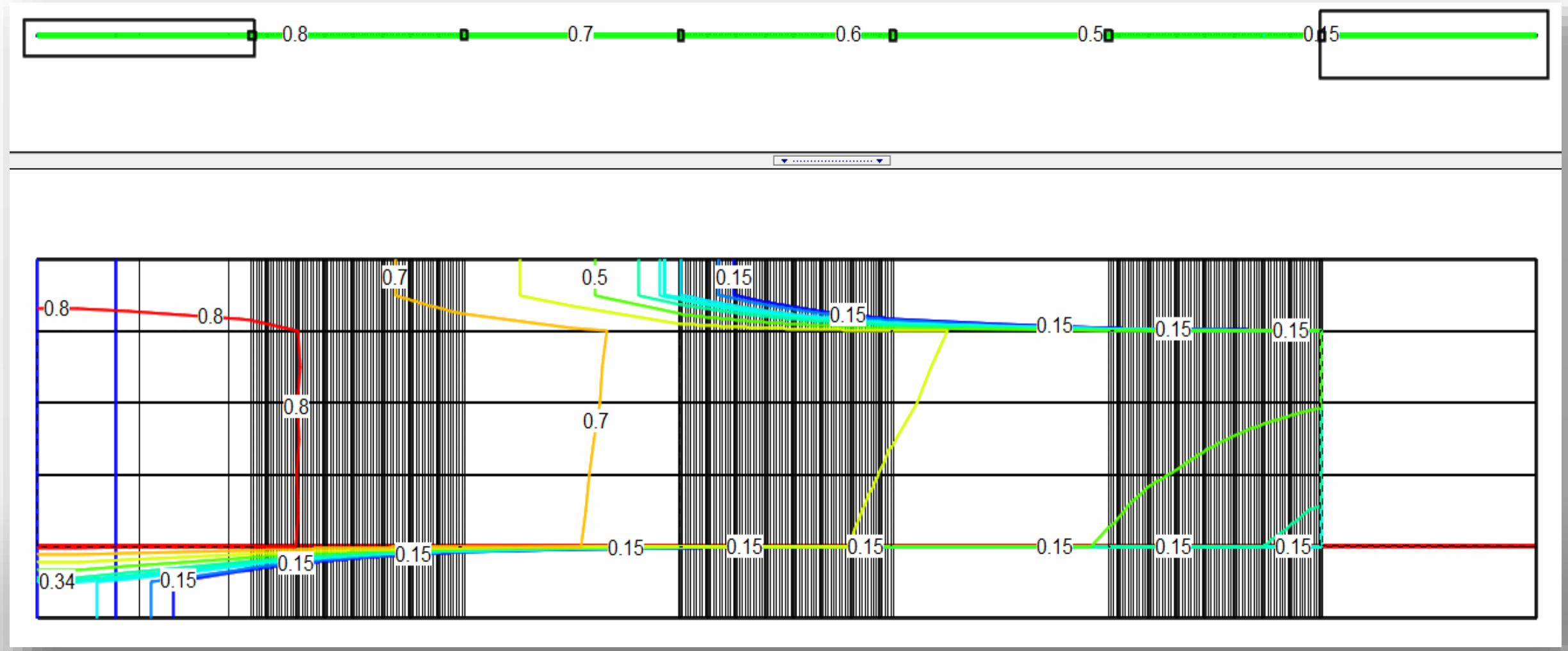
NUMERICAL SIMULATION
MODFLOW Model

- MODFLOW a U.S. Geological Survey modular finite-difference flow model
- High conductivity flow layers to simulate flow through conduits (MODE 2)

