An Evaluation of Dispersivity in Solute Transport Modeling of The Aquifer Storage and Recovery Project in Sukhothai Province
การประเมินการแพร่กระจายสำหรับแบบจำลองการเคลื่อนที่มวลสารในโครงการเติมน้ำลงสู่ชั้นน้ำบาดาลจังหวัดสุโขทัย

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ABSTRACT

Solute transport modeling is constructed as part of a recent, large-scale Aquifer Storage and Recovery (ASR) project in Sukhothai Province, Thailand. The model simulates movement of a chloride plume caused by injection of treated surface water into Upper and Lower aquifer during 30 and 90 days pilot tests. In this study, laboratory column tracer test on representative sample from the two aquifers are used to refine dispersivity parameter in the original model. Chloride breakthrough curves, obtained in three laboratory-scale test, provided a range of dispersion coefficients for performing solute transport model based on laboratory-scale dispersivity property. The evaluated new values are used in the original solute transport model, to illustrate the importance of site scale dispersivity of the groundwater injection zone. Groundwater model is established according to hydrogeology and the onsite hydraulic conductivity data. The results illustrate the movement of the chloride plume in both aquifer in the southeast direction in accordance with the groundwater flow model. For long term operation, ASR technology can be beneficial to groundwater resource of Sawankhalok district, Sukhothai province.

บทคัดย่อ

แบบจำลองการเคลื่อนที่มวลสารเป็นส่วนหนึ่งในการศึกษาโครงการเติมน้ำลงสู่ชั้นน้ำบาดาลจังหวัดสุโขทัย แบบจำลองนี้แสดงขอบเขตการเคลื่อนที่ของคลอไรด์ในชั้นหินให้น้ำระดับบนและระดับล่างขณะทดสอบระบบเติมน้ำระยะ 30 และ 90 วัน การประเมินค่าการแพร่กระจายของชั้นหินให้น้ำทั้งสองจะทำโดยการปล่อยสารติดตามผ่านตัวอย่างของชั้นหินให้น้ำที่บรรจุในคอลัมน์ สัมประสิทธิ์การแพร่กระจายคำนวณได้จากกราฟ

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การเปลี่ยนแปลงความเข้มข้นของคลอไรด์ ถูกใช้ในการประเมินคุณสมบัติการแพร่กระจายสำหรับแบบจำลองการเคลื่อนที่มวลสารซึ่งแสดงบริเวณที่มีการเติมน้ำลงสู่ชั้นน้ำบาดาล แบบจำลองการไหลน้ำบาดาลถูกสร้างขึ้นจากข้อมูลอุทกธรณีวิทยาและค่าสัมประสิทธิ์การยอมให้น้ำซึมผ่านซึ่งทดสอบ ณ สถานีเติมน้ำ ผลการทดลองพบว่าขอบเขตการเคลื่อนที่ของคลอไรด์ในชั้นหินให้น้ำทั้งสองนั้นเคลื่อนที่ไปในทิศทางตะวันออกเฉียงใต้เช่นเดียวกับแบบจำลองการไหลน้ำบาดาล ในระยะยาวเทคโนโลยีการเติมน้ำลงสู่ชั้นน้ำบาดาลนี้เป็นประโยชน์ต่อทรัพยากรน้ำบาดาลของอำเภอสวรรคโลก จังหวัดสุโขทัย

Keywords : Solute transport model, Dispersivity, Aquifer Storage and Recovery (ASR)
คำสำคัญ : แบบจำลองการเคลื่อนที่มวลสาร การแพร่กระจาย การเติมน้ำลงสู่ชั้นน้ำบาดาล

Introduction

The Upper Chao Praya River Basin in Sukhothai province is one of the main river basins in Thailand. Flood in rainy season and drought during summer are general situation of this area. Consequently, the Department of Groundwater Resources has initiated the pilot project about Aquifer Storage and Recovery (ASR) in Sawankhalok district, Sukhothai province as shown in figure 1 which displays the study area map and also the location of ASR site. The definition of ASR is the injection and storage of water through a well into an aquifer during times of excess precipitation, and recovery of that water through the same well, during time of drought [1].

