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

# การประเมินการแพร่กระจายสำหรับแบบจำลองการเคลื่อนที่มวลสาร ในโครงการเติมน้ำลงสู่ชั้นน้ำบาดาลจังหวัดสุโขทัย

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**ABSTRACT**

Solute transport modeling was constructed as part of a recent, large-scale Aquifer Storage and Recovery (ASR) project in Sukhothai Province, Thailand. The model simulated 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 were 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 were used in the original solute transport model, to illustrate the importance of site scale dispersivity of the groundwater injection zone. Groundwater model was established according to hydrogeology and onsite hydraulic conductivity data. The results illustrated 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 สัมประสิทธิ์การแพร่กระจายคำนวณได้จากกราฟการเปลี่ยนแปลงความเข้มข้นของคลอไรด์ ถูกใช้ในการประเมินคุณสมบัติการแพร่กระจายสำหรับแบบจำลองการเคลื่อนที่มวลสารซึ่งแสดงบริเวณที่มีการเติมน้ำลงสู่ชั้นน้ำบาดาล แบบจำลองการไหลน้ำบาดาลถูกสร้างขึ้นจากข้อมูลอุทกธรณีวิทยาและค่าสัมประสิทธิ์การยอมให้น้ำซึมผ่านซึ่งทดสอบ ณ สถานีเติมน้ำ ผลการทดลองพบว่าขอบเขตการเคลื่อนที่ของคลอไรด์ในชั้นหินให้น้ำทั้งสองนั้นเคลื่อนที่ไปในทิศทางตะวันออกเฉียงใต้เช่นเดียวกับแบบจำลองการไหลน้ำบาดาล ในระยะยาวเทคโนโลยีการเติมน้ำลงสู่ชั้นน้ำบาดาลนี้เป็นประโยชน์ต่อทรัพยากรน้ำบาดาลของอำเภอสวรรคโลก จังหวัดสุโขทัย

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

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## 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 situations 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 shows study area map and also a location of ASR site. Pyne (1995) explained that 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.

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 two main aquifers including the Upper and the Lower aquifers which are located between the depths of 35-44 and 74-83 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.

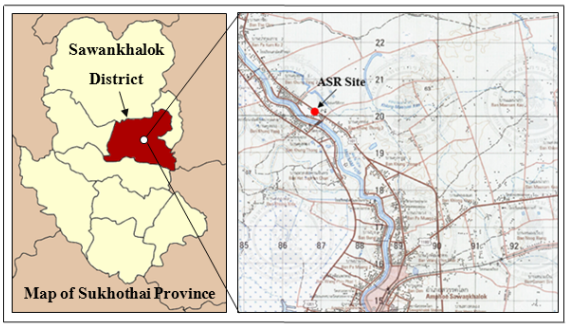


**Figure 1** Study area of ASR project in Sawankhalok district, Sukhothai province

Studying about solute transport modeling, a dispersivity has become significant parameter of the model particularly in an area of complex sedimentary layers. Vargas et al. (2013) demonstrated that the dispersivity property is an important parameter for solute transport modeling. 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 evaluating hydrodynamic dispersion and dispersivity. 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 were used to determined dispersivities. Samples were obtained from an injection wells during the construction of the ASR project and they were used in laboratory column studies. This study consists of three parts including the groundwater flow model, the column experiment and the solute transport model based on dispersivity property of the aquifers.

**Objectives of the study**

This study aimed to conduct laboratory tracer test on a 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**

**Groundwater modeling**

Groundwater model establishment was 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.

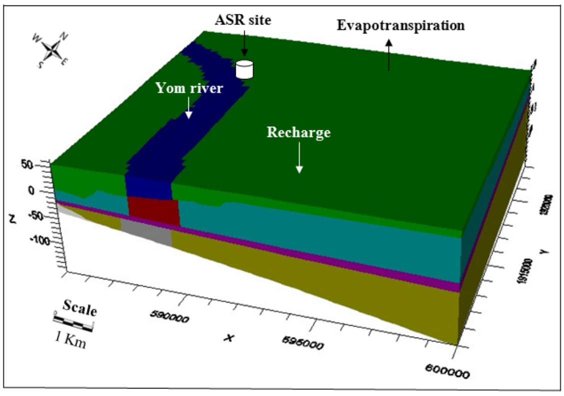


**Figure 2** Conceptual model of the study area

The study area is approximately 225 km$^2$ 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 conductivities and storativities. Other input parameters consisting of river package, initial head, recharge evapotranspiration and observation wells were 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.