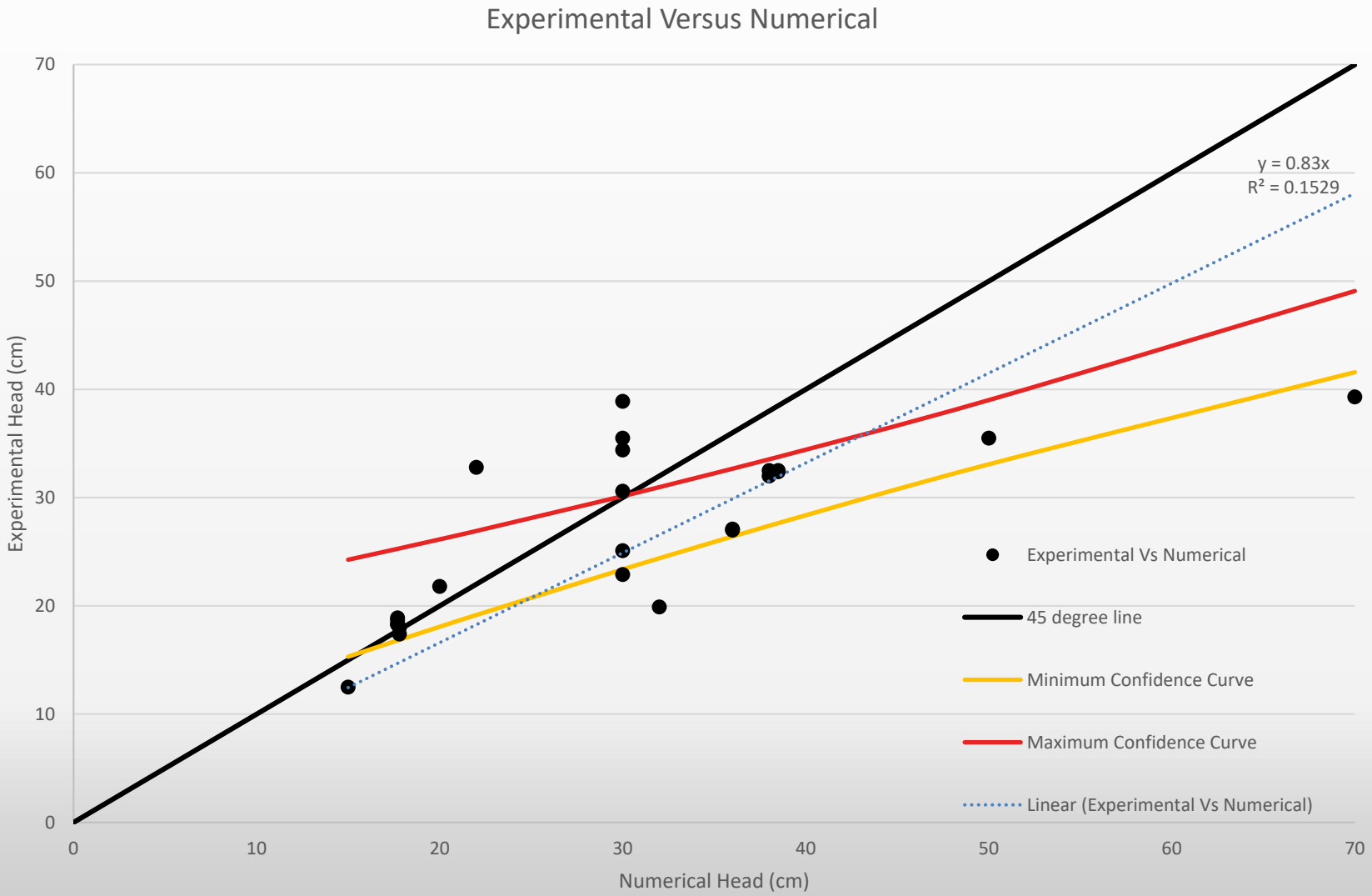


NUMERICAL SIMULATION

Software Results



EXPERIMENTAL VERSUS NUMERICAL



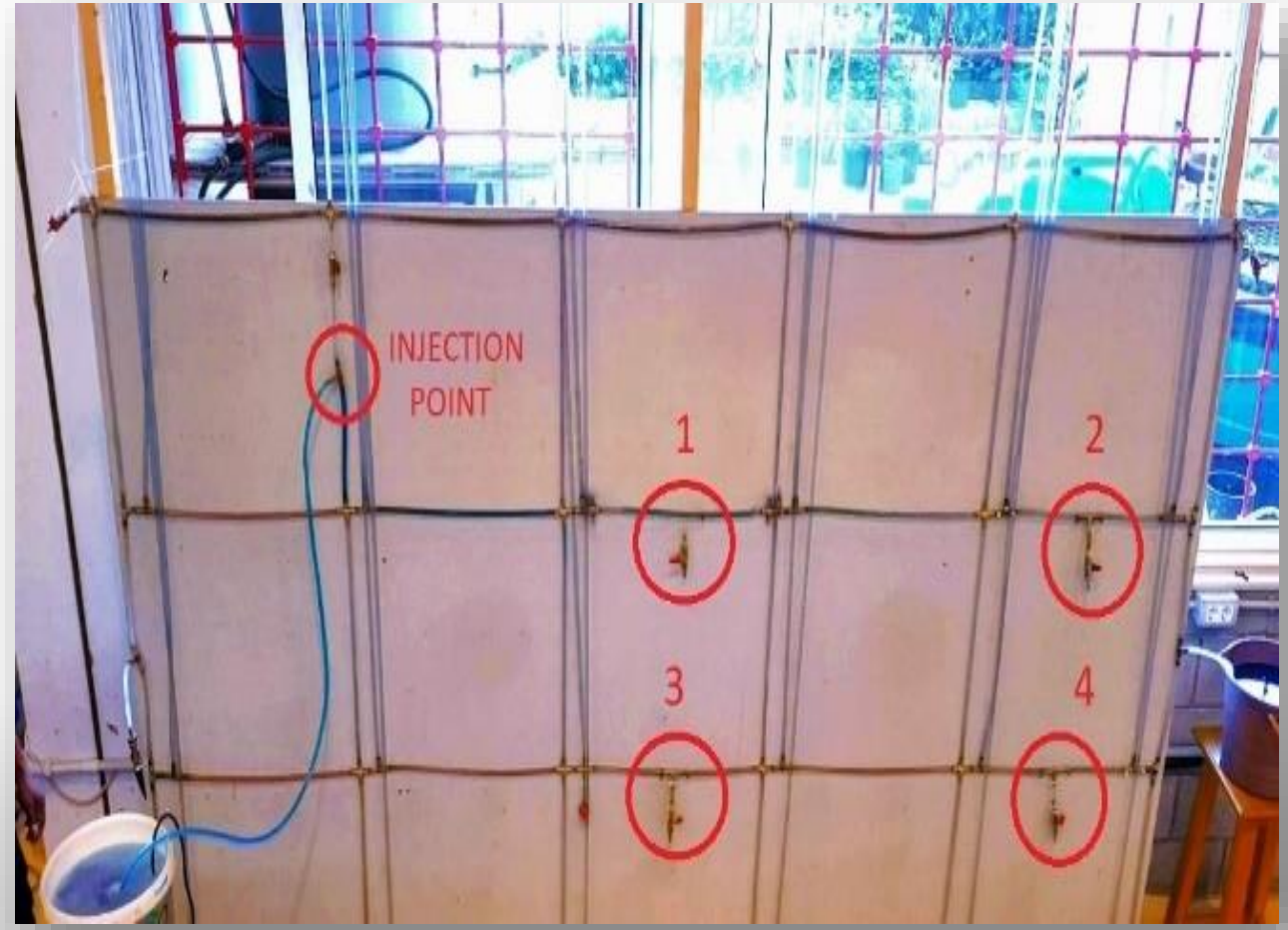
Experimental Head (cm)	Simulated Head (cm)
39.3	70
38.9	30
35.5	50
32.8	22
25.1	30
12.5	15
32.4	38.5
32.5	38.5
27.1	36
27	36
19.9	32
21.8	20
35.5	30
34.4	30
32	38
32.5	38
22.9	30
30.6	30
17.4	17.8
18	17.8
18.9	17.7
18.7	17.7
18.3	17.7
18.3	17.7

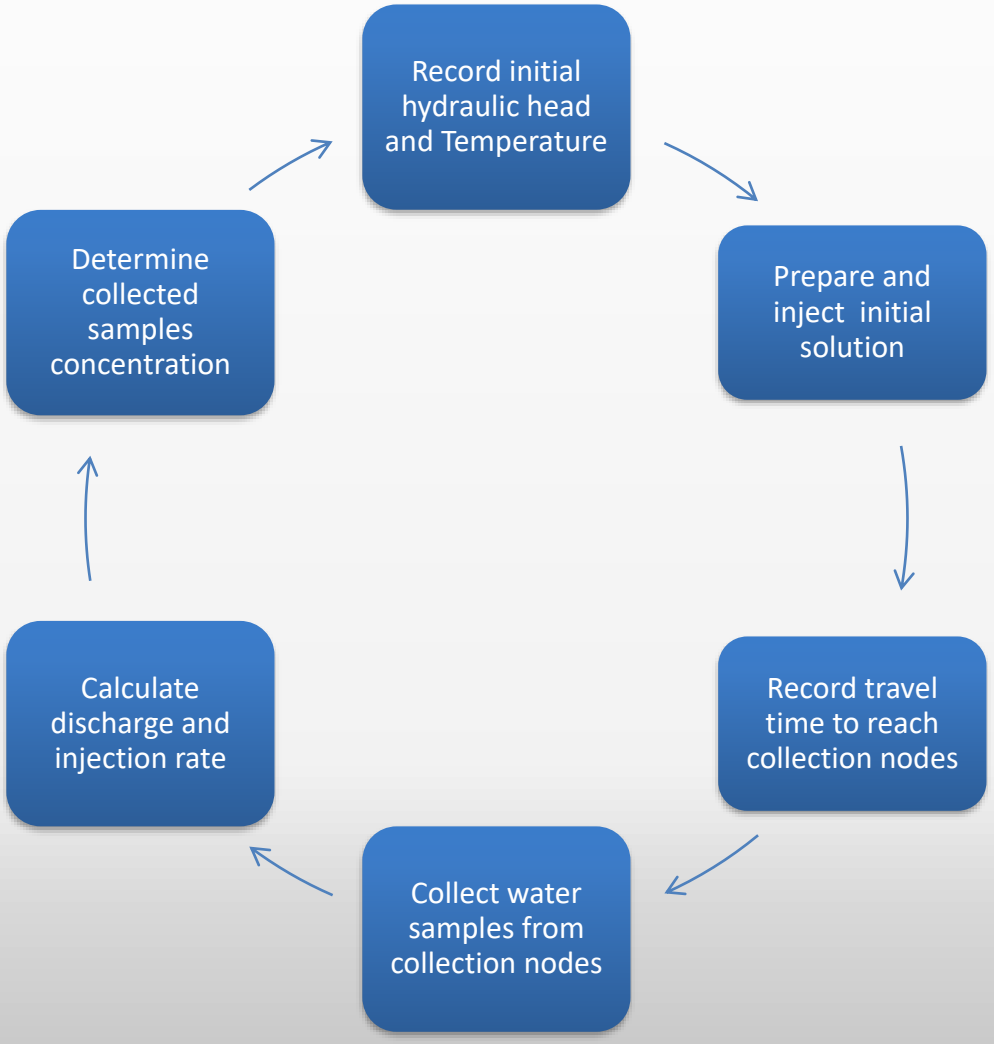
Contaminant Concentration Variation and Path lines