Geology of Sawankhalok area consists of thick alluvial sediment layers which are deposited in graben structural basin of the Northern Thailand. The basin contains Quaternary sand and gravel interbedded with clay layers approximately 90 m thick with some local areas are more than 100 m in thickness. The underlying bedrock is Permian limestone. Hydrogeology of Sawankhalok district composes of unconsolidated alluvial sediments of the Upper Chao Praya river basin. The ASR process which is groundwater injection have conducted in the two main aquifers including the Upper and the Lower aquifers which are located between the depths of 35 to 44 and 74 to 83 m above ground surface, respectively. However, there is significant heterogeneity within the aquifers due to various extension of clay lenses that separate both aquifers. During the demonstration, there was a question about the migration of injected water and one of the tools for solving this problem is the groundwater model which can simulate natural groundwater flow systems in the environment and solute transport modeling for representing the spread of conservative tracer plume as groundwater injection zone. Studying about solute transport modeling, a dispersivity has become significant parameter of the model particularly in an area of complex sedimentary layers therefore the dispersivity property is an important parameter for solute transport modeling [2]. It accounts for hydrodynamic mixing that occurs in porous media as a result of fluid flow through the heterogeneity of the aquifer. Therefore, an exact value of hydrodynamic dispersion and dispersivity properties need to be determined before conducting solute transport model. There are serveral experiments for the hydrodynamic dispersion and dispersivity evaluation. One of the efficient methods is a laboratory column study for one dimensional solute transport by evaluation of the relative concentration of the tracer passing through porous media. In this study, representative aquifer materials from the two ASR aquifers are used to determine dispersivity properties. Samples were obtained from an injection wells during the construction of the ASR project and they are used in laboratory column studies. The objectives of this study are to conduct laboratory tracer test on the repacked representative samples from the aquifer to yield laboratory-scale dispersivities, establish groundwater flow model, and perform solute transport model based on laboratory-scale dispersivities.

Methodology

Research methodology of this study consists of three parts including the groundwater modeling, the laboratory-scale dispersivity evaluation and the solute transport modeling. Firstly, the groundwater modeling explains about the groundwater model components, for instance, hydrogeological conceptual model, model discretization, boundary conditions and input parameters. Secondly, the laboratory-scale dispersivity evaluation describes about the laboratory column tracer experiments and the one dimensional solute transport model. Thirdly, the solute transport modeling that represents an application of solute transport model on the ASR pilot study of groundwater injection.

Groundwater modeling

Groundwater model establishment is conducted by Visual MODFLOW flex 2014 program which analyzes groundwater flow by finite different method. The conceptual model of the study area is presented in figure 2. The model consists of thick layers of unconsolidated sediment of the Upper Chao Praya river basin which can be classified into five layers according to hydrogeological data in table 1. The study area is approximately 225 km2 and 15 km width and length covering UTM coordinate from 585000 to 60000 East and 191000 to 1925000 North. The topography is ranging between 50-70 m above the mean sea level. Model discretization comprises of 65 rows and 75 columns that creates 4,875 grid cells and the size of each grid cell is 200 x 200 m. Table 2 lists hydraulic properties of each layer including hydraulic conductivity and storativity. Other input parameters consisting of river package, initial head, recharge evapotranspiration and observation wells are obtained from previous study. Moreover, the model structure and the distribution of input data such as hydraulic conductivity, river package and constant head in layers are presented in figure 3. Groundwater model is calibrated and run for groundwater flow simulation. After the model is adjusted, the next stage is to simulate solute transport model during ASR process. However, in order to perform solute transport model, dispersion parameter is another input data for the groundwater modeling program that can be determined for each aquifer in terms of heterogeneous dispersivity simulation.

The laboratory-scale dispersivity evaluation

This study follows the laboratory study of hydrodynamic dispersion coefficient and dispersivity by a 30 cm column which was filled with saturated porous media [3]. The 200 mg/L of chloride solution is introduced into the column as a tracer by three different flow rates that provides average linear velocity for each test. Furthermore, chloride concentration is measured from an effluent solution that comes out at the end of the column. This particular test simulates one dimensional solute transport model. For continuous input concentration, calculation can be expressed in term of pore volumes as equation (1) from [4].

$$\frac{C}{C_0} = 0.5\left[erfc\left(\frac{1-U}{2(UD*/v_iL)^{1/2}}\right)\right] \quad (1)$$

From equation (1), U is the number of effluent pore volumes and L is the column length, D* is hydrodynamic dispersion coefficient and vi is average linear velocity. From previous study [4], it is recommended to plotting breakthrough curve of an effluent relative concentration or $\left(\frac{C}{C_0}\right)$ as a function of [$(U - 1)/ U^{1/2}$] or pore volumes. If the data fits a straight line, then the use of a diffusion equation model approach was validated, and the dispersion coefficient could be calculated from the slope of the line. Anomalies in the data, resulting from dead-end pores, channeling, or improper column packing could be identified, in some cases, using this following graphical method. Defining $J = [(U - 1)/ U^{1/2}]$, the longitudinal (D_L) hydrodynamic dispersion coefficient can be calculated from this following expression.

