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ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

THE LINKED GIS AND GROUNDWATER MODEL: CASE STUDY OF ABANDON  
LANDFILL IN CHONBURI PROVINCE



Mr. Virat Wattanamekhinkul

สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

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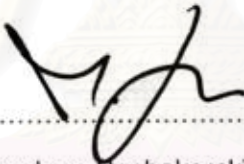
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ในการสร้างแบบจำลองทางคณิตศาสตร์ด้านการไหลของน้ำใต้ดินและการเคลื่อนที่ของสาร  
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KEY WORD: GROUNDWATER CONTAMINATION / SIMULATION / MODFLOW / LINKED GIS

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Numerical simulation of groundwater flow and contaminant transport often involves managing large input and output data sets. Geographic Information systems (GIS) are used to store, manipulate and visualize both spatial and non-spatial data. Because of these data manipulating capabilities, GIS have been linked to different simulation models in different research areas and are commonly used for groundwater modeling. LGGM.NET is a program for linking GIS and groundwater model that is created in the Visual Basic.NET language to take full advantage of GIS capabilities. The Arc view 3.3 and Visual MODFLOW 3.0 were selected to investigate the method of integrating the GIS and groundwater model. A real contamination scenario of the sanitary landfill of the Pattaya municipality was chosen as the project area for this study. The predicted groundwater level and lead contamination were calibrated with historical data from the period 1999 through 2003 obtained from the Pollution Control Department. Statistical measures indicated a good fit between the predicted and observed concentrations. The root mean square error (RMSE) showed that errors were approximately 1.66 m for simulation of groundwater levels and 0.029 mg/L for simulation of lead transport. The advantages of linked GIS and groundwater model are represented in the application studies which resulted in the analysis of affected area of contamination using GIS analysis tools. It was found that remediation by pump-and-treat systems gave the highest treatment efficiency while the natural attenuation and vertical cutoff wall gave almost the same results.

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**LIST OF ABBREVIATIONS**

<b>GIS</b>	= Geographical Information System
<b>LGGM.NET</b>	= Linked GIS and Groundwater Model
<b>MODFLOW</b>	= MODular finite-difference groundwater FLOW model
<b>MT3D MS</b>	= Modular Three-Dimensional Multispecies Transport Model Multi-Species
<b>Pb</b>	= Lead
<b>PCD</b>	= Pollution Control Department
<b>RDBMS</b>	= Relational Database Management System
<b>RMSE</b>	= Root Mean Square Error
<b>US EPA</b>	= United States Environmental Protection Agency



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# CHAPTER I

## INTRODUCTION

### 1.1 General

The rapidly growing economy and population of Thailand is resulting in the consumption of more and more natural resources. Consequently, more waste is created and the problem is becoming increasingly serious each day. Leachate from an abandon municipal landfill is a major source of groundwater contamination. All regions of Thailand are anxious about groundwater pollution because it creates a health and a difficult to solve problem.

The sanitary landfill of the Pattaya municipality was chosen as the project area for this study. This landfill is located in Tambon Huai Yai, Amphoe Banglamung, Chonburi province, overlaying the Colluvial deposits aquifer (Department of Mineral Resources, 1999). Since 1986, this landfill has been operated on 56,000 m<sup>2</sup> of land, it contains 426,800 m<sup>3</sup> of garbage and reached its full capacity in 1998 (Pollution Control Department, 1999).

Groundwater contamination found at the down gradient of the groundwater flow from the landfill as shown in Figure 1.1. Huai Chak Nok reservoir and Ban Chak Nok municipality are the sensitive areas; they are located to the east and south of the landfill, respectively. Visual MODFLOW is a computer program for practical applications in three-dimensional groundwater flow and contaminant transport simulations, was selected for this study because of the following reasons:

1. MODFLOW, the integrated package in Visual MODFLOW, is a modeling software that is often used in both the government and private sectors and also frequently used in academic research.
2. MT3D, which had been integrated with Visual MODFLOW, uses a mixed Eulerian-Lagrangian approach to solve the three-dimensional Advective-dispersive- reactive equation. Thus MTD3D is unique and suitable for use in a wide range of field problems.
3. The finite difference structure of MODFLOW and MT3D is compatible with raster output from ARC VIEW.

MODFLOW does have some disadvantages. Firstly MODFLOW does not provide a geographical reference and therefore simulations are often analyzed in an arbitrary “model space” (Shiva, 1998). Secondly the input interface of MODFLOW is based on finite differences and require cell by cell for a myriad of parameters (Ross, 1998). For these reason the MODFLOW model is somewhat inaccurate and difficult to reproduce. Moreover when large regions are modeled, an enormous amount of data will be required in order to create a digitized model. This makes MODFLOW models inconvenient and lead to arbitrary digitizing.

Integrating the Geological Information System (GIS) and groundwater model has many distinct advantages over the traditional model. The most important benefit of using the GIS is that everything is defined within a spatial context such as the distribution of precipitation, groundwater recharge, Digital Elevation Maps (DEMs), aquifer maps, soil map, hydrological storage structure, and so on, which all can be seen on a single map. Moreover, relationships between these components are easily determined because the GIS is essentially a database that can combine this information in an infinite number of ways (Kris, 1996).

Therefore, the aims of this study are to integrate the GIS and groundwater modeling (Visual MODFLOW 3.0) by using the converter program written by Visual Basic.NET, and to use this procedure for predicting the concentration of total lead in an aquifer under the sanitary landfill of the Pattaya municipality. Then the GIS will be used to represent the model’s result in order to analyze and plan for proper mitigation.

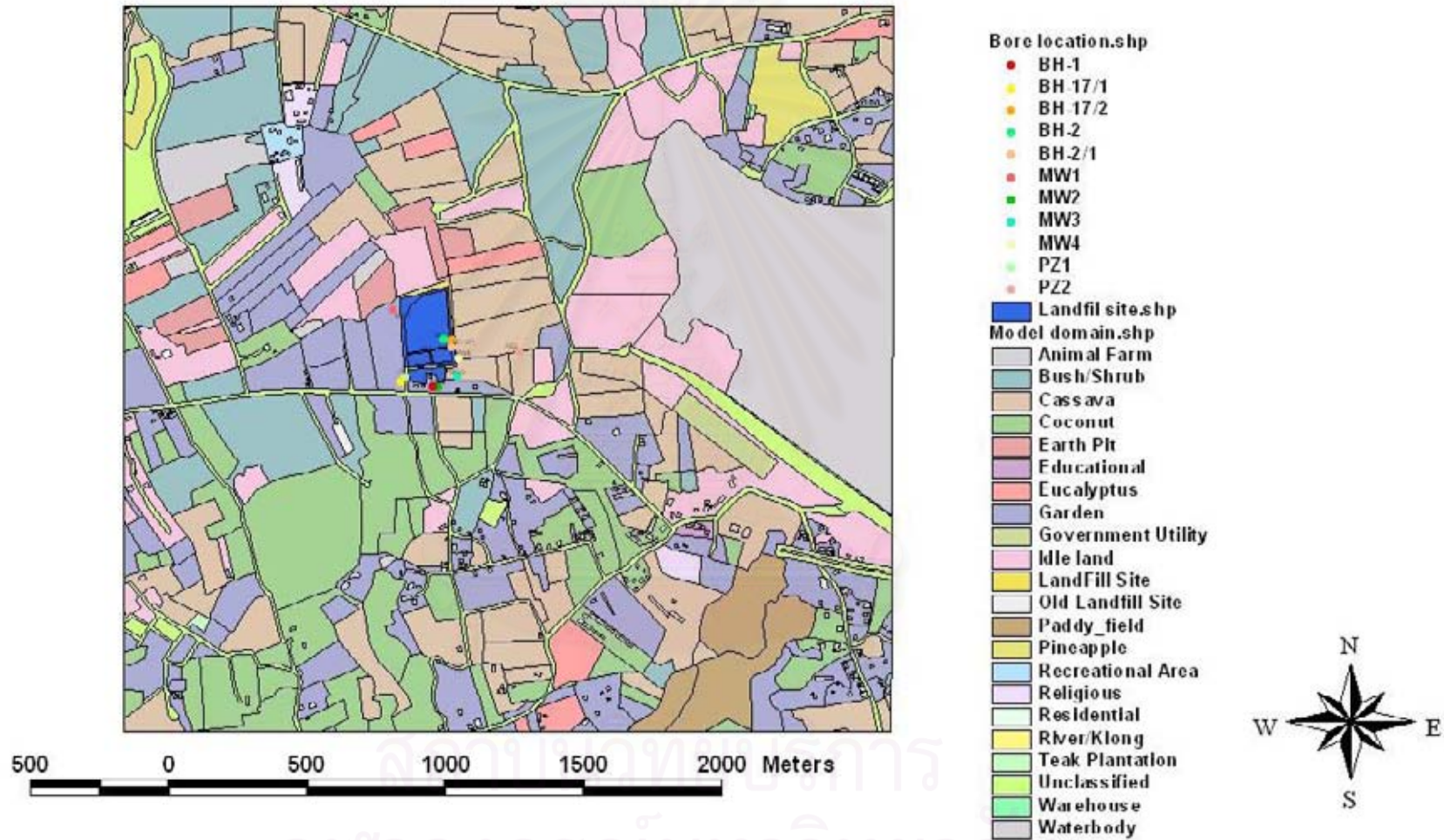
## **1.2 Objectives**

The objectives of the study can be summarized as follows:

1. To investigate the method of integrating the GIS (Specifically Arc View 3.3) and MODFLOW (Visual MODFLOW 3.0 interface).
2. To represent the advantages of result analysis from the method of integrating the GIS (Specifically Arc View 3.3) and Visual MODFLOW.