PART II: CONTAMINANT MOVEMENT THROUGH KARSTIC FORMATION

EXPERIMENTAL PROCEDURE

Contaminant Movement Experimental Steps

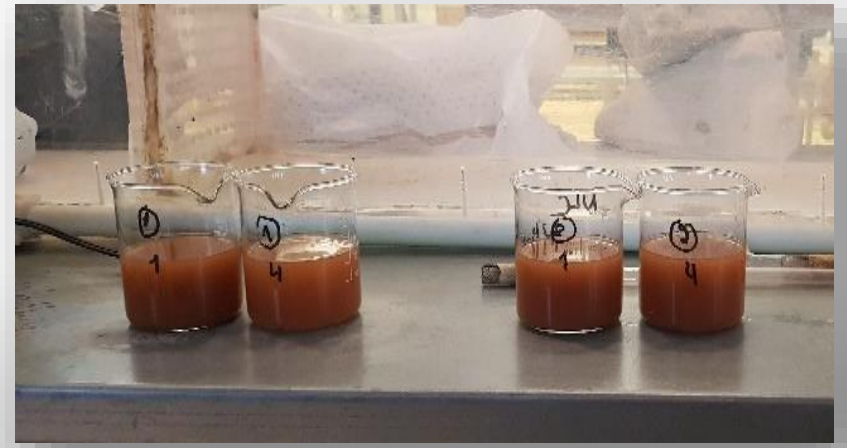




EXPERIMENTAL PROCEDURE (Cont'd)

Trials Input Data

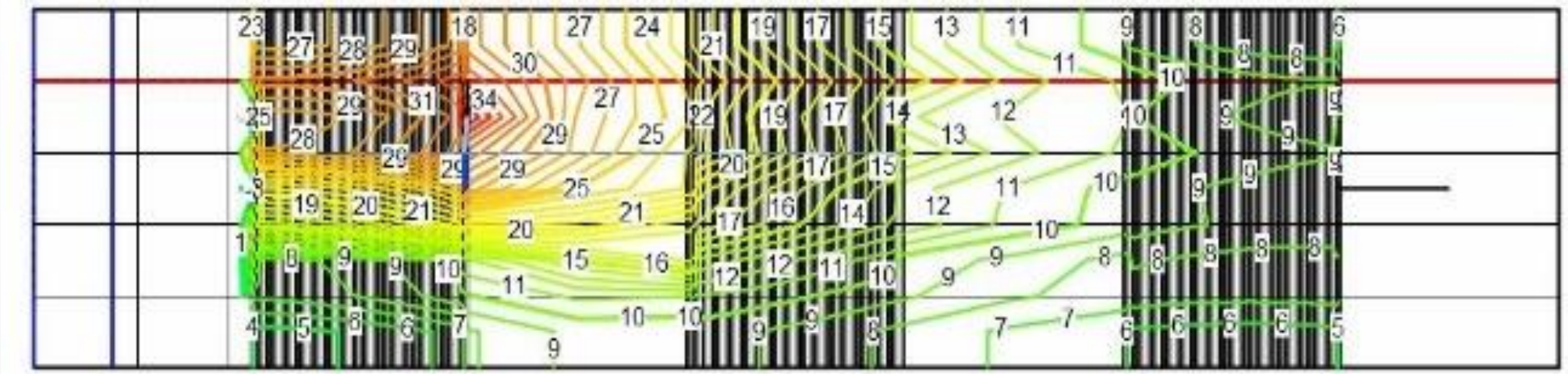
Input Data	Trial 1	Trial 2	Trial 3	Trial 4
Contaminated Water - Initial Concentration (mg/L)	23.20	11.80	36.30	16.50
Recharge Point Initial Concentration (mg/L)	0.00	0.20	0.00	0.00
Discharge Rate (m3/s)	1.77E-05	1.03E-05	1.13E-05	9.00E-06
Injection Rate (m3/s)	4.09E-05	2.93E-05	1.26E-05	1.47E-05
Initial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