$$D_L = \left(\frac{v_i L}{8}\right)(J_{0.84} - J_{0.16})^2 \quad (2)$$

The $J_{0.84}$ and $J_{0.16}$ correspond to relative concentrations $\left(\frac{C}{C_0}\right)$ of 0.84 and 0.16, respectively. The longitudinal hydrodynamic dispersion coefficient is assumed to be the sum of a mechanical dispersion part which is a linear function of the average pore water velocity and a molecular diffusion part. This is expressed as equation (3).

$$D_L = \alpha_L v_i + D^* \quad (3)$$

Considering α_L as the longitudinal dispersivity and D* is the molecular diffusion coefficient in the porous medium. Dispersivity value is evaluated by rearrangeing equation (3) as equation (4).

$$\alpha_L = \frac{D_L - D^*}{v_i} \quad (4)$$

Moreover, tranverse hydrodynamic dispersion coefficient, D_T , can be calculated from an approximate formula of [5].

$$D_T = D_L/10 \quad (5)$$

Then, the tranverse dispersivity, α_T can be calculated by equation (6).

$$\alpha_T = \frac{D_T - D^*}{v_i} \quad (6)$$

The representative samples of the Upper (36 to 40 m) and Lower (78 to 82 m) aquifers are obtained from the ASR wells construction during a bore drilling process.

Representative samples of the both aquifers are presented in figure 4 which consist of figure 4A and 4B for the Upper aquifer and 4C and 4D for the Lower aquifer. Samples were tested for grain size analysis and the porosity of the Upper and the Lower aquifer are 40.6 and 31.1 percent, respectively [6].

Figure 5 shows a 30 cm acrylic column with 10 cm diameter and an Electrical Conductivity (EC) meter that is inserted at the end of the column. Figure 6 shows installation of the laboratory column tracer experiment of this study. A constant head dispenser releases 200 mg/L sodium chloride solution with different flow rates depending on the height of an adjustable platform. The heights from the dispenser to the column are set up as 50, 75 and 100 cm for three different flow rates including the R1, R2 and R3 test and flow rates are presented in table 3. The variation of flow rates might have an effect on dispersivity. Samples are repacked into the column according to their depth and, are saturated over night with distilled water before begin a tracer test. The three flow rates introduce the tracer pass through the column but after finishing one test, it is flashed out by distilled water until an EC value is as low as possible normally it takes around an hour then the next test can be started. Detecting EC value change is 24 hours per test and they are recorded every 30 minute. EC values are converted into chloride concentration using this following equation from [7].

$$Cl\ (mg/L) = EC(dS/m) \times 140 \quad (7)$$

However, from previous research of column studies on many sediments, the laboratory values of longitudinal dispersivity ranges from about 0.01 to 1 cm with ratio of longitudinal to tranverse dispersivities ranges from 5 to 25 [8].

Solute transport modeling

According to ASR pilot study plan, treated surface water was injected into the Upper and Lower aquifers through the onsite injection wells for the duration of 30 and 90 days .The injection water consisted of high concentration of chloride due to an addition of Polyaluminum chloride (PACl) during the treatment process. Therefore, chloride concentration are used as a conservative tracer which become a target for observing migration plume of injected water. Moreover, chemical data of injected water and groundwater sample from observation wells are established as chemical background of the model. In this solute transport simulation, longitudinal and tranverse dispersivity values of aquifers from the column experiment are applied as input parameter.

Results

Groundwater flow model of Sawankhalok

Groundwater model simulates groundwater flow pattern of both the Upper and Lower aquifers as shown in figures 7 and 8 which represent groundwater flow pattern of Sawankhalok district that the regional hydraulic gradient of both aquifers is northwest to southeast direction following the topographic gradient of the study area. The hydraulic head contours of the Upper aquifer ranges from 45 to 50 m and the hydraulic head contours of the Lower aquifer ranges from 44 to 49 m and all of the hydraulic heads are measured above the mean sea level. Generally, hydraulic heads of the Upper aquifer is slightly one meter higher than the Lower aquifer because the aquifer characteristics are heterogeneous unconsolidated confined aquifer and the various hydraulic properties especially the hydraulic conductivity of the second layer and the forth layer. Moreover, The root mean square error of the model calibration is 8.9 percent which considers under the acceptable limit of error.

Dispersivity evaluation of the Sukhothai ASR site

Average linear velocity

After the column is repacked, average linear velocity or v_i is calculated for each of the three flow rates according to variation of dispenser heights as presented in table 4. The average linear velocity is important for the laboratory-scale dispersivity because the advecting tracer is traveling through porous media at the same rate as the average linear velocity of the groundwater and this parameter is essential for the next step of dispersivity determination.