**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 |

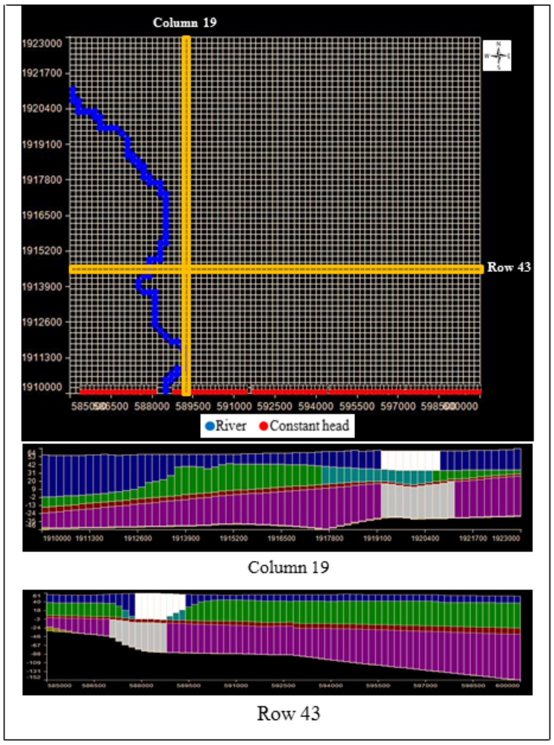


**Figure 3** Distribution of input data including river package and constant head in the first layer and cross-section of hydraulic conductivity of grid cells in layers.

Groundwater model were calibrated and run for groundwater flow simulation. After the model was adjusted, the next stage was 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.

**Dispersivity evaluation**

**Laboratory column tracer experiment**

Pickens and Grisak (1981) conducted a laboratory study of hydrodynamic dispersion coefficient and dispersivity by a 30 cm column that was filled with saturated porous media. The 200 mg/L of chloride solution was introduced into the column as a tracer by three different flow rates that provides average linear velocity for each test. Furthermore, chloride concentration was measured from an effluent solution that came 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 Brightham (1974)

$$\frac{C}{C_0} = 0.5\left[erfc\left(\frac{1-U}{2(UD_L/\,v_iL)^{1/2}}\right)\right] \qquad (1)$$

Where $U$ is the number of effluent pore volumes and $L$ is the column length, $D_L$ is longitudinal hydrodynamic dispersion coefficient and $v_i$ is average linear velocity. Brigham (1974) recommended that 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 hydrodynamic dispersion coefficient can be calculated from this expression

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

Where $J_{0.84}$ 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

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

Where $\alpha_L$ is the longitudinal dispersivity and $D^*$ is the molecular diffusion coefficient in the porous medium. Dispersivity value is evaluated by rearrangeing (3) as

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

Moreover, tranverse hydrodynamic dispersion coefficient, $D_T$, can be calculated from an approximate formula of Hulla (1999)

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

Then, the tranverse dispersivity, $\alpha_T$ can be calculated by

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

The representative samples of the Upper (35-44 m) and Lower ( 74-83 m) aquifers are obtained from the ASR wells during a construction of the site. Representative samples of the both aquifers are presented in figure 4 which consists 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 porosity of the Upper and the Lower aquifer are 40.6 and 31.1 percent, respectively (SNT, 2010).

Figure 5 shows a 30 cm acrylic column with 10 cm diameter and an Electrical Conductivity (EC) meter that was 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 were 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 were repacked into the column according to their depth and, were saturated over night with distilled water before begin a tracer test.

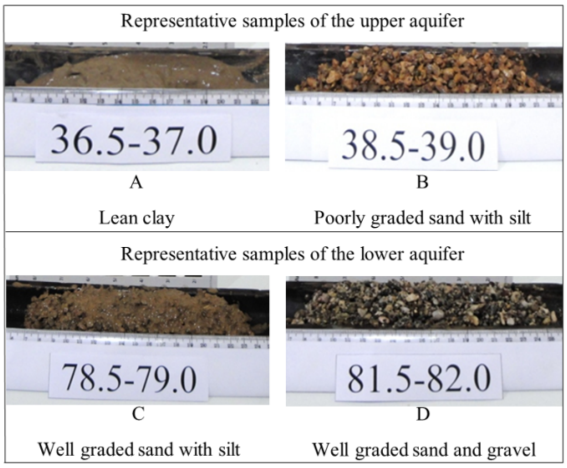


**Figure 4** Representative samples of the Upper (4A, 4B) and Lower ( 4C, 4D) aquifer with their depth above ground surface (SNT, 2010)