NUMERICAL RESULTS

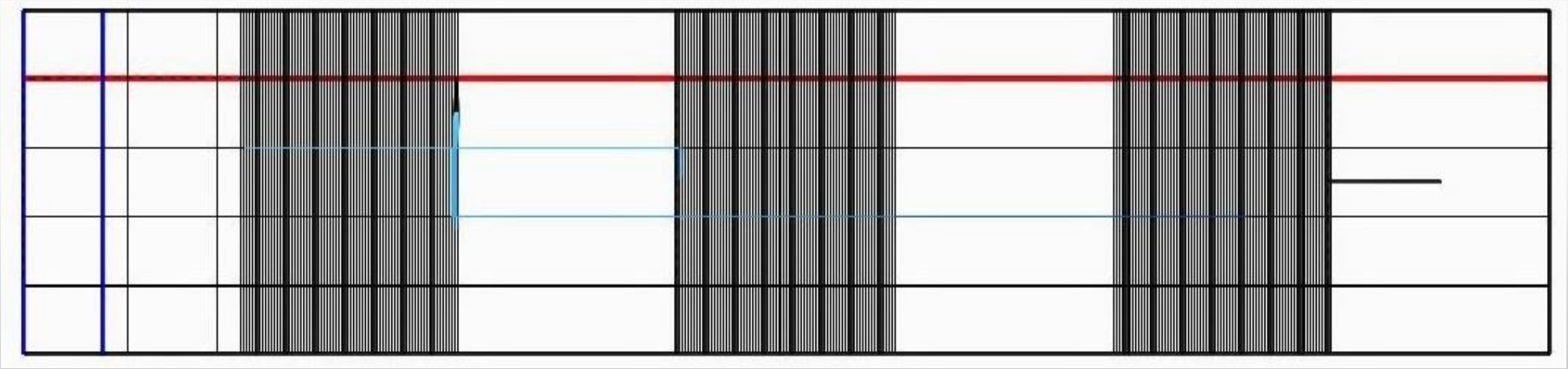
MODFLOW-MT3DMS PACKAGE

Concentration Variation



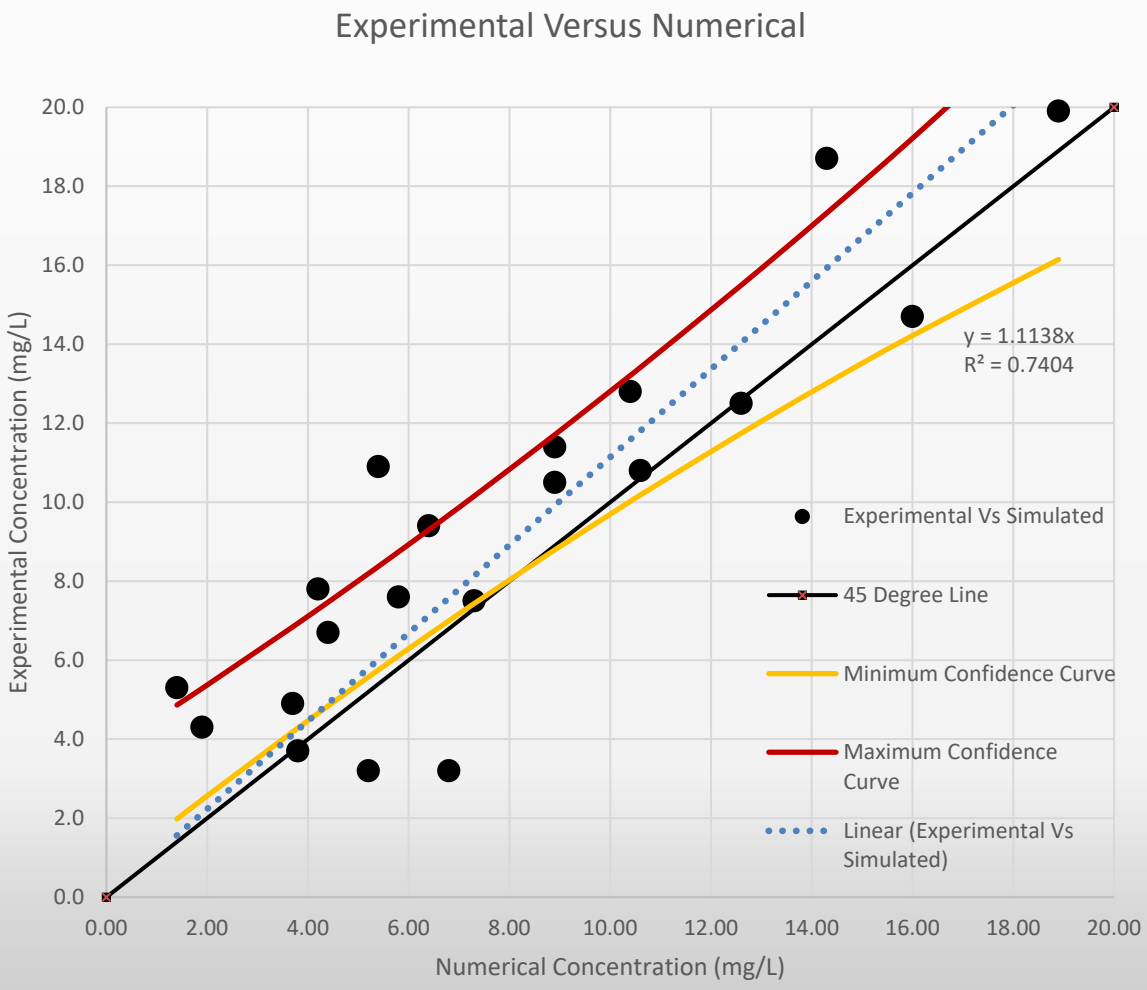
MODFLOW-MODPATH PACKAGE

Contaminant Travel Time

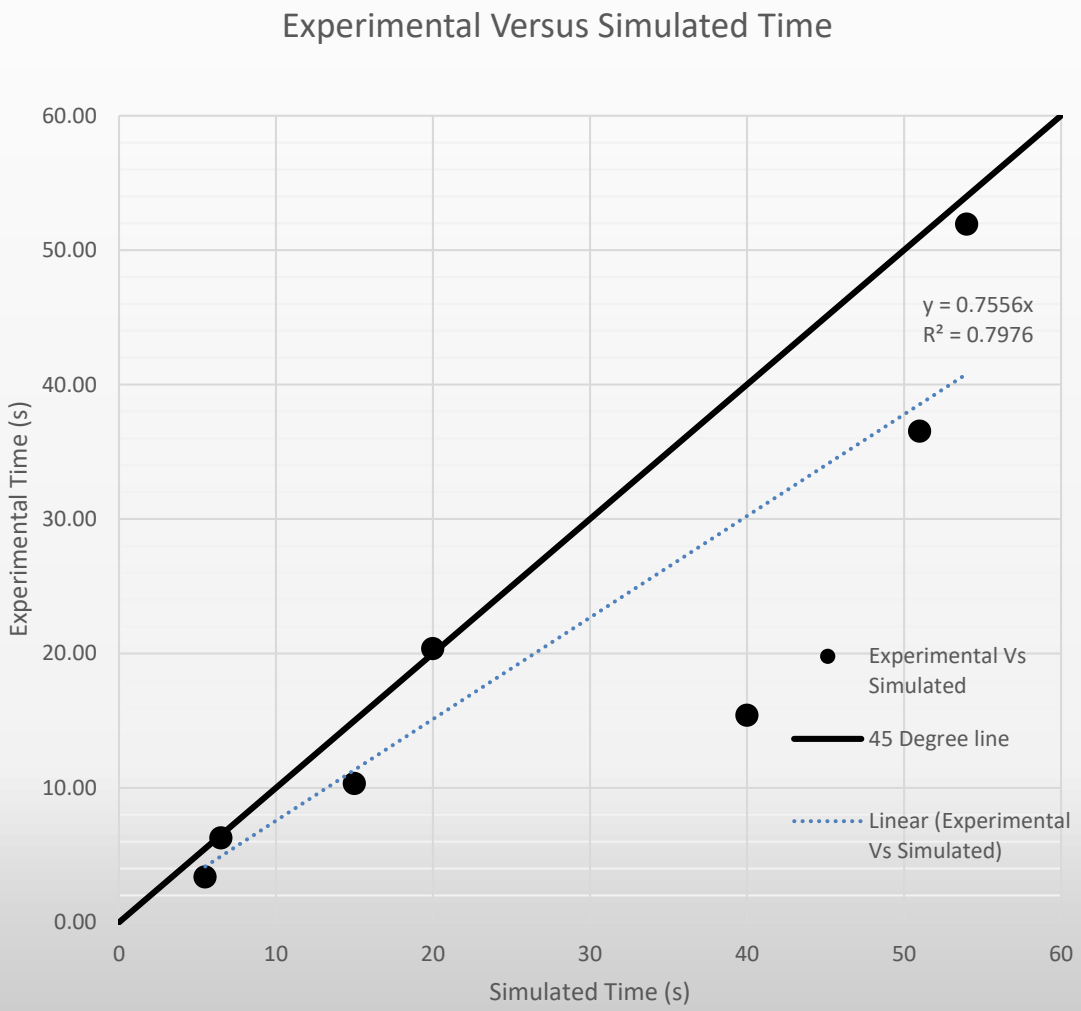


EXPERIMENTAL VERSUS NUMERICAL

Contaminant Concentration



Contaminant Travel Time



MATHEMATICAL METHOD

Regression Equation

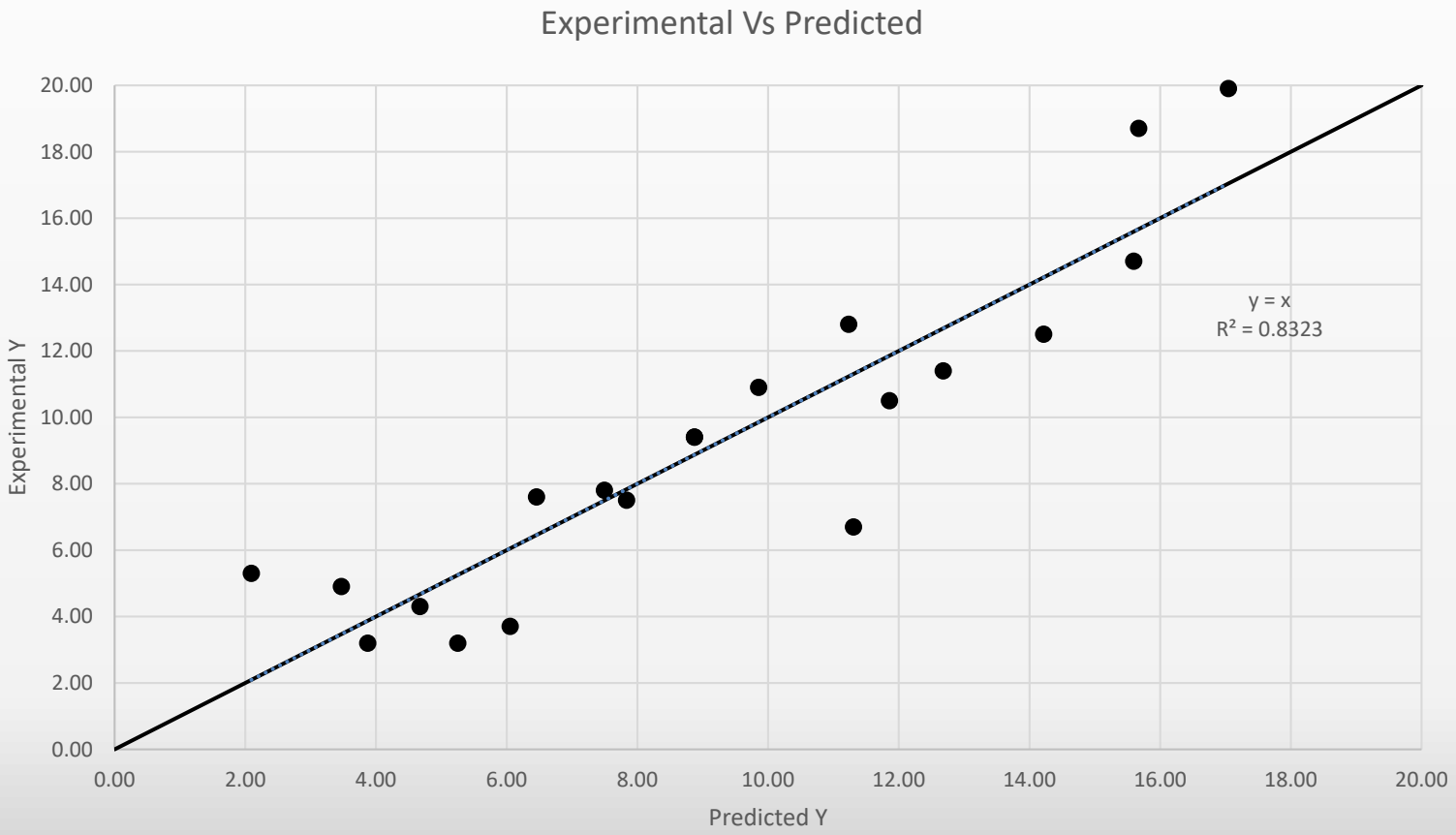
- Mathematical Prediction of Contaminant Concentration at a Certain Node
- Least Square Method to generate a regression equation that best fits experimental data
- Multiple linear regression equation generated using LINEST function