Hydrodynamic dispersion coefficient and dispersivity

Figures 9 and 10 represent breakthrough curves of effluent relative concentration or $\left(\frac{C}{C_0}\right)$ as a function of $[(U-1)/U^{1/2}]$ or pore volumes. The data is fitted as a straight line therefore the use of a diffusion equation model approach is validated, and the hydrodynamic dispersion coefficient can be calculated.

For the hydrodynamic dispersion coefficients determination, longitudinal (D_L) and tranverse (D_T) hydrodynamic dispersion coefficients are illustrated in table 5 and 6. The average value of D_L and D_T of the Upper aquifer are 2.53 x 10^{-4} cm^2/s and 2.53 x 10^{-5} cm^2/s, respectively. The average value of D_L and D_T of the Lower aquifer are 1.45 x 10^{-4} cm^2/s and 1.45 x 10^{-5} cm^2/s, respectively. For the dispersivity determination, longitudinal (α_L) and tranverse (α_T) dispersivities are shown in table 7 and 8. The average value of α_L and α_T of the Upper aquifer are 0.12 cm and 0.012 cm, respectively. The average value of α_L and α_T of the Lower aquifer are 0.18 cm and 0.018 cm, respectively.

Solute transport modeling of Sukhothai ASR site

The longitudinal or horizontal and tranverse or vertical dispersivities of laboratory column tracer experiment of the Upper and Lower aquifers are applied as input parameter of the Sukhothai ASR site solute transport model. The heterogeneous dispersion coefficients and dispersivities are added in a function of dispersion parameter of the second and forth layer of the model. From the background groundwater chemistry data of the ASR site, the solute transport model performs as a condition of continuous groundwater injection into both aquifers by the two ASR wells for the duration of 30 and 90 days. The injection rate of the Upper aquifer is 240 m^3/day and 3,240 m^3/day for the Lower aquifers. Chloride concentration works as a tracer to express the plume of groundwater injection and, the migration within the aquifers. Figures 11 and 12 illustrate solute transport model at Sukhothai ASR site of the Upper aquifer at depth of 20-45 m, and figures 14 and 15 represent solute transport model at Sukhothai ASR site of the Lower aquifer at depth of 55-90 m. Moreover, solute transport simulation in 3D are presented in figures 16 and 17.

The chloride concentration plume of both aquifers appear to arrive in the same direction as well as the regional groundwater flow pattern in southeast direction from the high hydraulic head area to the recharge area where hydraulic head is lower. According to the groundwater injection, the spread of chloride concentration plume of the Lower aquifer is larger than the Upper aquifer because of the greater amount of groundwater injection and the heterogeneity of dispersivity and hydraulic conductivity properties of each aquifers.

Discussion and Conclusion

The groundwater model of Sawankhalok district, Sukhothai province represents groundwater system of the study area that flow in southeast direction. Hydraulic heads of the second layer or Upper aquifer at depth of 20 to 45 m are approximately a meter higher than the forth layer or Lower aquifer at depth of 55 to 90 m. In order to determine dispersivity property of the two aquifers, Laboratory tracer tests on repacked representative samples provide breakthrough curve of effluent relative concentration of chloride for dispersivity evaluation. The results are validated and the laboratory-scale dispersivity property of the two aquifers are applied to the original groundwater model for the solute transport model simulation according to the continuous groundwater injection test for 30 and 90 days in the Upper and Lower aquifers. From the laboratory-scale dispersivity evaluation, The longitudinal (D_L) and tranverse (D_T) hydrodynamic dispersion coefficient of the Upper aquifer are 2.53 x 10-4 cm^2/s and 2.53 x 10^{-5} cm^2/s and the longitudinal (D_L) and tranverse (D_T) hydrodynamic dispersion coefficient of the Lower aquifer are 1.45 x 10^{-4} cm^2/s and 1.45 x 10^{-5} cm^2/s, respectively. Moreover, the longitudinal (α_L) and tranverse (α_T) dispersivity of the Upper aquifer are 0.12 and 0.012 cm and the longitudinal (α_L) and tranverse (α_T) dispersivity of the Lower aquifer are 0.18 and 0.018 cm, respectively. Using an actual dispersivity data instead of estimated value provides an exact natural condition of the study area. The outputs of solute transport model illustrate that the chloride concentration contour disperse in northwest to southeast direction which is identical to the regional hydraulic gradient of Sawankhalok district.