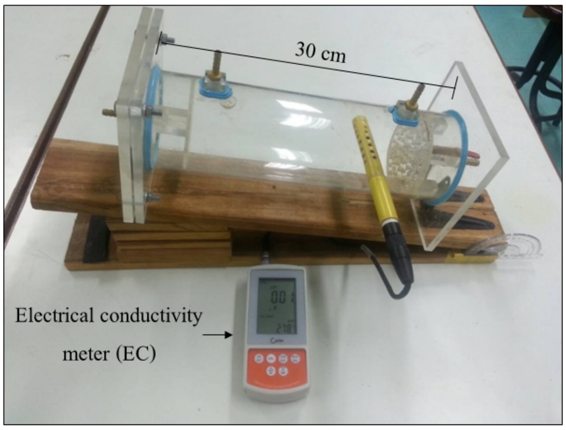


**Figure 5** Acrylic column and Electrical Conductivity (EC) meter

**Table 3** Flow rates of column tracer experiment

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

Three flow rates of tracer were passed through the sample but after finishing one test, it was flashed out by distilled water until an EC value was as low as possible normally it takes around 1 hour then, the next test was started. Detecting EC value change was 24 hours per test and they were recorded every 30 minute. EC value was converted into chloride concentration using this following equation from Boman et. al (2002)

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

However, Anderson (1979) conducted column studies on many sediments and the laboratory values of longitudinal dispersivity ranges from about 0.01 to 1 cm with ratios of longitudinal to tranverse dispersivities ranging from 5 to 25.

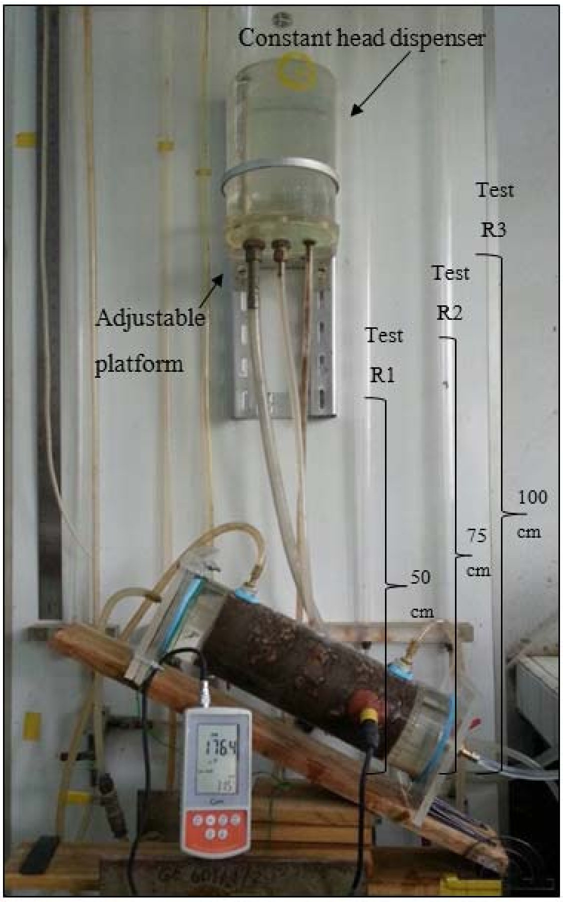


**Figure 6** Installation of column tracer experiment

**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 (PAC) during the treatment process. Therefore, chloride concentration as a conservative tracer has become a target for observing migration plume of injected water. Moreover, chemical data of injected water and groundwater from observation wells were established as chemical background data of the model. In this solute transport simulation, longitudinal and tranverse dispersivity values of aquifers from the column experiment were applied as input parameter.

**Results**

**Groundwater flow model of Sawankhalok**

Groundwater model simulated groundwater flow pattern of both the Upper and Lower aquifers in southeast direction as shown in figures 7 and 8. Hydraulic heads of the Upper aquifer are slightly higher than the Lower aquifer in some location especially the upper part of the study area but the lower part or recharge area shows similar hydraulic head. The root mean square error of model calibration is 8.9 percent. Groundwater flow pattern of both main aquifers are different because each layers of the model consists of various hydraulic properties especially the hydraulic conductivity of the second layer at depth (20 -45m) and the forth layer at depth (55-90 m).