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

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

MATHEMATICAL METHOD

Statistical Analysis



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

F-Test Results	
F-value	10.75623
Alpha	0.05
V1	6
V2	13
Probability of a higher F value	0.000212
F-critical	2.93

Effect of Hydrogeological and Well Characteristics on Contaminant travel distance

Field Test Validation through Software Simulation

PART III: CASE STUDY

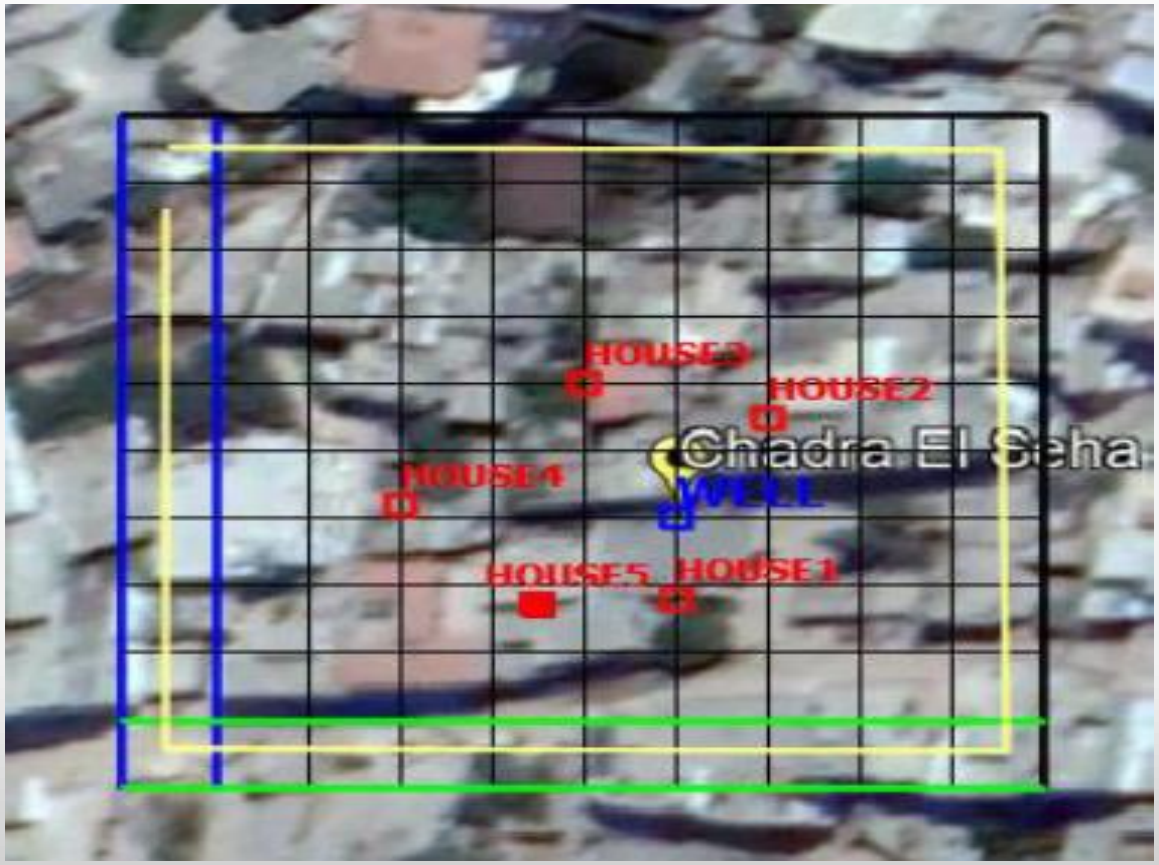
METHODOLOGY

Chadra El Seha Well

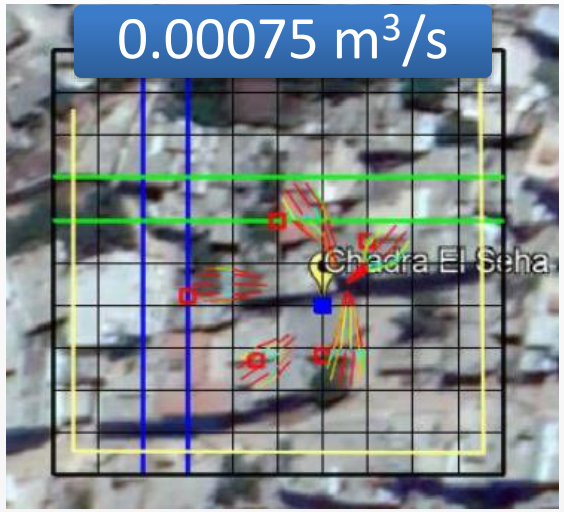
Laboratory Testing

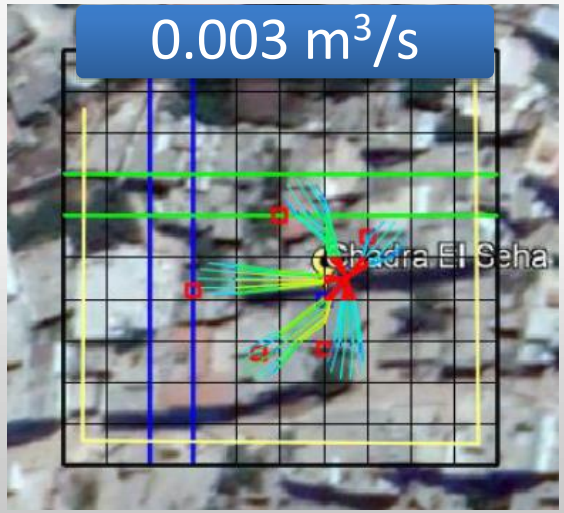
Parameter	Unit	Test Results	Standards (WHO)	Methods
Physical and Chemical Properties				
pH	Pt. Co scale	8.02	6.5-8.5	Electrometric
Turbidity	NTU	0.9	5	Turbidity
Nitrate	mg/l	20.54	10	Colorimetric
TDS	mg/l	258.33	1500	Evaporation
Ammonia	mg/l	0.0457	0.2	Colorimetric