Furthermore, the solute transport models based on the heterogeneous laboratory-scale dispersivities property indicate the migration of chloride concentration plume which can also be considered as groundwater injection zone. According to the ASR pilot study, the groundwater injection zone of the Upper aquifer is approximately 300 m and the Lower aquifer is around 600 m away from the ASR site where the injection well are located. In conclusion, the groundwater injection zone of the Lower aquifer is significantly larger than the Upper aquifer because of the difference in groundwater injection rate and aquifer heterogeneity of the Upper Chao Phraya river basin that cause the pattern of the solute migration to vary from the homogeneous condition. Finally, for long term operation, ASR technology can be beneficial to groundwater resource of Sawankhalok district, Sukhothai province.

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Table 1 Hydrogeological data

Layer no.	Depth (m)	Lithology	Aquifer
1	0-20	Clay and clayey sand	Aquiclude
2	20-45	Gravelly sand with clay lenses	Upper aquifer
3	45-50	Clay and clayey sand	Aquiclude
4	55-90	Gravelly sand interbeded with clay lenses	Lower aquifer
5	90-95	Bedrock	Aquitard

Table 2 Hydrualic properties of each Hydrogeological layers

Layer no.	Hydraulic conductivity (m/day)		Storativity	
	Kx, Ky	Kz	Ss	Sy
1	1.1-2.8	0.7	0.0002	0.2
2	29-32	7.6	0.0005	0.002
3	1.5-2.5	0.8	0.0001	0.002
4	33-37	8.2	0.0004	0.002
5	0.6	0.2	0.0001	0.002

Table 3 Flow rates of column tracer experiment

Test	Flow rate (ml/s)
R1	7.63×10^{-3}
R2	1.04×10^{-2}
R3	2.55×10^{-1}

Table 4 Average linear velocity of each tests

Test	The Upper aquifer (cm/s)	The Lower aquifer (cm/s)
R1	5.12×10^{-4}	4.06×10^{-4}
R2	6.05×10^{-3}	5.20×10^{-3}
R3	9.72×10^{-3}	8.26×10^{-3}

Table 5 Longitudinal (D_L) and tranverse (D_T) hydrodynamic dispersion coefficients of the Upper aquifer

Test	D_L (cm^2/s)	D_T (cm^2/s)
R1	4.11×10^{-5}	4.11×10^{-6}
R2	1.80×10^{-4}	1.80×10^{-5}
R3	5.39×10^{-4}	5.39×10^{-5}

Table 6 Longitudinal (D_L) and tranverse (D_T) hydrodynamic dispersion coefficients of the Lower aquifer

Test	D_L (cm^2/s)	D_T (cm^2/s)
R1	3.75×10^{-5}	3.75×10^{-6}
R2	1.12×10^{-4}	1.12×10^{-5}
R3	2.86×10^{-4}	2.86×10^{-5}

Table 7 Longitudinal (α_L) and tranverse (α_T) dispersivities of the Upper aquifer

Test	α_L (cm)	α_T (cm)
R1	0.067	0.0067
R2	0.101	0.0101
R3	0.206	0.0206

Table 8 Longitudinal (α_L) and tranverse (α_T) dispersivities of the Lower aquifer