## **1.3 Hypothesis**

1. The integrated GIS and MODFLOW can be used to simulate the groundwater flow and distribution of lead in groundwater and manage the result as database.
2. The GIS can be used to analyze and determine the effects of the contamination and site remediation method.



**Figure 1.1** Locations of the observation wells in the study area.



## CHAPTER II

### THEORETICAL BACKGROUND AND LITERATURE REVIEW

#### 2.1 Background

##### 2.1.1 Landfill Leachate

Leachate is the liquid that results from rain, snow, dew, and natural moisture, which percolates through the waste in a landfill or dump. While migrating through the waste, the liquid dissolves salts, picks up organic constituents, and leaches heavy metals, such as iron, mercury, lead, and zinc from cans, batteries, paints, pesticides, cleaning fluids, and inks. The organic strength of landfill leachate can be greater than 20 to 100 times the strength of raw sewage (USEPA, 2002). This “landfill liquor” is potentially a potent polluter of soil and groundwater. The majority of open dumps and old sanitary landfills do not have liners or proper drainage systems to divert the leachate. As a result, the leached material is generally absorbed into the ground and then possibly into groundwater, surface water, or aquifer systems.

Heavy metals contained in waste have for years been disposed of in dumps and landfills. The mobility of the heavy metals may be enhanced by the complexing capacity of the organic matter leaching from the landfill and by the content of colloidal matter in the leachate and the leachate-polluted groundwater. It is an established fact that organic matter in landfill leachate binds heavy metals strongly (Christensen et al., 1996) and that colloidal matter has a high affinity for heavy metals (Gounaris, Anderson and Holsen, 1993). The presence of organic complexes and colloidal-bound heavy metals in leachate-polluted groundwater affects the total concentration as well as the behavior of heavy metals in the aquifer.

Lead is a kind of heavy metal that was typically found in landfill leachate because it is a majority ingredient in batteries, paints, pesticides, cleaning fluids, and inks. Moreover, from the exploration on contamination situation of Pollution Control Department (1999), lead was classified as the most seriously problem in leachate. The survey result on leachate quality is shown in Appendix D.

## 2.1.2 Lead

### 2.1.2.1 Introduction

Lead is a naturally occurring bluish-gray metal typically found in the earth's crust. It has no characteristic taste or smell. Metallic lead does not dissolve in water and does not burn. Lead can combine with other chemicals to form what are usually known as lead compounds or lead salts (Eco-USA.net, 2006). Some lead salts dissolve in water better than others. Some natural and manufactured substances contain lead but do not look like lead in its metallic form. Some of these substances can burn for example, organic lead compounds in some gasoline.

The release of lead into the air is now less than the release of lead into the land. Most of the lead in inner city soils comes from old houses painted with paint containing lead and previous automotive exhaust emitted when gasoline contained lead. Landfills may contain waste from lead ore mining, ammunition manufacturing, or other industrial activities such as battery production.

### 2.1.2.2 Chemical and Physical Properties

The chemical and physical properties of lead are shown in Table 2.1.

Although lead has four valence shell electrons, there are only two ready for ionizing. The +2 oxidation state of lead in inorganic compounds is more common than +4. The inorganic compounds of lead are generally poorly soluble. Some of the salts forms with organic acids, e.g., lead oxalate, which is also insoluble.

**Table 2.1** Chemical and physical properties of lead

CASRN (Chemical Abstracts Service Registry Number)	7439-92-1
Chemical formula	Pb
Atomic number	82
Molecular weight	207.19 g/mol

Specific gravity	Lead, 11.34; Lead ore, galena, 7.3 – 7.6; Lead oxide (yellow), 9.5 – 9.9
Vapor pressure	10 mmHg. at 1,160 °C
Color	Bluish or silvery-grey soft metal
Melting point	327.5 °C
Boiling point	1,740 °C at atmospheric pressure
Natural isotopes (in order of abundance)	208, 206, 207 and 204

### 2.1.2.3 Toxicity

The toxic effects from exposures to inorganic lead form a continuum of biochemical effects to clinical effects. These effects involve several organ systems and biochemical activities. The most sensitive effects in infants and children involve the nervous system. For adults with excess exposure, the concerns are peripheral neuropathy (neurotoxicity) and/or chronic nephropathy (kidney toxicity). However, the critical effect of lead in the general population of adults is hypertension. Effects on the heme system provide biochemical indicators of lead exposure in the absence of chemically detectable effects. Other target organs are located in the gastrointestinal, reproductive and skeletal systems.

## 2.2 Geographical Information System (GIS)

A GIS is any manual or computer-based set of procedures used to store and manipulate geographical reference data (Aronoff, 1989). The GIS database consists of 2 basic types of data: graphical data and non-graphical data.

1. Graphic data, i.e., vector structure and raster structure, are used to represent a map image in the computer. There are three major graphic elements of data in the vector system: point, line and polygon. The raster system consists of several square or rectangular fixtures called grid cells. Each grid cell contains a number, which represents the data that are used to construct the map (Kerdput, 1999).

2. Non-graphic data, i.e., textual data or attributes data, represent the characteristic details or information which is related to the graphic data. They are often stored in conventional alphanumeric formats and linked by GIS technology.

Spatial data (graphic data), such as display pictures or coordinate of point, lines or areas, make up the components of a map; whereas attributes data (non-graphic data), show the details related to those points, lines or area features (Antenucci, 1991).

### **2.3 Arc View 3.3**

The Arcview GIS software package, developed by the Environmental Systems Research Institute, was used as the computer development environment for this research. In the past several years, Arcview has emerged as the industry leader in desktop GIS software. All activities within Arcview are organized as a project, which may consist of a number of views, tables, charts, layouts and scripts (Maidment, 1998). Files created in Arcview are called projects and are denoted by an ".apr" file extension. Vector data files in Arcview are called shape files. The functions of Arcview include: displaying shape files in a view, viewing and editing the related attribute tables of this view, plotting charts to display spatial information, and creating layouts of the view and related tables and charts. Specialized Arcview software, called extensions, is required to manipulate and analyze the raster and TIN data. The Arcview Spatial Analyst extension is designed for creating, querying, mapping, and analyzing raster data (ESRI, 1999). GIS data in Arcview can be manipulated using Avenue, a customization and development programming language embedded in the software package.

The Arcview interface can be used to preprocess GIS spatial data into model input arrays. The spatial data are stored in three different types (point, line and polygon) of shape files or coverage. Observation data such as well logs, pumpage and groundwater levels are stored in the point shape files. Model data related to river and irrigation canals are stored in line shape files. Model data such as the area distribution of soil types, hydraulics conductivity and recharge are stored in polygon-shaped files.

## 2.4 Visual Modflow 3.0 Model

Visual MODFLOW is a computer program for three-dimensional groundwater flow and contaminant transport modeling. Visual MODFLOW is also an integrated package that combines MODFLOW, MT3DMS, etc. It helps users to interpret and predict groundwater flow and quality.

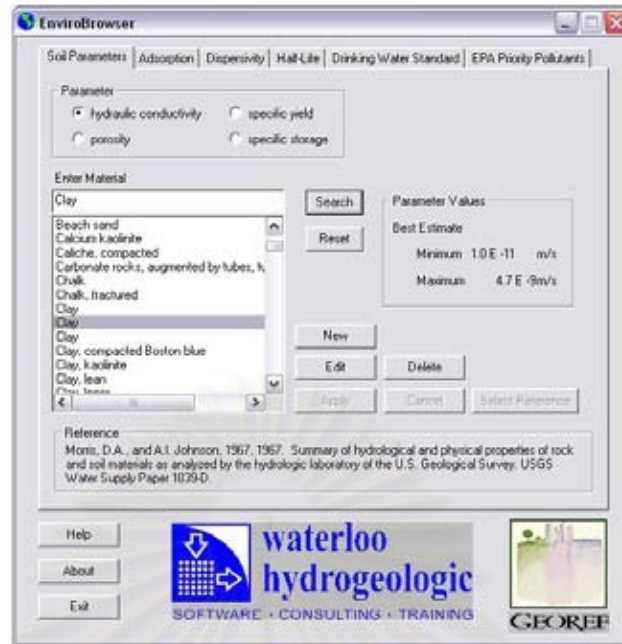
MODFLOW is a computer program that simulates three-dimensional groundwater flow through a porous medium by using the finite-difference method (Arlen et al., 2000). This model can also calculate hydraulic head, drawdown, and the volumetric budget for use in another purpose.