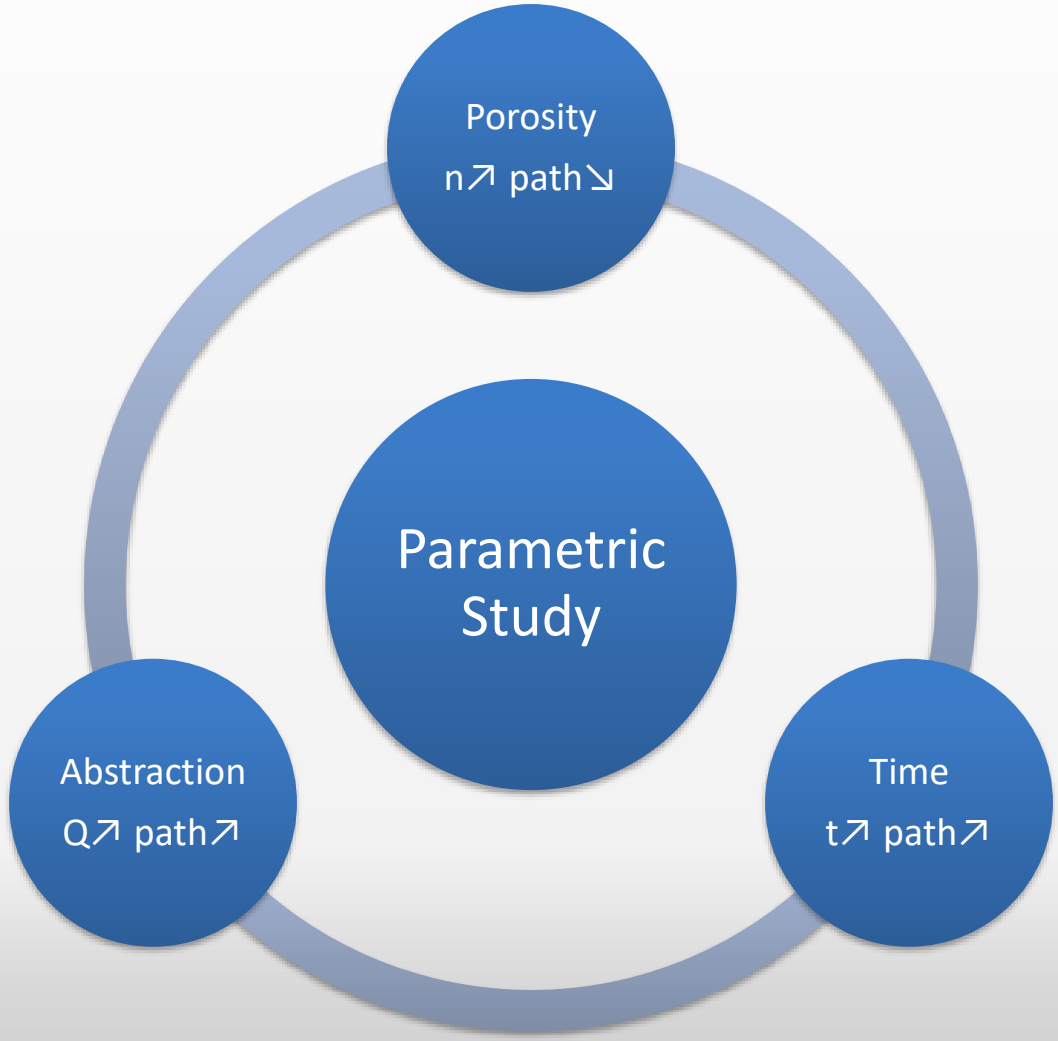
Software Model

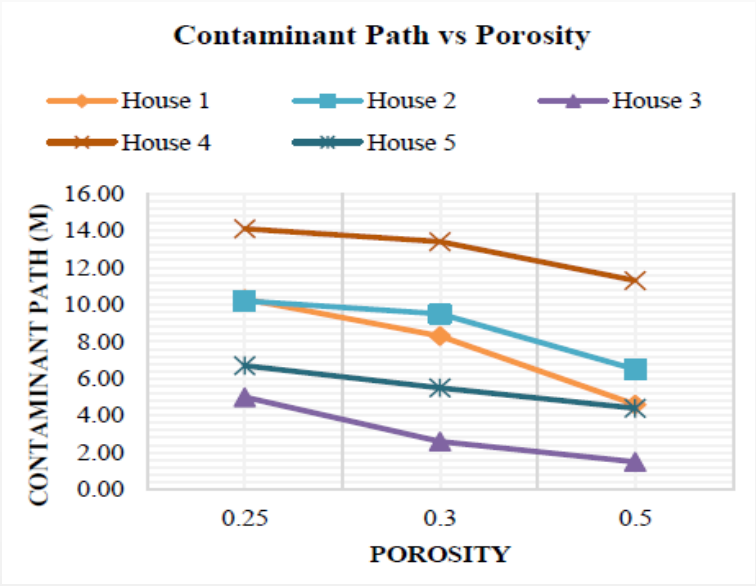


PARAMETRIC STUDY







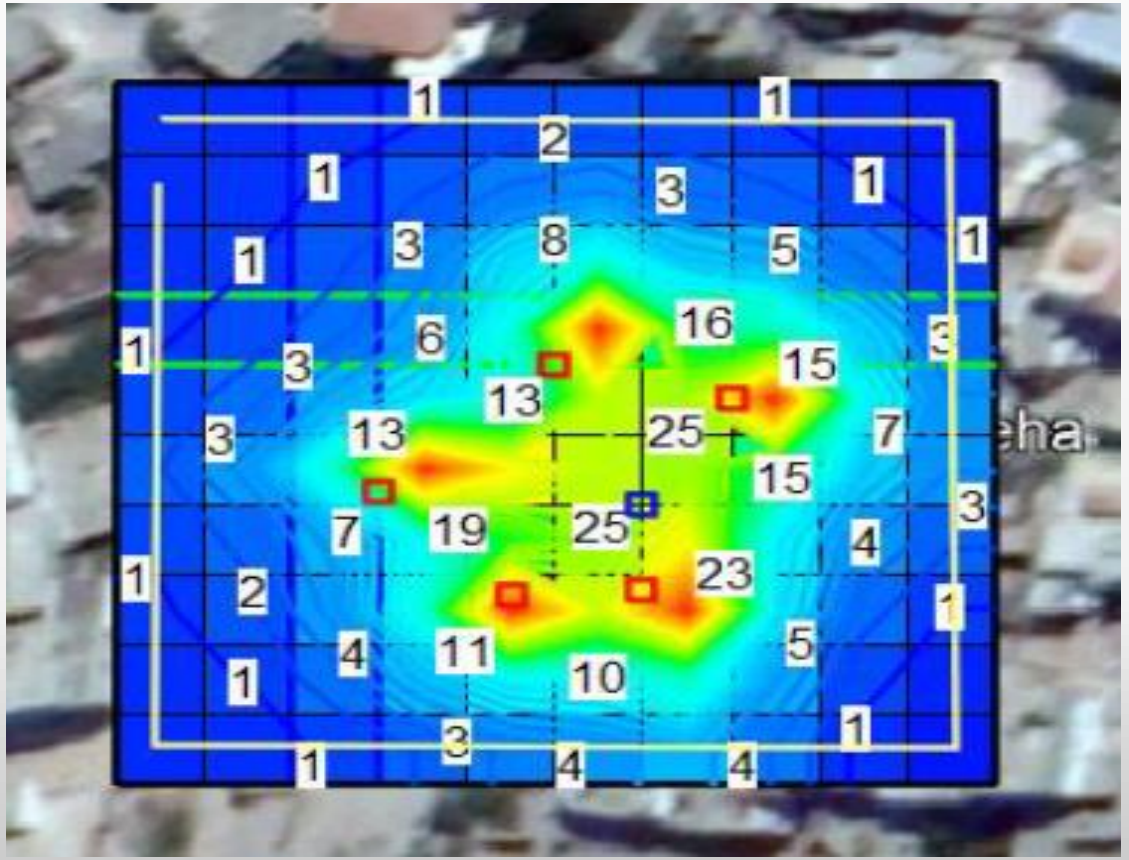


FIELD DATA VALIDATION

Lab result:
N-Conc = 20.54mg/L

Time period: 5 years

Model result:
N-Conc = 25mg/L



Protection Measures based on Chemical Contaminant Transport

Guidelines on Pumping Regime, Sanitation System, and Solid Waste Disposal

PART IV: GROUNDWATER MANAGEMENT PROGRAM

METHODOLOGY

Chadra El Seha Well | Chadra El Madraseh Well | Chadra El Nahr Well

Physical Analysis

- Temperature, pH, TDS, Turbidity, Conductivity

Chemical Analysis

- Nitrate, Ammonia

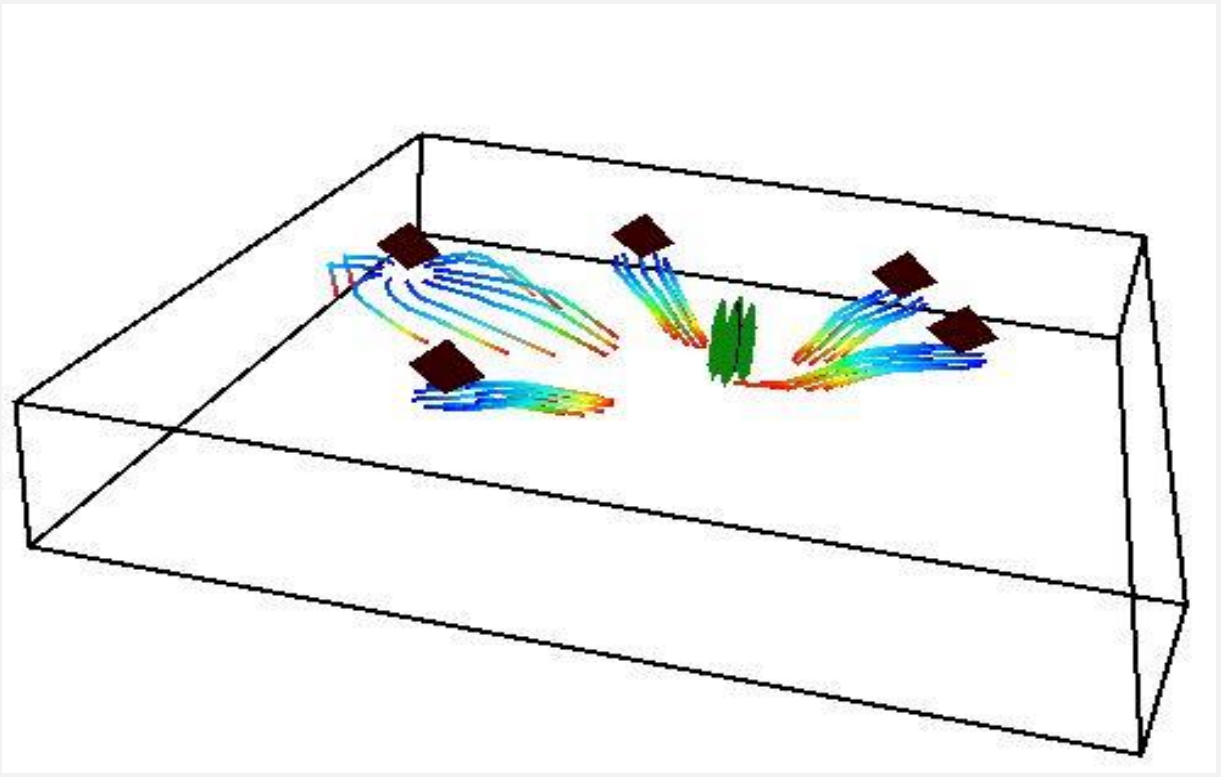
Bacteriological Analysis

- E-Coli, Other Microorganisms

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

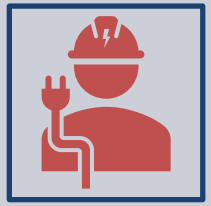
Results:

- **Physical Analysis:** Conductivity not met for all wells.
- **Chemical Analysis:** Nitrate Concentration not met for Chadra El Seha Well.
- **Bacteriological Analysis:** All wells met WHO standards.



SOFTWARE MODELING

PROTECTION MEASURES



Pumping Regime PM1:

Determine a safe Abstraction rate for 5 years design period