Test	α_L (cm)	α_T (cm)
R1	0.082	0.0082
R2	0.175	0.0175
R3	0.294	0.0294

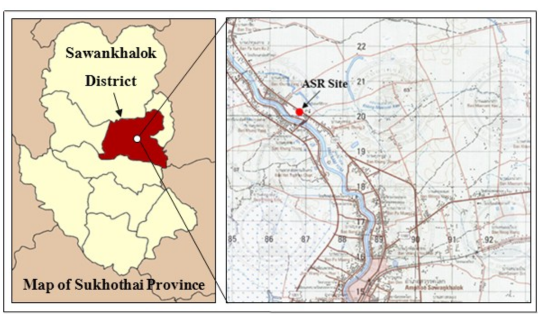

Figure 1 Study area of ASR project in Sawankhalok district, Sukhothai province

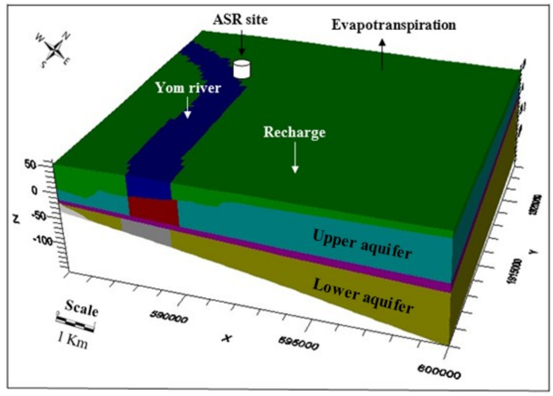

Figure 2 Conceptual model of the study area

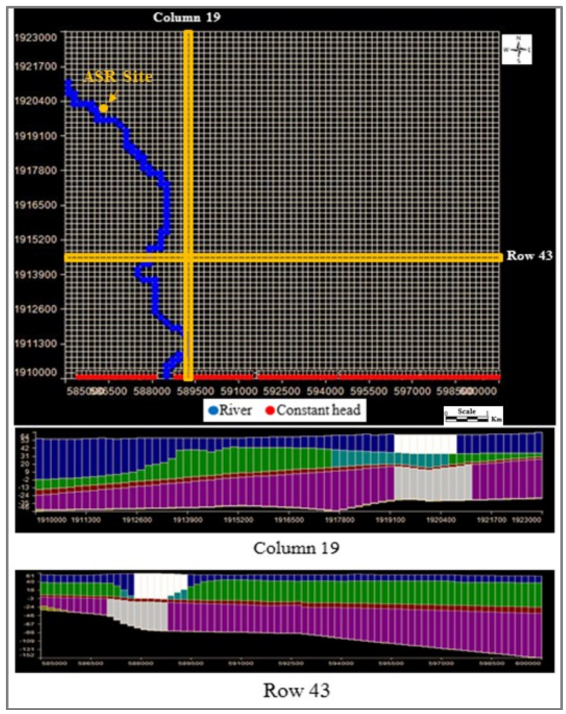

Figure 3 Distribution of input data including river package and constant head in the first layer and cross-section of hydraulic conductivity of grid cells in layers.

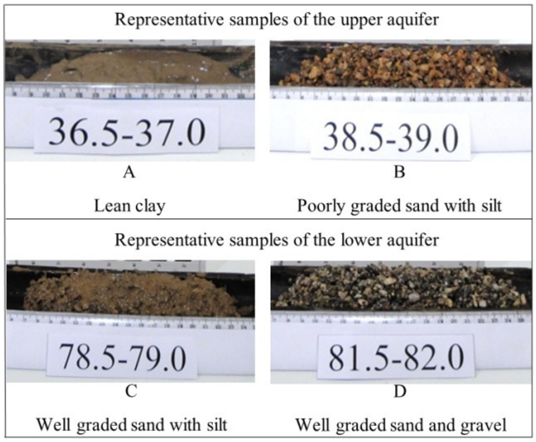

Figure 4 Representative samples of the Upper (4A, 4B) and Lower (4C, 4D) aquifer with its depth above ground surface (SNT, 2010)