MT3DMS is a Modular Three-Dimensional Multispecies Transport Model, which was originally developed by Chunmiao and Wang in 1990. MT3DMS has a comprehensive set of options and capabilities for simulating the advection, dispersion/diffusion, and chemical reactions of contaminants in groundwater flow systems under general hydrogeologic conditions (Chunmiao and Wang, 1999).

## 2.5 EnviroBrowser 3.0

The EnviroBrowser 3.0 application is a public domain database of thousands of physical and chemical environmental parameters. These parameters include hydraulic conductivity, porosity, adsorption, dispersivity, half-lives, and EPA priority pollutants. Figure 2.1 show user interface of EnviroBrowser 3.0 for query soil parameters.

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**Figure 2.1** User interface of EnviroBrowser 3.0

The tabs on the top of the EnviroBrowser interface categorize the types of information available. The scrollable/searchable list of available materials is located on the left side of the window.

## 2.6 Relevant Equations

### 2.6.1 Darcy's Law

Darcy's law states that the flow rate through a porous medium is proportional to the head loss and inversely proportional to the length of flow path. The law applies to situations where flow is laminar (Paul, Kenneth and Thomas, 1984). The equation that describes this phenomenon is

$$Q = KA(h_2 - h_1)/L$$

Where

V = groundwater flow rate (m<sup>3</sup>/s);

K = hydraulic conductivity (m/s);

A = area normal to the direction of flow (m<sup>2</sup>)

$h_2 - h_1$  = head difference on a line parallel to the direction of the flow (m);

L = length of the flow path between  $h_1$  and  $h_2$  (m).

### 2.6.2 Continuity Equation

The development of the groundwater flow equation in the finite-difference form follows from the application of the continuity equation: the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Under the assumption that the density of ground water is constant, the continuity equation expressing the balance of flow for a cell is as follows (McDonald and Arlen, 1988):

$$\Delta Q_i = S_s \frac{\Delta h}{\Delta t} \Delta V$$

where

- $Q_i$  = flow rate into the cell ( $m^3/s$ )
- $S_s$  = specific storage in the finite-difference formulation (1/m)
- $\Delta h$  = volume of the cell ( $m^3$ )
- $\Delta V$  = change in head over a time interval of length  $\Delta t$

### 2.6.3 Groundwater Flow Equation

The groundwater flow equation that is used in MODFLOW is based on two basic relationships: Darcy's law and the equation for the conservation of mass. The partial-differential equation of ground-water flow used in MODFLOW is as follows (McDonald and Arlen, 1988):

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t}$$

where

$K_{xx}$ ,  $K_{yy}$ , and  $K_{zz}$  = hydraulic conductivity along the x, y, and z coordinate axes (m/s)

$h$  = potentiometric head (m)

$W$  = volumetric flux per unit volume ( $s^{-1}$ )

$S_s$  = specific storage of the porous material ( $m^{-1}$ )

$t$  = time (s)

### 2.6.4 Continuity Equation in a Finite Difference Form:

A groundwater simulation occurs over time and space. A time loop, boundary-line loop, and cell-polygon loop are created to account for all dimensions. Initially (time step zero) the total head is known for each cell. Flow across all boundaries is determined using the discretized momentum equation. The sum of all the flows across a cell's boundary, including flux, recharge, and pumping are then used to determine new values for the total head. The time step is then incremented and calculations over the lines and polygons are repeated. A finite difference form of the continuity equation is used to calculate the change in total head for a groundwater cell (Kris, 1996):

$$\Delta t^t \cdot [A_i \cdot (R_i^t - P_i^t)] + \sum_j V_{ij}^t = A_i \cdot S_i \cdot (h_i^t - h_i^{t-1})$$

where

- h = the total head (m)
- S = the storativity
- R = the recharge to the aquifer (m/s)
- P = the pumpage from the aquifer (m/s)
- V = the volume of water calculated from the flux equations (m<sup>3</sup>)
- A = the area of the cell (m<sup>2</sup>)

### 2.6.5 Contaminant Transport Equation

The partial differential equation describing the fate and transport of contaminants of species  $k$  in 3-D, transient groundwater flow systems can be written as follows (Chunmiao and Wang, 1999):

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_j} \left( \theta D_{ij} \frac{\partial C^k}{\partial x_j} \right) - \frac{\partial}{\partial x_j} (\theta v_j C^k) + q_3 C^k + \sum R_n$$

where

- $\theta$  = porosity of the subsurface medium, dimensionless
- $C_k$  = dissolved concentration of species  $k$  (kg/m<sup>3</sup>)
- $t$  = time (s)



- $x_{i,j}$  = distance along the respective Cartesian coordinate axis (m)  
 $D_{ij}$  = hydrodynamic dispersion coefficient tensor ( $m^2/s$ )  
 $v_i$  = seepage or linear pore water velocity, m/s ; it is related to the specific discharge or Darcy flux through the relationship,  $v_i = q_i / \theta$   
 $q_s$  = volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative) ( $1/s$ )  
 $C_s$  = concentration of the source or sink flux for species  $k$  ( $kg/m^3$ )  
 $\Sigma R_n$  = chemical reaction term, can be biochemical and geochemical reactions ( $kg/m^3/s$ )

### 2.6.6 Advection

Advective transport is the transport of solutes by the bulk movement of groundwater. Advection is the most important process dividing dissolve contaminant migration in the subsurface. For many field-scale contaminant transport problems, the advection term dominates over other terms (Todd, 1999). The linear groundwater velocity in the direction of the groundwater flow caused by advection is given by:

$$v_x = -\frac{K}{n_s} \frac{dH}{dL}$$

where

- $V_x$  = average linear velocity (m/s)  
 $K$  = hydraulic conductivity (m/s)  
 $n_s$  = effective velocity  
 $dH/dL$  = hydraulic gradient

### 2.6.7 Hydrodynamic Dispersion

Hydrodynamic dispersion is the process whereby a contaminant plume spreads out in directions that are longitudinal and transverse to the direction of plume migration.

Hydrodynamic dispersion,  $D$ , has two components, mechanical dispersion and molecular diffusion. For one-dimensional flow, hydrodynamic dispersion is represented by the following equation (Freeze and Cherry, 1979):

$$D_x = \alpha_x V_x + D^*$$

Where

$D_x$  = longitudinal coefficient of hydrodynamic dispersion in the x direction [ $m^2/s$ ]

$\alpha_x$  = longitudinal dispersivity [m]

$V_x$  = average linear groundwater velocity [m/s]

$D^*$  = effective molecular diffusion [ $m^2/s$ ]

### 2.6.8 Sorption

Sorption is the process whereby dissolved contaminants partition from the groundwater and adhere to the particles comprising the aquifer matrix. The sorption of dissolved contaminants onto the aquifer matrix results in the slowing down (retardation) of the contaminant relative to the average advective groundwater flow velocity and a reduction of concentrations in groundwater (Todd, 1999).

The linear sorption isotherm assumes that the sorbed concentration ( $\bar{C}$ ) is directly proportional to the dissolved concentration ( $C$ ):

$$\bar{C} = K_d C$$

Where  $K_d$  is the distribution coefficient,  $m^3/kg$ . The retardation factor is thus given by

$$R = 1 + \frac{\rho_b}{\theta} \frac{\partial \bar{C}}{\partial C}$$

## 2.7 Remediation Technology

### 2.7.1 Natural Attenuation

Natural attenuation makes use of natural processes to contain the spread of contamination from chemical spills and reduce the concentration and amount of

pollutants at contaminated sites. Natural attenuation is also referred to as intrinsic remediation, bioattenuation, or intrinsic bioremediation and is an in situ treatment method (TOSC, 2006). This means that environmental contaminants are left in place while physical, biological and chemical processes degrade the contaminants of concern. Natural attenuation is often used as one part of a site cleanup that also includes the control or removal of the source of the contamination.