Sanitation System PM2:

Determine a safe setback distance based on actual abstraction rate and for a design period of 5 years

Solid Waste Disposal PM3:

Determine a safe setback distance based on actual abstraction rate and for a design period of 5 years

PROTECTION MEASURES

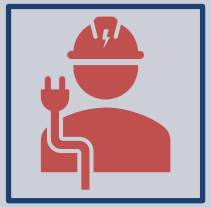
# PM	Variable			Protection Measure
PM1	Well	Distance to Critical Source - m	Time Period - year (day)	Safe Abstraction Rate - m3/d
	Chadra El Seha	12	5 (1825)	63.1
	Chadra El Madrase	28		110.6
	Chadra El Nahr	105		2004.5
PM2/3	Well	Actual Abstraction Rate - m3/d	Time Period - year (day)	Safe Setback Distance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

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)

Well considered safe, if:

- Actual abstraction rate < Safe abstraction rate
- Actual setback distance > Safe distance of critical source

OPERATIONAL PROCEDURES



Pumping Regime:

- Well/Pump Alternation
- Water Metering System

Sanitation System:

- Routine Operation and Maintenance
- Emptying Septic Tanks and Desludging

Solid Waste Disposal:

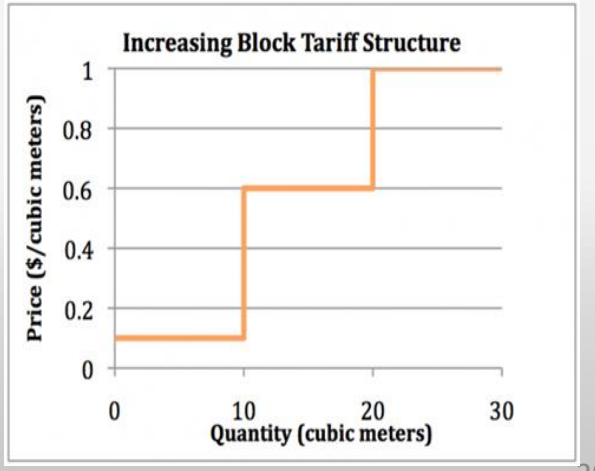
- Waste Sorting at Source
- Dumpsite Relocation