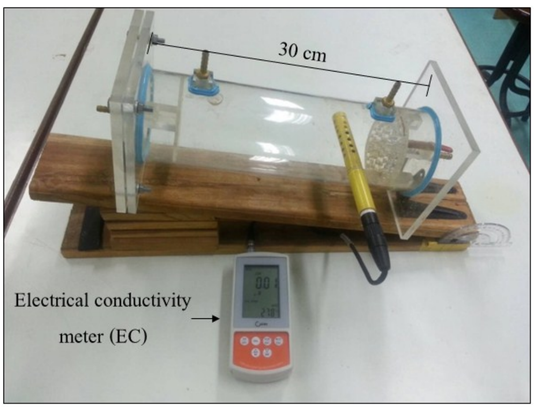

Figure 5 Acrylic column and Electrical Conductivity (EC) meter

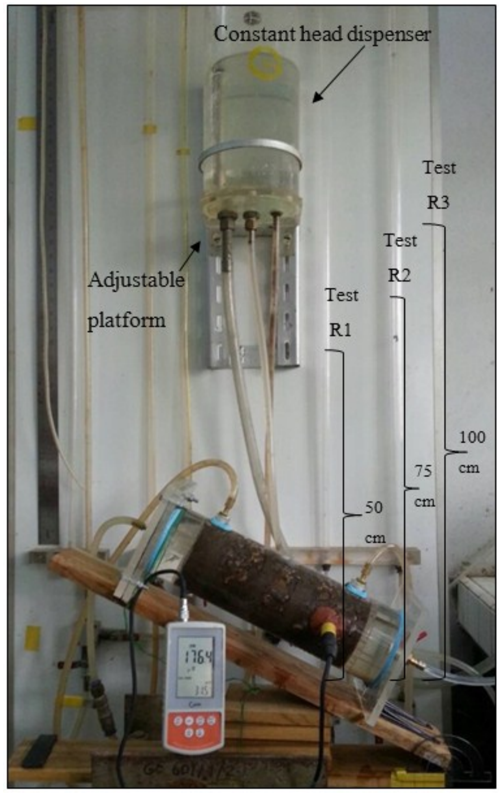

Figure 6 Installation of column tracer experiment

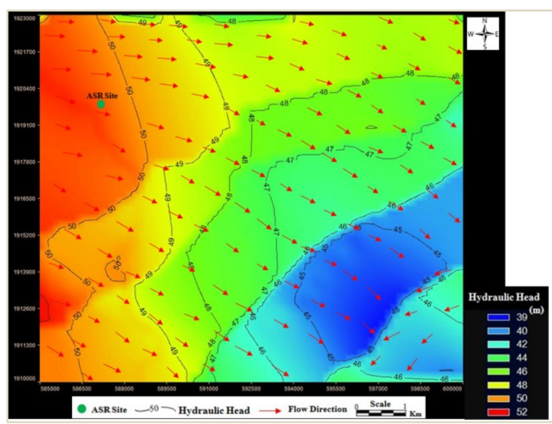

Figure 7 Groundwater flow pattern of the Upper aquifer or second layer at depth of 20-45 m

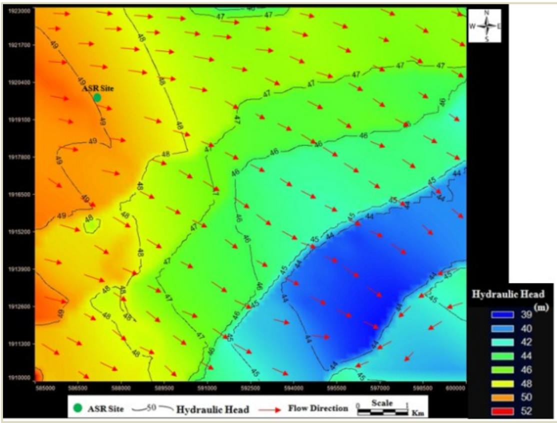

Figure 8 Groundwater flow pattern of the Lower aquifer or forth layer at depth of 55-90 m

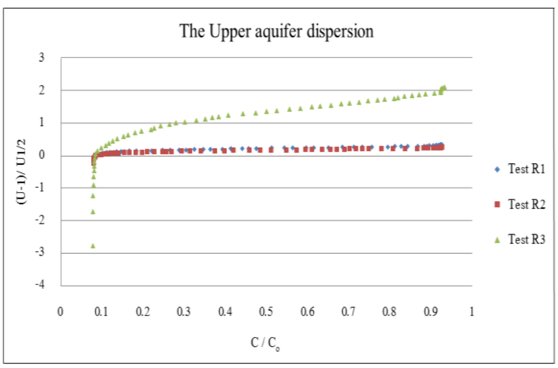

Figure 9 The Upper aquifer dispersion

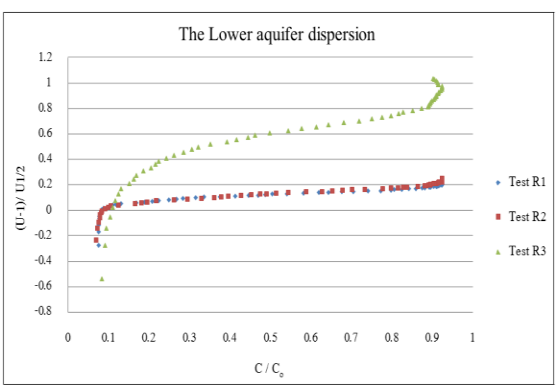

Figure 10 The Lower aquifer dispersion

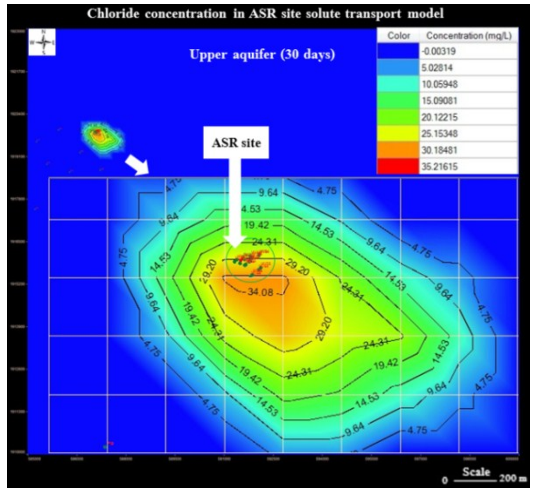

Figure 11 Solute transport model of the Upper aquifer at Sawankhalok district for 30 days