Natural attenuation processes occur at all sites, but to varying degrees depending on the types and concentrations of the contaminants and the hydrologic and geologic characteristics of the site (DOE, 1999). Natural attenuation may reduce the potential risks posed by site contaminants in one of three ways, depending upon the type of contaminant:

1. Contaminants may be transformed to a less toxic form through destructive processes (e.g., biodegradation, radioactive decay);
2. Potential exposure levels may be reduced by lowering concentration levels (e.g., dilution, dispersion); and
3. Contaminant mobility and bioavailability may be reduced by sorption to the soil or rock matrix.

### **2.7.2 Pump & Treat Systems**

Among the methods for remediation contaminated groundwater, Pump-and-Treat Systems are the most commonly used. More than 35% of the remedial investigation-feasibility studies of contaminated sites select pump-and-treat as the clean up method (USEPA, 1990).

Pump-and-Treat Systems involves extracting contaminated groundwater through recovery wells or trenches and treating the groundwater by ex situ (aboveground) processes, such as air stripping, carbon adsorption, biological reactors, or chemical precipitation. In the pump-and-treat system design, the exaction well field is configured to contain and remove a contaminant plume from the aquifer. Once the flow rate and contaminant concentrations of the extracted water are estimated, then the treatment system is designed that can remove enough contaminants to meet effluent standards for reinjection or surface water discharge (USEPA, 1990). Where

reinjection is used to dispose of the effluent, an injection well field is designed to aid in hydraulically isolating the plume as remediation proceeds (McKinney and Minder, 1996).

Variables in the design of a typical pump-and-treat systems include (USEPA, 1990):

- The number and pumping rate of groundwater extraction points (determined by such factors as the extent of contamination and the productivity of the contaminated aquifer)
- The ex situ treatment processes employed (determined by such factors as system throughput and the contaminants that require remediation)
- The discharge location for the effluent from the treatment plant (determined by such factors as location of the site and regulatory requirements)

### **2.7.3 Vertical Cutoff Wall**

A vertical cutoff wall is a structure that acts as a barrier to prevent horizontal flow of contaminated groundwater. There are several approaches that have been used to control groundwater flow (NAVFAC, 2006).

- Sheet pile cutoff walls are constructed by driving interlocking steel or high-density polyethylene (HDPE) into the ground. The joints between individual sheets are typically plugged with clay slurry (steel sheets) or an expanding gasket (HDPE sheets).
- Slurry walls can be constructed using the trench method. A trench is dug and back filled with a slurry mixture of bentonite and native materials. Typical slurry wall installed by trenching ranges in width from about 0.5 to 2 m and can be installed to depths of up to approximately 50 m, depending on the site geology.
- Grouting wall is constructed by injecting fluids under pressure into the ground. The grout moves away from the zone of injection, fills pores in the formation, and solidifies, which reduces the hydraulic conductivity of the formation. Typical grouting compounds include cement, bentonite, and silicate.
- Geomembranes are synthetic sheets installed in open or slurry-supported trenches to control contaminant spread. The sheets generally are constructed of

either HDPE or polyvinyl chloride (PVC). This technology is still in the development stage and there are concerns regarding long-term performance.

## 2.8 Literature Review

The integration of hydrogeological modeling and the GIS approach is accepted and widely applied in many places in the world.

Kolm (1995) presented the methodology for an integrated, multidisciplinary, step-wise approach for conceptualizing, characterizing and numerical simulating a ground-water flow system using the geographic information system. This approach consists of (1) data gathering and preparation, (2) field (on-site) conceptualization, (3) surface characterization, (4) subsurface characterization, (5) hydrogeological characterization, (6) hydrologic system characterization, and (7) numerical model simulation.

Carma and Kolm (1995) applied the procedure advocated by Kolm (1995), to conceptualize and characterize the Jackson Hole alluvial aquifer. Primary data were collected to construct a GIS database in ARC/INFO. All data that were essential to modeling were then converted from vector data to raster grid data and exported in an ASCII array. Then the ASCII array was rearranged to a MODFLOW acceptable format and used to simulate the groundwater flow system. The simulated results were converted to a graphical display by the utility codes of ARC/INFO.

Watkins, McKinney and Maidment (1996) studied a method of linking model and groundwater modeling. There are three methods of combining the two models:

- 1) Linked GIS-Groundwater Models: ARCMOD is the easiest method but it consumes a lot of memory and require a lot of time to run model
- 2) Integrated GIS-Groundwater Model: MODFLOWARC, this linked method requires a high capability to write an advanced program to adjust the calculation method in MODFLOW. Results are reflected to the lesser calculation time and storing of data.

Groundwater Models Embedded in GIS: This method uses intrinsic modeling capabilities in the GIS. This method not only requires a high capability to write an

advance program but also the know-how to use the functions in the GIS to create a model. This method is advantageous because the user may conveniently import data in terms of vector and transfer it to raster which can be easily calculated and displayed by the many functions in the GIS. However, this method has some limitations. It can not be used to model a complex aquifer and grid cell size is required to be uniformly equal.

Chindasanguan (1997) simulated the groundwater condition in Kamphaeng Phet province from 1997-2002. In this study, MODFLOW under a GMS interface was conducted to simulate the 3 layers of aquifer and groundwater flow in Kamphaeng Phet province. Based on the results of the groundwater simulations in the province from 1997-2002, it can be concluded that in areas, most pumping came from the demand of water in agriculture that caused a continual decrease in the groundwater level at the rate of 1-2 meters annually. The suggestion to maintain and recover the water table was to reduce the pumping rate at 5% per year for 3-4 years.

Lasserre, Razack and Banto (1998) developed a simple GIS-linked model, for the assessment of nitrate transport in groundwater. The GIS-linked model uses the Pascal computing language to create the transport model and directly incorporate it into a GIS subroutine. This transport model used AgriFlux (unsaturated zone transport model) to simulate water and nitrate fluxes living the root zone and used MODFLOW to establish the hydraulic conductivity (K) distribution. Finally, the GIS-linked model was validated by compare with MODFLOW-MT3D.

Ross (1998) developed a relational database management system (RDBMS), in SQL program language, to store and manipulate borehole information. The spatial information was managed in the GIS. Then all of the manipulated information was converted into an ASCII grid format and imported to MODFLOW via GMS model pre/post processing. This different strategy has been applied to the Lower Darling model, which is a groundwater flow model used for the Murray Geological Basin. The calibration results have a standard derivation and mean absolute error of 2.25 m and 2.43 m, respectively.

Kerdput (1999) selected a potential solid waste disposal area in Pathum Thani province using the GIS as a tool for consideration. The overlay technique and weight

rating system were taken into consideration under this study. The selection criteria related to the solid waste disposal site namely, climate, surface water, groundwater, soil suitability, geology, land use, transportation, administration and socio-economic conditions. The suitable areas for sanitary landfill were classified into 5 classes that ranged from the most suitable area to the least or unsuitable area. The most suitable area was located in Amphoe Nuangsua and the capital cost was about 125 – 250 million Baht per square kilometer.

Ming and Donald (2001) studied the linkage of Arcview and MODFLOW and MT3D. This approach is to write an additional AVENUE which is Arcview language. The study determined that the GIS can help the user to manage, analyze and display the graphics of a database. In addition, the GIS can store the model calibration results and parameters of a model. Moreover the GIS can create decision-making data and also create a Spatial Overlay and an answer-finding process of the model.

Viravigrom (2003) developed a database, for stored data, and developed the GWMML\_CU program for linking the database with groundwater flow modeling. The use of MODFLOW under a GMS interface was selected for the groundwater simulation of the Chanasutr irrigation project area. The calibrated result (with data from 1999-2002) could be used to analyze the water budget in the area. The simulation results produced the relationship of the groundwater table and groundwater pumpage in each irrigation block.

## **CHAPTER III**

### **METHODOLOGY**

The details in this chapter describe the study area, the process for GIS data management, the creation of a converter program, and process of the modeling procedure. The study area is a Pattaya municipality landfill located in Tambon Huai Yai, Amphoe Banglamung, Chonburi province. The existing data used in this research were collected from many public service agencies and most of them were available as GIS coverages. For example, groundwater contamination data were gathered from the Pollution Control Department, while the location of wells and groundwater levels was gathered from the Ground-water Resource Department. The process of GIS data management and the creation of a converter program involved GIS database development, the use of the LGGM.NET Converter Program and the transfer of converted files to simulate the groundwater flow and contaminant transport in Visual MODFLOW. Then the modeling process began; it consisted of the following steps: 1) model creation, 2) model verification, 3) model calibration and 4) application study.

The model creation phase describes the Visual MODFLOW interface, sets up the model domain, assigns model property boundaries and selects the numeric engine to run the model. The accuracy of the model's execution in the assumed conditions was described in the model validation phase. The model calibration phase involves the adjusted input data based on the model output until the deviation between the computed results and measurement data is acceptable. This phase also includes the statistical analysis for determining the fit of the predicted data with the existing data. Finally the calibrated model is used to simulate a scenario of reducing the total lead concentration in the groundwater. The objective of the remediate simulation step is to describe the advantage of the GIS-linked groundwater model to keep as information for further decision making on selecting remediation scenario.