PUMPING REGIME

Pump Alternation

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

Water Metering



SANITATION SYSTEM

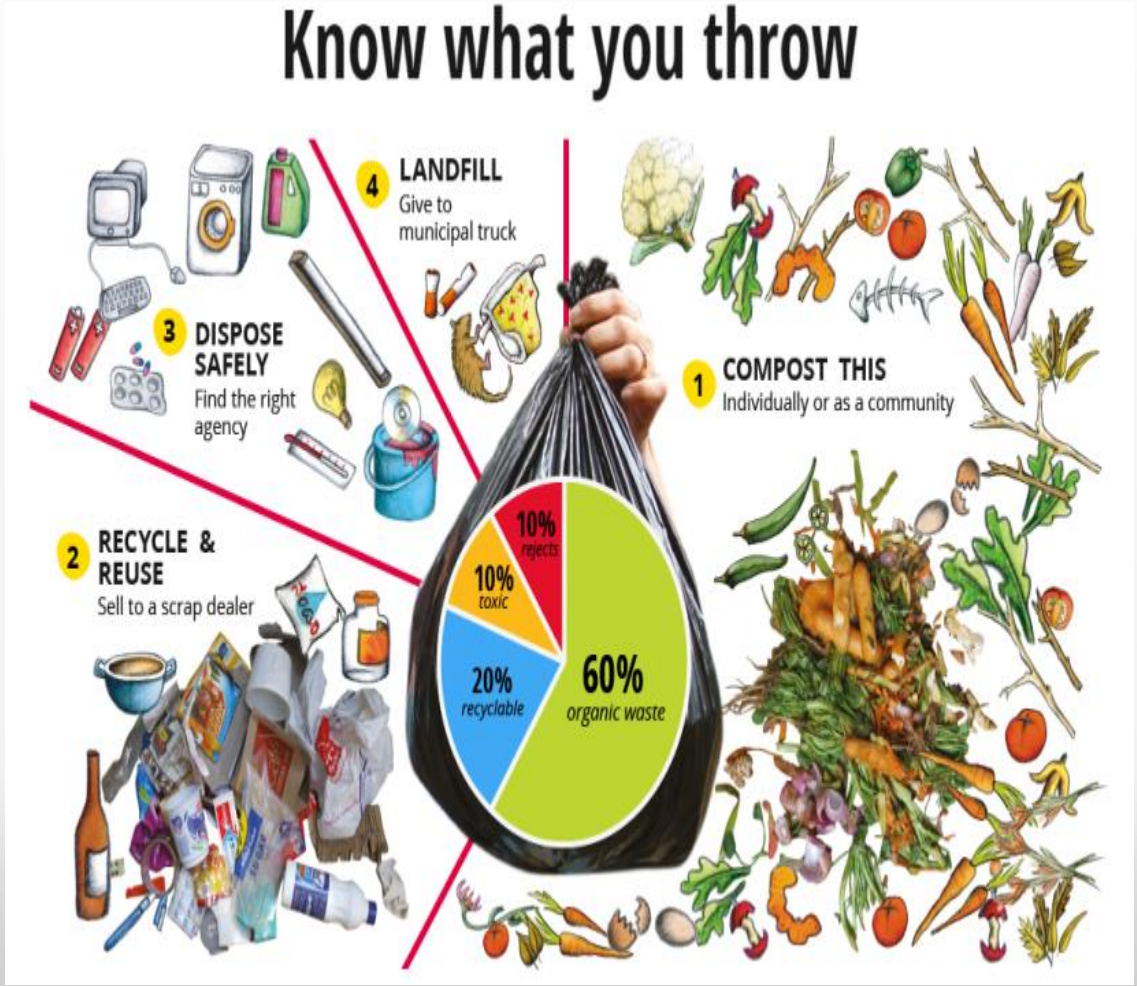
Routine Operation and Maintenance

- Monitoring of community health
- Monitoring of the state of latrines and other waste disposal
- Monitoring of the disposal of sewage (where applicable)

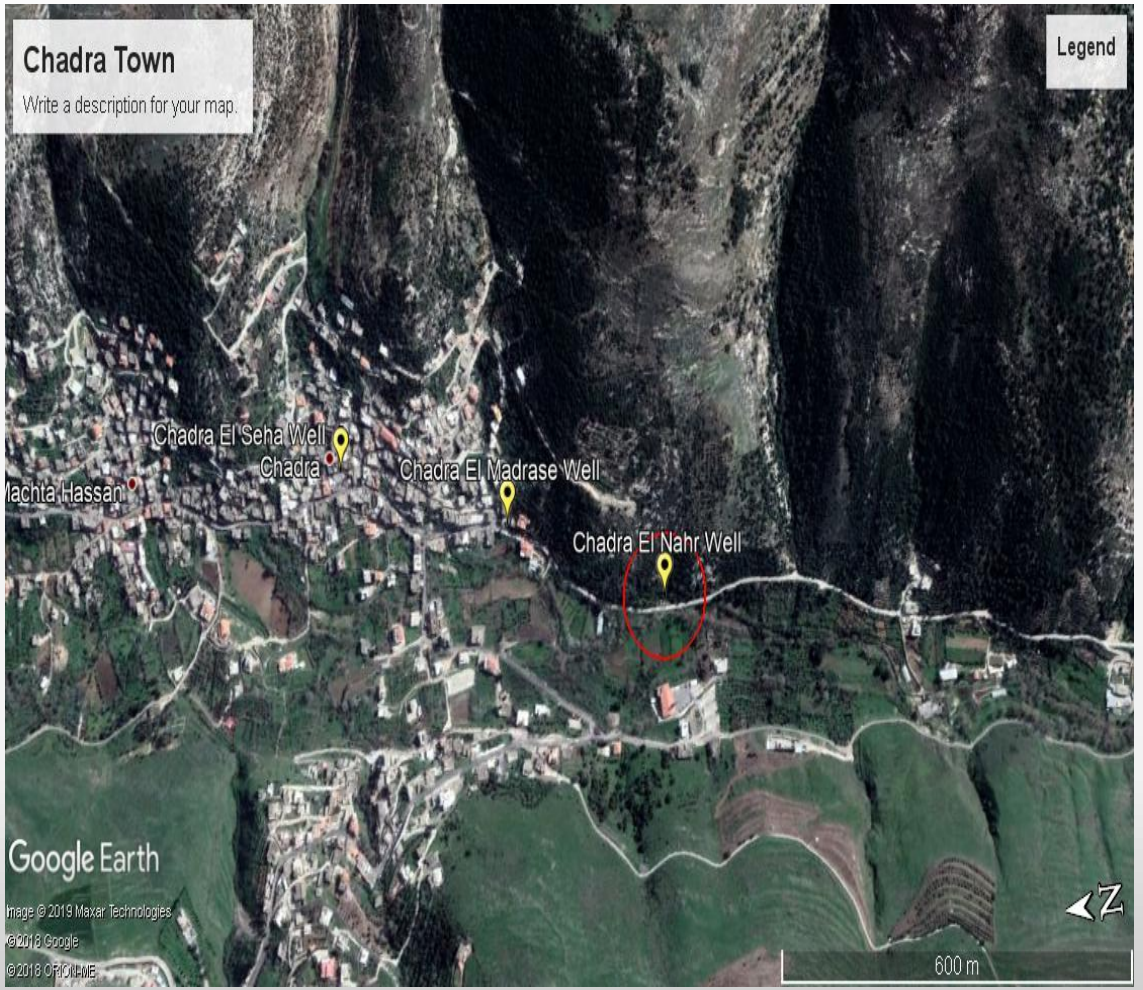
Regular Desludging

SOLID WASTE DISPOSAL

Sorting at Source



Dumpsite Relocation



COMMUNITY OUTREACH

CONCLUSION

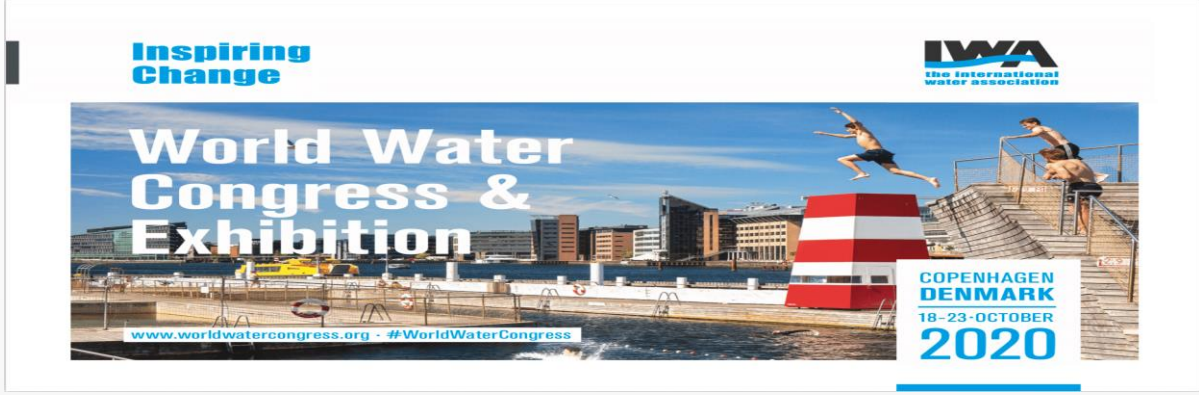
1- Numerical model results reflected experimental ones to a large extent, and provided a powerful tool to identify potential groundwater pollution and in designing safe abstraction points.

2- Regression Model can be replicated to an actual field case to predict contaminant concentration and prevent possible water contamination.

3- Software simulation reflected actual field test results despite several assumptions made on hydrogeological and chemical transport properties.

4- Management program methodology based contaminant movement is applicable at any geological setting

PUBLICATIONS



"Assessment of Groundwater Flow and Contaminant Transport in a Karstic Formation in Lebanon"

"Using Finite Difference Approach to Model Nitrate Contaminant Transport to a Contaminated Well "

PUBLICATIONS

"Tracking of Chemical Contaminant Transport and Concentration variation Through a Karstic formation using finite difference approach"

"Evaluation of Chemical Contaminant Transport to Assess and Manage Groundwater Resources Quality in Akkar Region, Lebanon"

THANK YOU