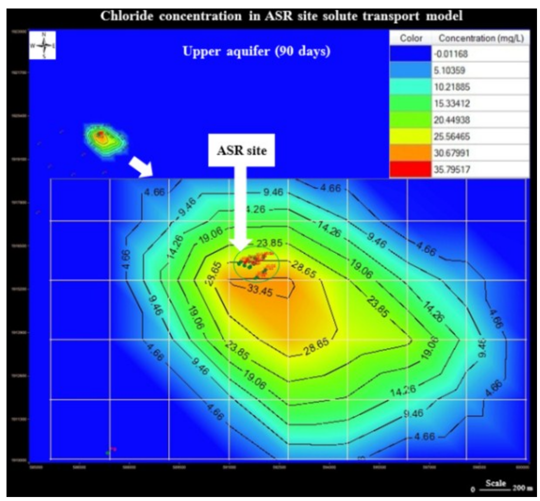

Figure 12 Solute transport model of the Upper aquifer at Sawankhalok district for 90 days

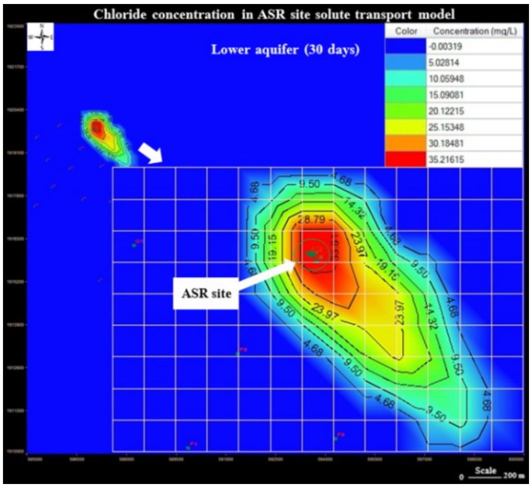

Figure 13 Solute transport model of the Lower aquifer at Sawankhalok district for 30 days

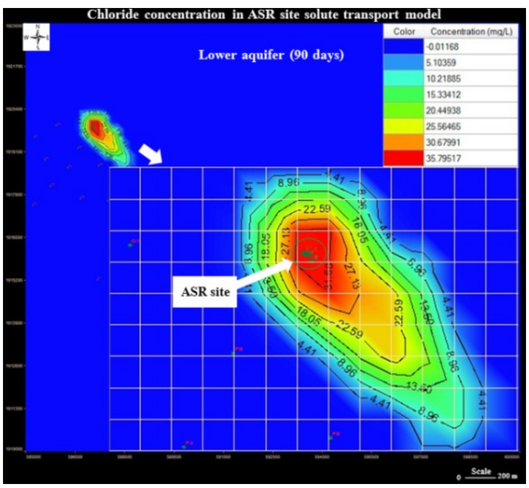

Figure 14 Solute transport model of the Lower aquifer at Sawankhalok district for 90 days

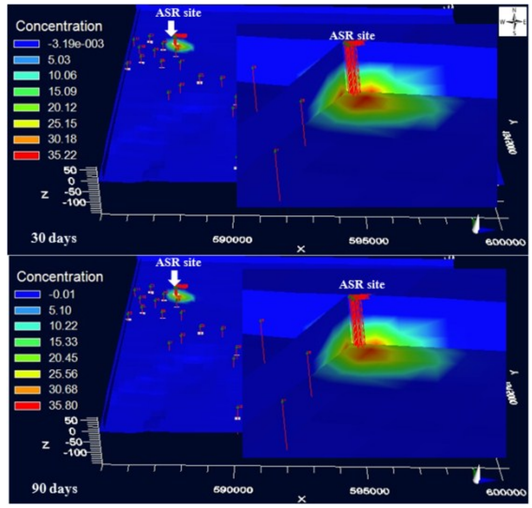

Figure 15 Solute transport model of the Upper aquifer at Sawankhalok district in 3D

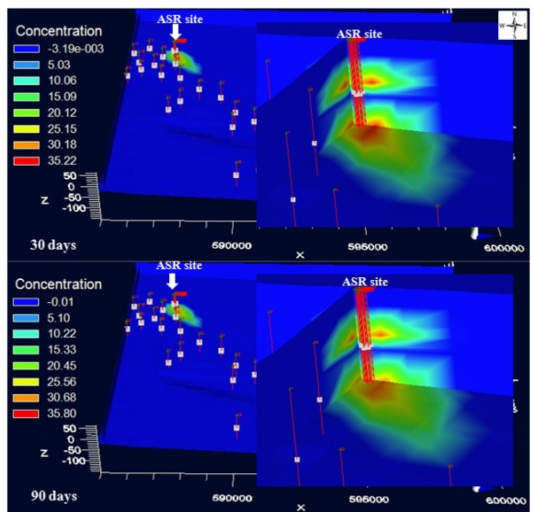

Figure 16 Solute transport model of the Lower aquifer at Sawankhalok district in 3D