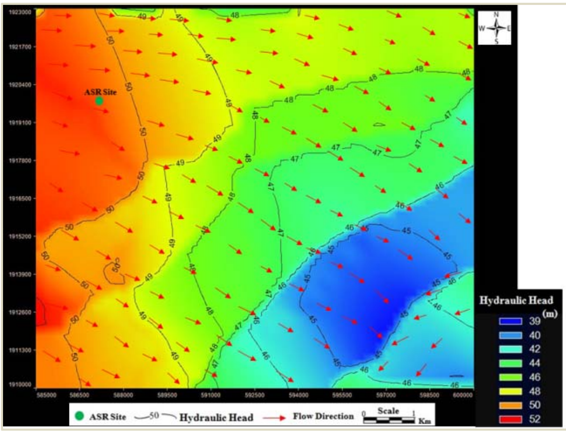


**Figure 7** Groundwater flow pattern of the Upper aquifer or second layer at depth of 20-45 m

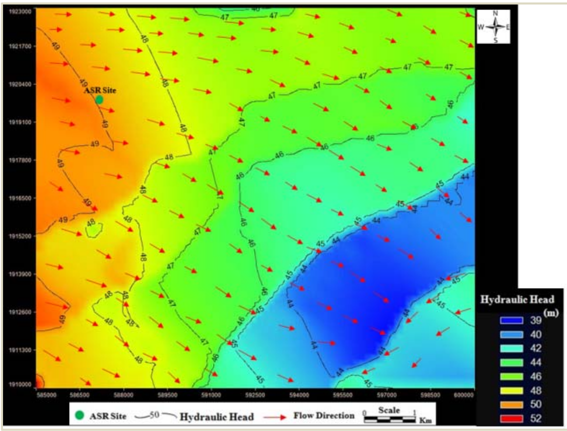


**Figure 8** Groundwater flow pattern of the Lower aquifer or forth layer at depth of 55-90 m

**Dispersivity evaluation of Sukhothai ASR site**

**Average linear velocity**

After the column was repacked, average linear velocity or $v_i$ was calculated for each of the three flow rates according to variation of dispenser heights as presented in table 4.

**Table 4** Average linear velocity of each test

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

**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 was fitted as a straight line, therefore the use of a diffusion equation model approach was validated, and the hydrodynamic dispersion coefficient can be calculated.

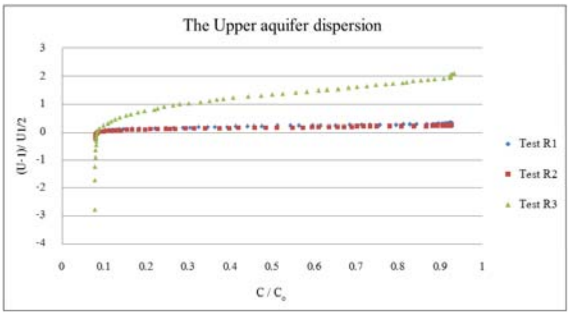


**Figure 9** The Upper aquifer dispersion

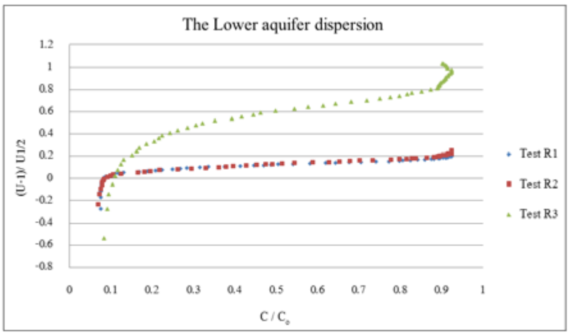


**Figure 10** The Lower aquifer dispersion

Longitudinal ($D_L$ ) and tranverse ($D_T$) hydrodynamic dispersion coefficients are illustrated in tables 5 and 6. The average value of $D_L$ and $D_T$ of the Upper aquifer are $2.53 \times 10^{-4}$ $cm^2/s$ and $2.53 \times 10^{-5}$ $cm^2/s$, respectively. The average value of $D_L$ and $D_T$ of the Lower aquifer are $1.45 \times 10^{-4}$ $cm^2/s$ and $1.45 \times 10^{-5}$ $cm^2/s$, respectively.