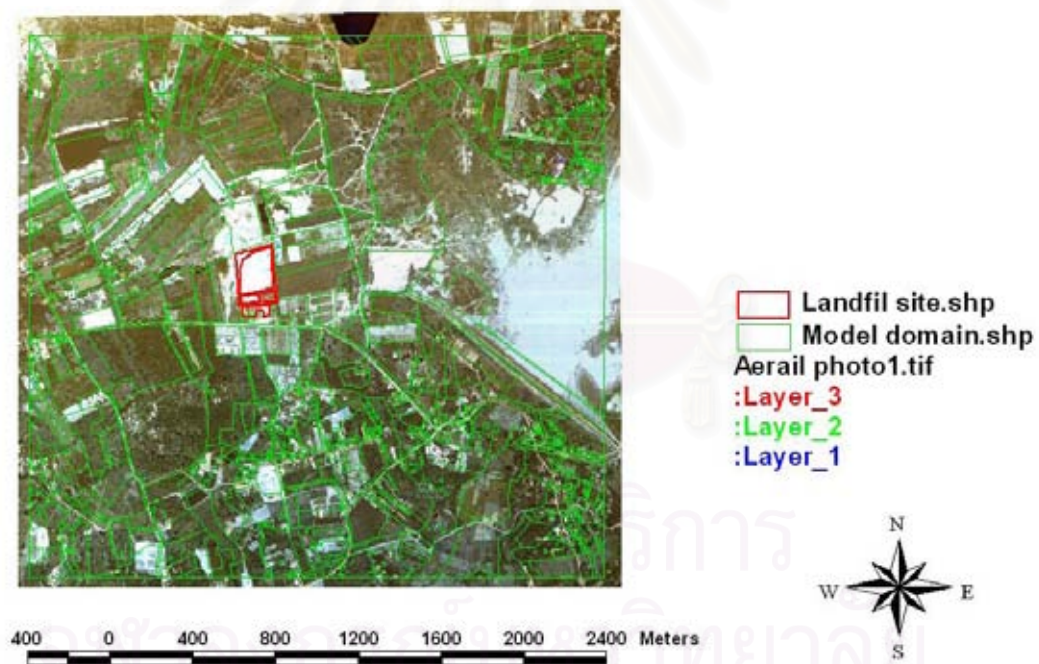


### 3.1 Study area, Land utilization, Groundwater uses and quality

#### General information

The sanitary landfill of the Pattaya municipality was built in 1986 and was in operation for about 13 years on an operational area of 56,000 m<sup>2</sup> with an open-dumping practice. When in operation, it collected about 17 ton/day of garbage and it reached full capacity of 426,800 m<sup>3</sup> of garbage in 1998 (Pollution Control Department, 1999).

The overall topography of the study area is a high land with a gradual slope to the southeast and the Huai Chak Nok reservoir. The surface soil mostly is sandy clay mixed with silt, which is suitable for agriculture activities. Figure 3.1 is an aerial photo, which represents the study area of the Pattaya municipality landfill.

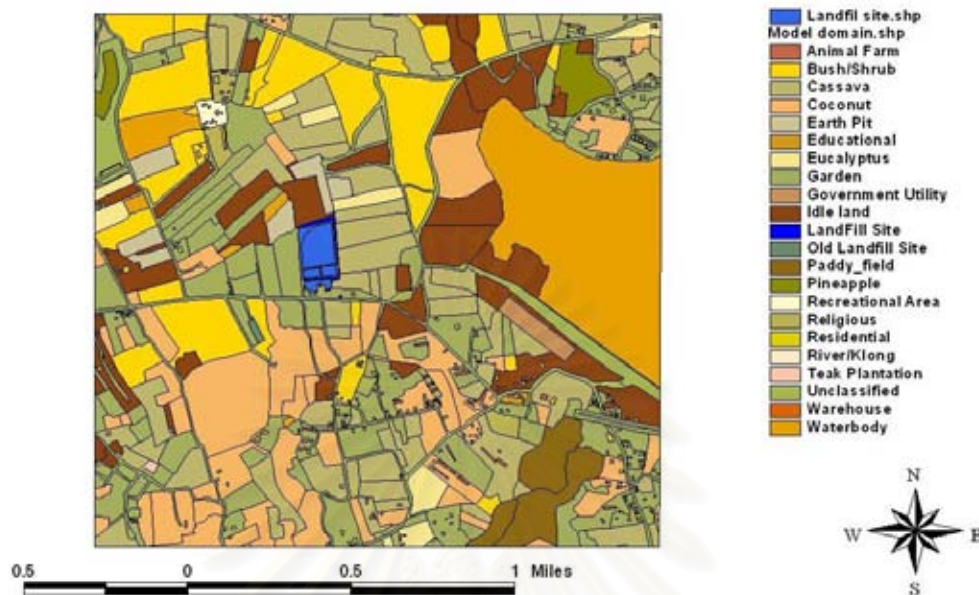


**Figure 3.1** Aerial photo of the sanitary landfill of the Pattaya municipality

#### Land Utilization

The land use of the study area can be classified as shown in Figure 3.2. Most of the land utilization around the landfill was made up of agricultural crops such as

cassava, pineapple, coconut and sugarcane. The community was densely located to the south and the east of the landfill.



**Figure 3.2** Land Utilization around the study area

### **Groundwater use and quality**

In 1999, the Pollution Control Department had surveyed 27 artesian wells around the landfill within the radius of 1 km. There were 2 deep wells (> 40 m in depth) used for consumption. From the survey, there were not any problems in terms of water quality. Of the other 25 shallow wells (4 - 11 m. from the depth to the surface), there were 11 wells that met water quality standards, but the rest possessed some minor problems in terms of the color, odor and oily film on the water surface.

### **3.2 Existing data survey and description**

The existing data in this study were collected from government agencies, mainly the Pollution Control Department (PCD). However, the collected data by PCD was up to only the year 2003 because the landfill was renovated into a gymnasium; therefore, the monitoring wells were demolished. In this section, the existing data were categorized into three parts: (1) Well Location, Groundwater Level and Total Lead Concentration Data; (2) Geological Data; (3) Hydrogeological Data; and (4) Meteorological Dat

### 3.2.1 Well location, groundwater level and total lead concentration data

In this study area there are 7 head observation wells and 4 concentration monitoring wells. The location of each well is shown in Figure 3.3, below.



**Figure 3.3** Location of each well

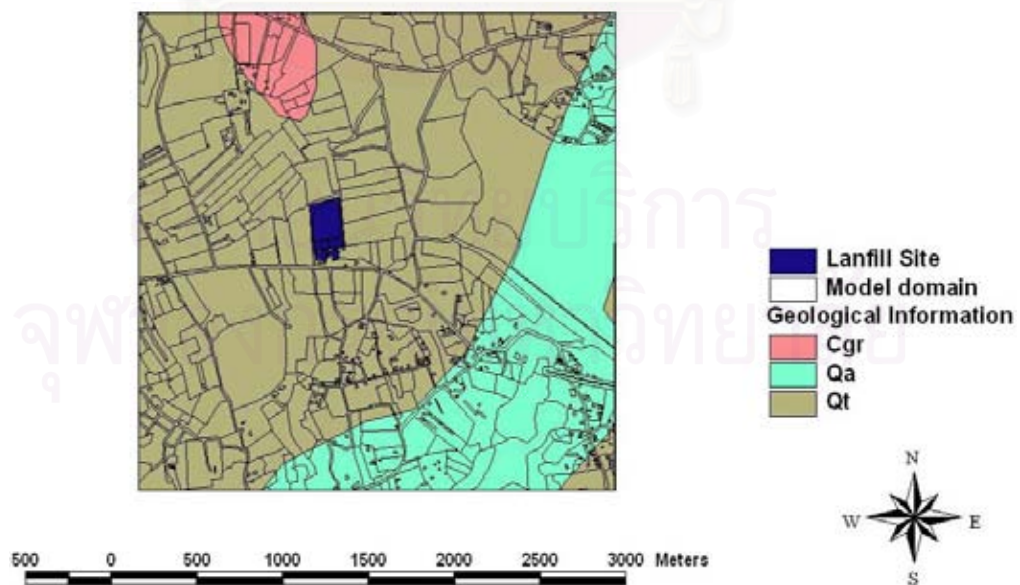
The research study in 1999 and continuous monitoring of groundwater quality by the Pollution Control Department found that the groundwater level in 1999 varied from 8.51 – 25.22 m. Observations of the total Lead concentrations had been conducted since 1999, and the values varied from 0.003 – 0.267 mg/l. The observation head and concentrations varied depending on the time and well location which was affected by the hydraulic gradient. The value observation head and concentrations are summarized in Table 3.1

**Table 3.1** Summary of the observation head and concentrations (Pollution Control Department, 1999- 2003)

Well Name	UTM East Coordinate system	UTM North Coordinate system	Screen Depth (m)	Observation Head (m) (07/02/1999)	Observed Concentration (mg/l)					
					07/02/1999	06/20/2000	01/23/2001	12/25/2001	03/13/2003	07/03/2003
MW1	708764	1425082	24.5	25.22	0.01	0.041	0.012			
MW2	708928	1424804	16.22	17.35	0.01	0.015	0.015	0.01		
MW3	708997	1424841	10.87	16.48	0.01	0.011	0.012	0.003	0.032	0.008
MW4	709002	1424909	17.44	17.41	0.01	0.043	0.199	0.037	0.267	0.106
PZ1	708808	1424839	11.44	19.59						
PZ2	709219	1424933	4.23	13.03						
Le_well	708969	1424933	20	23.9						
Shallow1	708415	1424849	15	19.13						
Shallow2	709049	1424819	10	13.56						
Shallow3	709376	1424629	8	8.51						
Shallow4	709097	1424453	12	10.15						

### 3.2.2 Geological information

Most of the aquifer area in this study consisted of high and low terrace deposits, laterite, gravel, sand, silt and clay. Figure 3.4 illustrates the geological information of the study area. The details of Figure 3.4 are presented in Table 3.2.



**Figure 3.4** Geological Information of the study area by the Geological Survey Division, Department of Mineral Resources

**Table 3.2** Geological Information of the study area

<b>Unit symbol</b>	<b>Description</b>	<b>Rock type</b>	<b>Age description</b>
<b>Cgr</b>	Coarse-medium-grained, leucocratic-mesocratic, locally porphyritic biotite muscovite granite, pegmatite vein and quartz dike	Igneous rocks	Carboniferous
<b>Qa</b>	Alluvial deposit, beach sand	Sedimentary and metamorphic rocks	Recent (Quaternary)
<b>Qt</b>	High and low terrace deposits, laterite, gravel, sand, silt and clay	Sedimentary and metamorphic rocks	Quaternary

### 3.2.3 Meteorological data

The information from the Meteorology Department from 1986 – 2004, collected from the Pattaya Station, showed that the average rainfall intensity was 1094.9 mm/year, the temperature was 27.7 Celsius, and evaporation was 1800.7 mm/year. The metrology information is shown in Appendix D

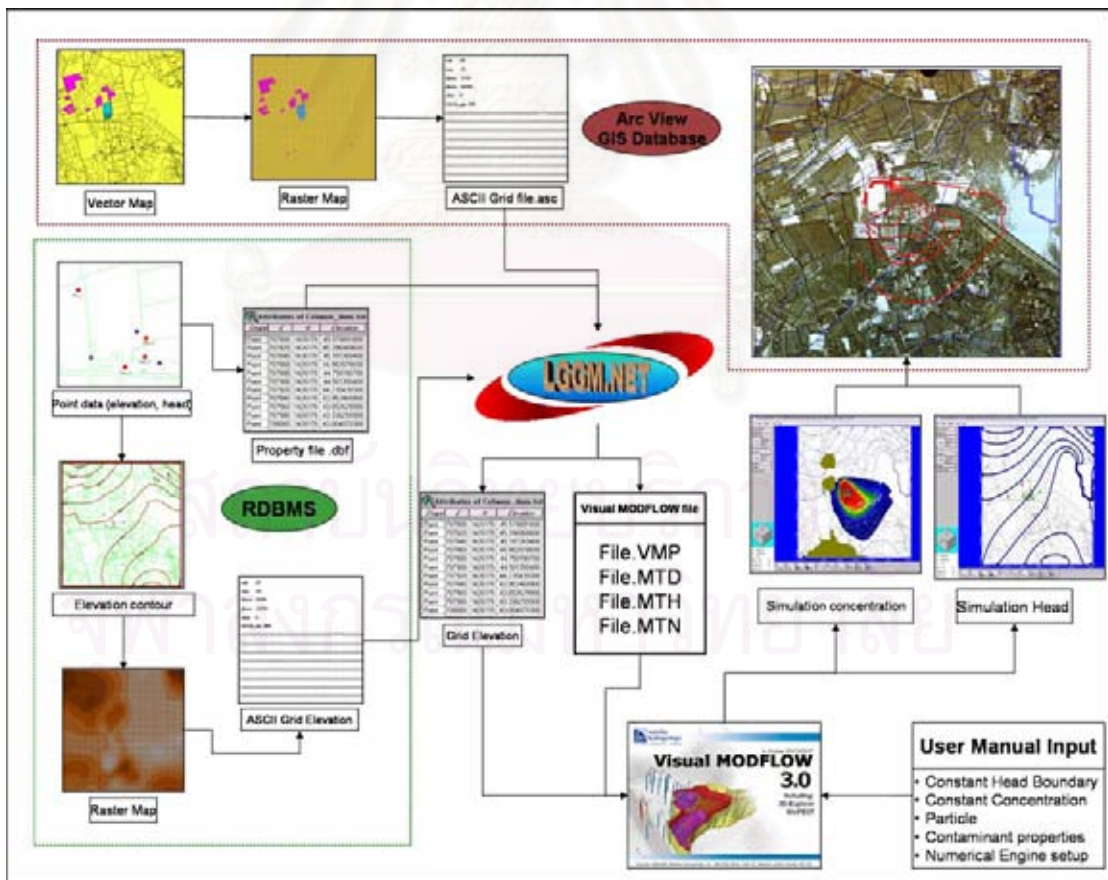
In this study, the rainfall information was used to calculate the recharge boundary by multiplying it with the infiltration rate.

### 3.3 Data converting and transferring approach

Arc View 3.3 and Visual MODFLOW 3.0 are run under the Windows Operating system. The integration of both programs was required because the Visual MODFLOW required a strict format of input files (Carrera, 2005).

GGM-Linked.NET is the converter program created by Visual Basic.Net. This program was developed to convert GIS data into input files for Visual MODFLOW. The link achieved with LGGM.NET between GIS and the Groundwater model is demonstrated in Figure 3.5, in which the GIS database operations are enclosed by a dashed line. It also shows that once a simulation is complete, the simulation head and concentration can be represented in GIS as the vectors maps.

The GIS database will be managed and exported into the ASCII file format and their relative database file. For example, the GIS of rainfall will consist of a coverage file, which will illustrate the distribution of the rainfall area, and a relative data base file, which will contain the historical rainfall information. The GIS exported files will be transferred to and converted by the LGGM.NET program. The result from LGGM.NET is the Visual MODFLOW files, such as file.vmp, which contain the flow properties data, file.mtd, which contains the dispersion data. With some user manual input and the results from LGGM.NET, Visual MODFLOW can be operated. The simulated result from Visual MODFLOW is equipotent head and contaminant distribution which can instantly be exported to a GIS coverage file. Transferring the simulation results in GIS can increase the analysis capacity of the model results. For example, GIS can crop the plume of the contaminant coverage with the population in the household coverage. The result is the number of people who have the potential of suffering from groundwater contamination.



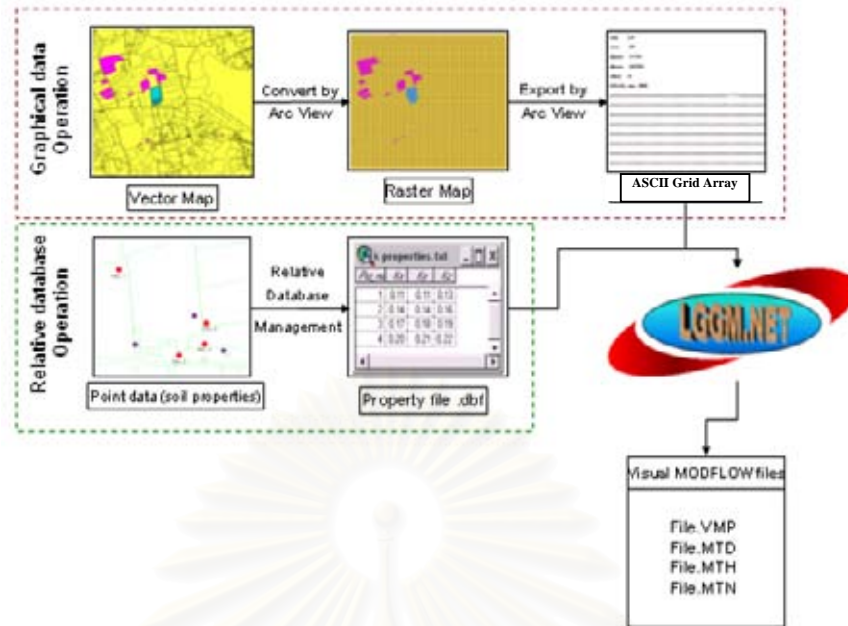
**Figure 3.5** Interaction of LGGM.NET between GIS and Visual MODFLOW

### 3.3.1 GIS Database development and data management

The data in this study were obtained from many government agencies, most of which were stored in GIS database files. GIS database files can be categorized into two types: graphic data and attribute data.