**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 x $10^{-5}$ | 4.11 x $10^{-6}$ |
| R2 | 1.80 x $10^{-4}$ | 1.80 x $10^{-5}$ |
| R3 | 5.39 x $10^{-4}$ | 5.39 x $10^{-5}$ |

**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 x $10^{-5}$ | 3.75 x $10^{-6}$ |
| R2 | 1.12 x $10^{-4}$ | 1.12 x $10^{-5}$ |
| R3 | 2.86 x $10^{-4}$ | 2.86 x $10^{-5}$ |

Longitudinal ($\alpha_L$) and tranverse ($\alpha_T$) dispersivities are shown in tables 7 and 8. The average values of $\alpha_L$ and $\alpha_T$ of the Upper aquifer are 0.12 cm and 0.012 cm, respectively. The average value of $\alpha_L$ and $\alpha_T$ of the Lower aquifer are 0.18 cm and 0.018 cm, respectively.

**Table 7** Longitudinal ($\alpha_L$) and tranverse ($\alpha_T$) dispersivities of the Upper aquifer

| Test | $\alpha_L$ (cm) | $\alpha_T$ (cm) |
|---|---|---|
| R1 | 0.067 | 0.0067 |
| R2 | 0.101 | 0.0101 |
| R3 | 0.206 | 0.0206 |

**Table 8** Longitudinal ($\alpha_L$) and tranverse ($\alpha_T$) dispersivities of the Lower aquifer

| Test | $\alpha_L$ (cm) | $\alpha_T$ (cm) |
|---|---|---|
| R1 | 0.082 | 0.0082 |
| R2 | 0.175 | 0.0175 |
| R3 | 0.294 | 0.0294 |

**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 were applied in solute transport modeling of the Sukhothai ASR site at Sawankhalok district . The average values were 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, solute transport model performed 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 was 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 how it migrates 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 are 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 groundwater flow pattern that migrates in southeast direction from the high hydraulic head 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.

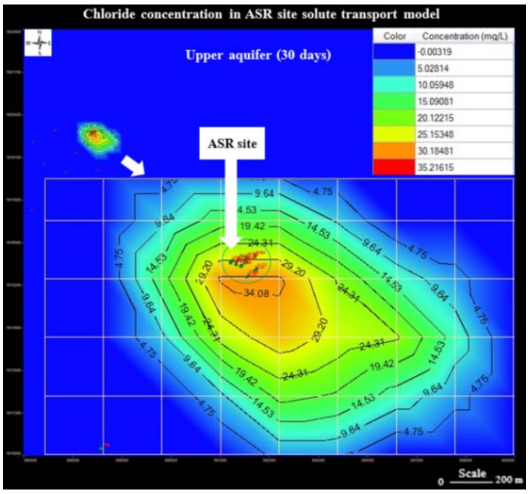


**Figure 11** Solute transport model of the Upper aquifer at Sawankhalok district for 30 days

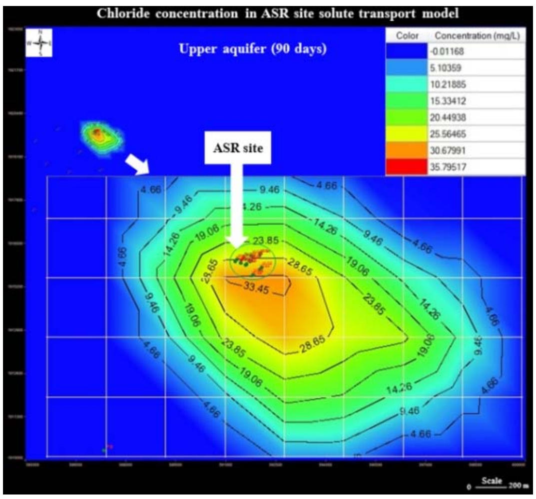


**Figure 12** Solute transport model of the Upper aquifer at Sawankhalok district for 90 days

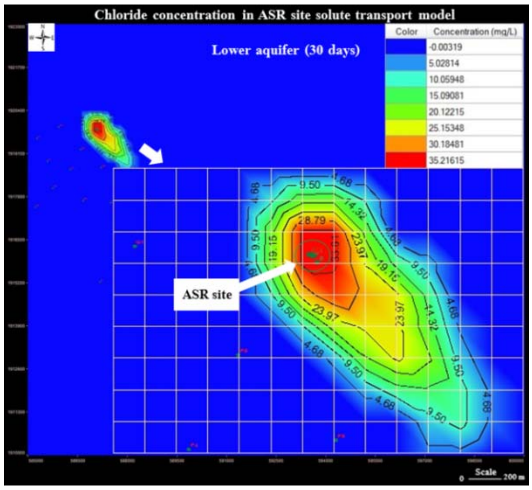


**Figure 13** Solute transport model of the Lower aquifer at Sawankhalok district for 30 days

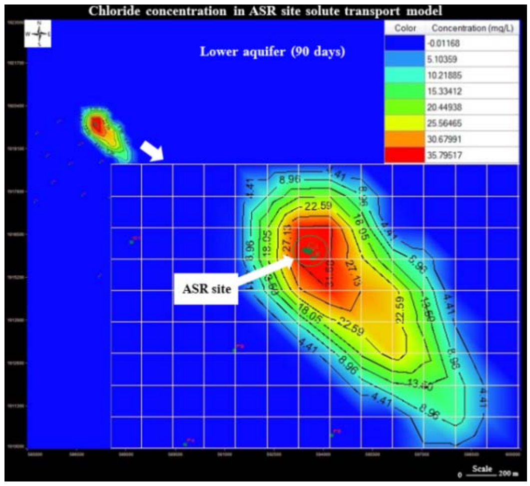


**Figure 14** Solute transport model of the Lower aquifer at Sawankhalok district for 90 days

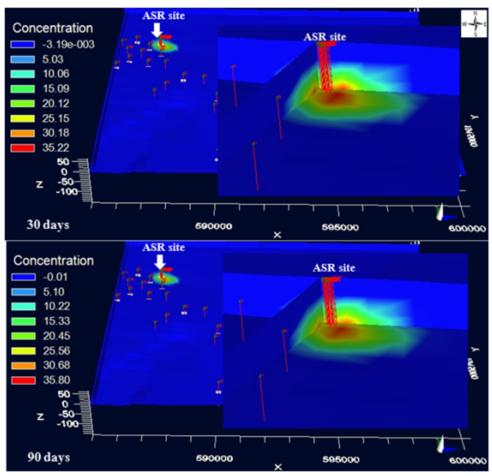


**Figure 15** Solute transport model of the Upper

aquifer at Sawankhalok district in 3D

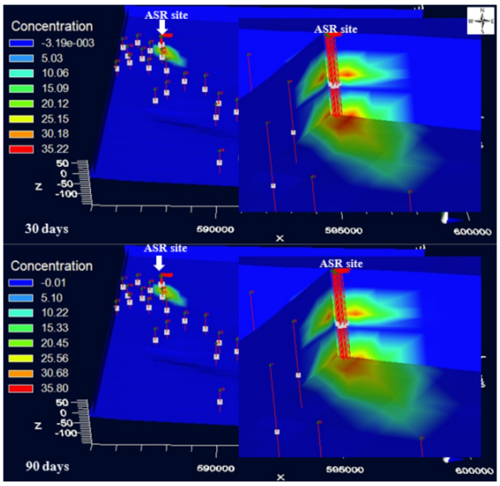


**Figure 16** Solute transport model of the Lower aquifer at Sawankhalok district in 3D

**Discussion and Conclusions**

Groundwater model of Sawankhalok district, Sukhothai province represents groundwater flow pattern of the study area that moves in southeast direction. Hydraulic heads of the second layer or Upper aquifer at depth of 20-45 m are approximately 1 m higher than the forth layer or Lower aquifer at depth of 55-90 m in some area. In order to determine dispersivity property of the two aquifers, Laboratory tracer tests on repacked representative samples provided breakthrough curve of effluent relative concentration of chloride for dispersivity evaluation. The results were valid and lab-scale dispersivity property of the two aquifers were applied to the original groundwater model for solute transport model simulation according to the continuous groundwater injection test for 30 and 90 days in the Upper and Lower aquifers. Using an actual dispersivity data instead of estimated values provided an exact natural condition of the study area. In addition, Solute transport models based on heterogeneous dispersivities from lab-scale property indicate migration of chloride concentration plume which can be considered as groundwater injection zone. Model outputs show the spread of chloride concentration plumes in southeast direction as well as the groundwater flow model. Finally, for long term operation, ASR technology can be beneficial to groundwater resource of Sawankhalok district, Sukhothai province.

**Acknowledgements**

This study was granted by Integrated Water Resource Management Research and Development Center of Northeast Thailand, Faculty of Agriculture and Graduate School Khon Kaen University. Sukhothai ASR information was supported by SNT Consultants Company and groundwater modeling software was supported by Earth Sciences Department, Emporia State University.

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