The graphic data that is stored in the vector format is called a coverage file. The coverage file is used to display the coordinates of a graphic feature in Universal Transverse Mercator (UTM). In this study, the graphic data were used to determine the grid cell value. The converting of graphic data to an ASCII grid array is called “graphical data operation.” This process consist of (1) converting the Vector Map into a Raster Map by the “convert to grid” command in the Arc view and (2) exporting the grid cells value to an ASCII grid file.

However, the ASCII grid array alone is inadequate for the simulation of a groundwater model because the ASCII grid array can only store one value in each grid cell, which is not enough to fulfill the model’s requirement. Therefore the relative database or attribute data were required to extend the information from the data in the ASCII grid array. Fortunately the attribute data are usually stored in table format. Thus the modeler only needs to select and rearrange the information which is related to the graphic data or ASCII grid array to create the relative property file. After receiving both the ASCII grid array and relative property file, LGGM.NET can be used to create the Visual MOFLOW files.



**Figure 3.6** GIS Database Development and Data Management Process

### 3.3.2 Converter program

The concept of the LGGM.NET converter program is to produce the necessary information for the exterior model's input files. LGGM.NET will execute the format of the GIS data in order to obtain the proper input files for Visual MODFLOW. The LGGM.NET converter program, consisting of 5 converter modules, is run under the windows operation system by way of menu choices. Each of modules will receive the GIS data both as ASCII grid files and properties file:

\***.VMP** module required 4 property files which are conductivity, storage, recharge, and evapotranspiration, as well as it required ASCII grid files as the same number of created layer.

\***.MTD** module required a property files which is Dispersion property and also it required ASCII grid files as the same number of created layer.

\***.MTN** module required a property files which is Constant concentration and also it required ASCII grid files as the same number of created layer.

\***.MTH** module required a property files which is Recharge concentration it required ASCII grid files as the same number of created layer.

**Elevation** module required only one ASCII grid file which are Digital Elevation MAP (DEM).



### 3.3.3 Output files structure

The Output files structure of LGGM.NET must be similar to Visual MODFLOW input files or in an acceptable format and structure. In this study, the Visual MODFLOW input files were stored in the ASCII text format. Therefore, the output files were also created in the ASCII format. The LGGM.NET output file structure can be categorized into three storing types: in the integer index array, in the assigned condition grid cell, and in the table structure. Examples of each file structure are shown in Appendix B.

#### **Type 1: Store in the integer index array**

This type of file contains a property value list followed by one integer array for each model layer. The integers in the arrays reference the property numbers in the property value list. File types stored in the integer index array include file.vmp, file.mtd and file.mtn.

#### **Type 2: Store only assigned condition grid cell**

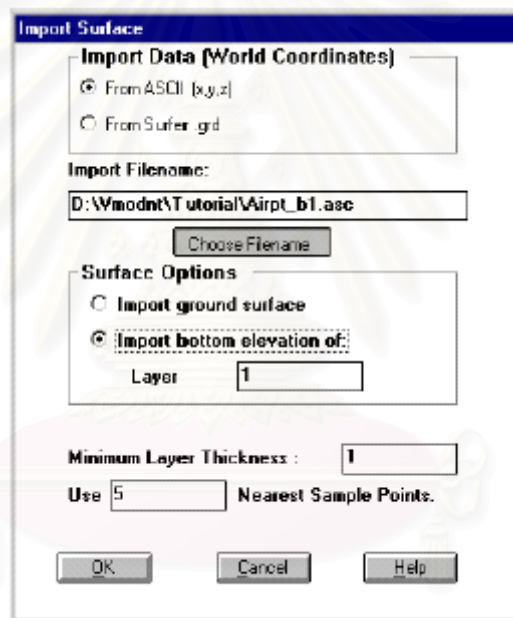
This file type only saves boundary condition data for grid cells where the boundary conditions are assigned. The file.mth file type is stored in this structure.

#### **Type 3: Store in the table structure**

This output file type is not a Visual MODFLOW file. This file structure was designed to proper for the “import layer surface elevation” of Visual MODFLOW. Importing the layer surface elevation can be achieved through two options: by importing Surfer.GRD files or ASCII .txt files. In this study, the second option was selected. The layer elevation data was imported from an ASCII text file with three columns of data containing the X-coordinate, Y-coordinate and Z-elevation. This data file did not contain any header information and each column of data was space or comma separated.

### 3.3.4 Transferring output files

After completely converting of all output files by LGGM.NET, the file name of type 1 and 2 must be the same as the project name, which are assigned when creating model. Then “Generate” is clicked to create the Visual MODFLOW files from LGGM.NET. These files are then manually brought to replace the former files, which have been created by Visual MODFLOW. The steps for type 3 data importing are as follows:, Input > Grid > Import Elevation, on the Main Menu screen of Visual MODFLOW. The import surface dialog will appear as shown in Figure 3.7. Then select the “From ASCII (x,y,z)” in the import Data frame to import surface elevation file.



**Figure 3.7** Import Surface dialog which contain “Import Data” frame

### 3.4 Conceptual modeling approach

In this research, Lead was selected as the contaminant. As the basic concept of model, groundwater quality is dependent on several parameters; namely, hydraulic properties, dispersion boundary, constant head boundary, and recharge boundary. Thus, these factors were adjusted until the calculated on head, concentration as well as the observed value are reliable.

Visual MODFLOW 3.0 was selected to represent the procedure of the linked-GIS and groundwater model. This section will represent the applications for model development, which are the temporal condition, model parameters, model creation steps, model verification, and model calibration.

### **3.4.1 Temporal condition**

Visual MADFLOW can simulate using either the steady-state condition or transient condition.

#### **Steady-state condition**

In the steady-state scenario, the parameters of groundwater flow and concentration of the water quality are kept constant throughout the study. Visual MODFLOW will automatically run by using the first time period of each boundary condition to simulate groundwater flow.

#### **Transient condition**

In the transient scenario, the parameters of groundwater flow and concentration of the water quality are varied as a function of time. Visual MODFLOW will automatically merge all different time period data of each pumping well and boundary condition into the stress period format, which is required by MODFLOW. The stress period will be defined as a time period, in which all the stresses, boundary conditions, and pumping rates, of the systems are constant.

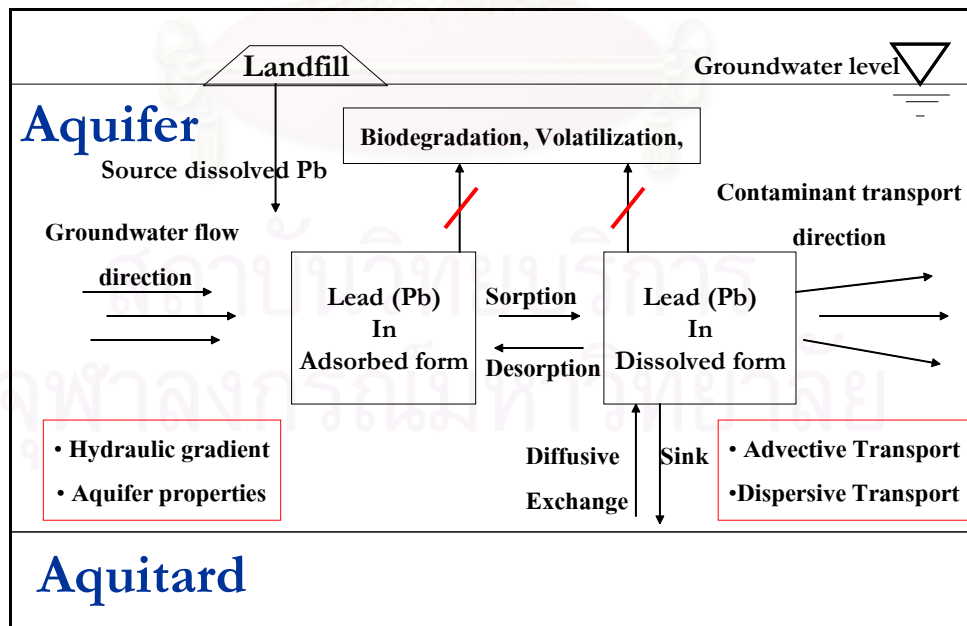
### **3.4.2 Principals of the Physico–Chemical Components of Lead contaminant analysis**

The determination of a conceptual model is a necessary step before the development of model scenarios because the relationships between physical properties and chemical reactions are very complex. The simplification of numerous input data was required for the data link. Therefore, the simulation phenomena through the conceptual model will be described in this section.

The input sources of groundwater contamination consisted of municipal and industrial discharges, urban and agricultural runoff, landfill seepage, and waste dumping from injection wells. However, in this study, the seepage from landfill leachate was the only a contamination source that would be of concern. The important chemical phenomena in groundwater pollution are as follows:

1. Volatility through the unsaturated zone.
2. Precipitation, Solution and Redox-reaction through the Acids-Bases condition.
3. Precipitation and solution through the solubility of substance.
4. Surface phenomena such as ion-exchange adsorption and molecular adsorption between dissolved and particulate forms in the aquifer.
5. Transport of the substance due to advection and dispersion.
6. Biological Activities such as biodegradation and biochemical reactions.

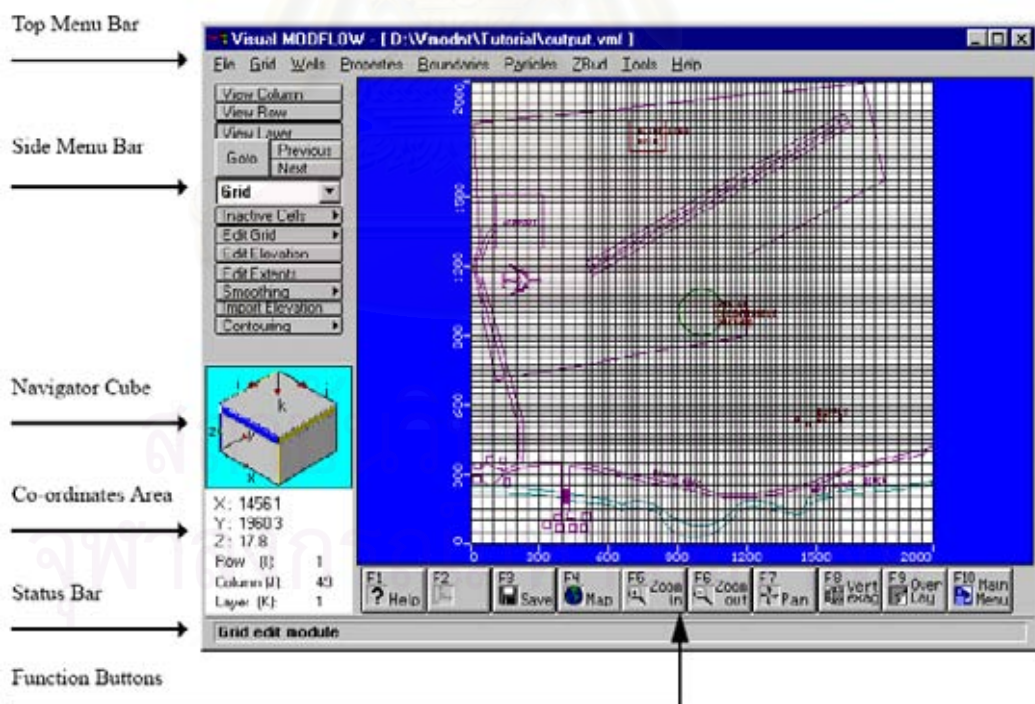
The conceptual model in this study is shown in Figure 3.8. Biological activities and the photolysis and volatilization of lead are neglected because the degradation by microbial and volatilization of lead in nature occur at a very low level.



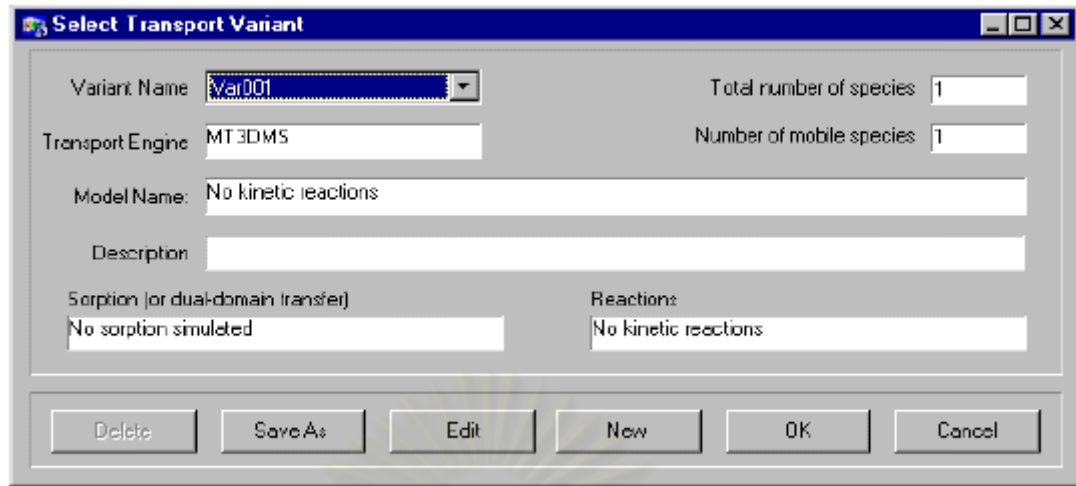
**Figure 3.8** Conceptual model of lead contamination in the aquifer

### 3.4.3 Model scenario

After the conceptual model was defined, the process of model simulation began with assigning and inputting relevant data into the model. Visual MODFLOW 3.0 required sets of data through their input menu screens as shown in Figure 3.9. The steps of inputting data consisted of (1) generate a new model by assigning the number of row, column, layer and unit that use in the model; (2) edit grids and surface elevation; (3) add pumping wells and monitoring wells; (4) assign flow properties such as hydraulic conductivity, specific storage, specific yield and porosity; (5) assign flow boundary condition such as constant head boundary, recharge boundary and river boundary; (6) assign particle tracking; (7) set up the transport model by set up the numerical engine for simulate groundwater flow and contaminant transport; (8) assign the contaminant transport properties such as distribution coefficient, dispersion coefficient; and (9) assign contaminant transport boundary conditions such as recharge concentration and constant concentration.



**Figure 3.9** Input screen layout of Visual MODFLOW 3.0



**Figure 3.10** Set up screen layout of the numerical engine for simulate contaminant transport

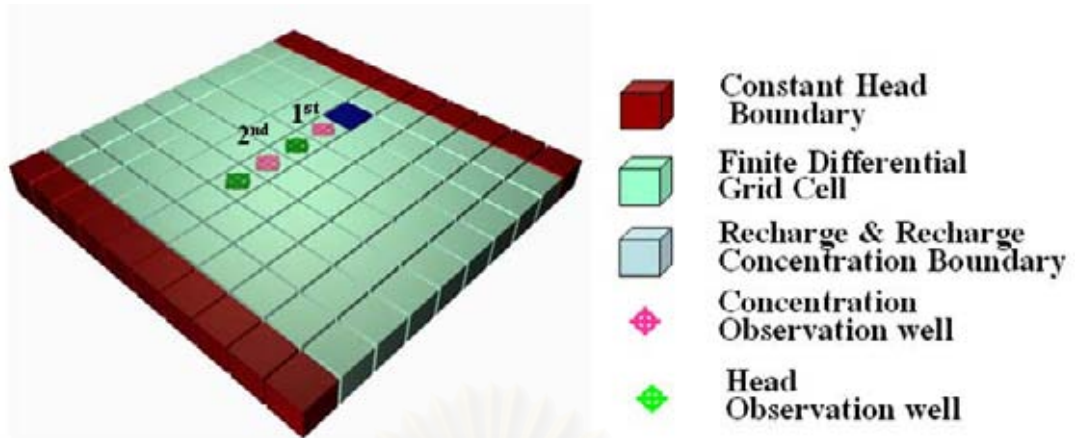
### 3.4.4 Model validation

Model validation scheme was created to verify the accuracy between the simple model execution and GIS-linked groundwater model. The difference between simple model execution and GIS-linked groundwater modeling is the requirement of data converting and transferring approach process in the GIS-linked groundwater model. The result from this section should be a guideline to develop a field scenario later.

In this section, simple scenarios were constructed as a grid layer with 10 columns and 10 rows. There are two head observation wells and two concentration wells constructed at the down gradient. The contaminant adsorption on the aquifer media followed linear isotherm sorption, and the groundwater flow factors were varied according to the following descriptions:

1. Setting up the transient flow with contaminant loading. Figure 3.11 represents the simple scenario study of condition 1.

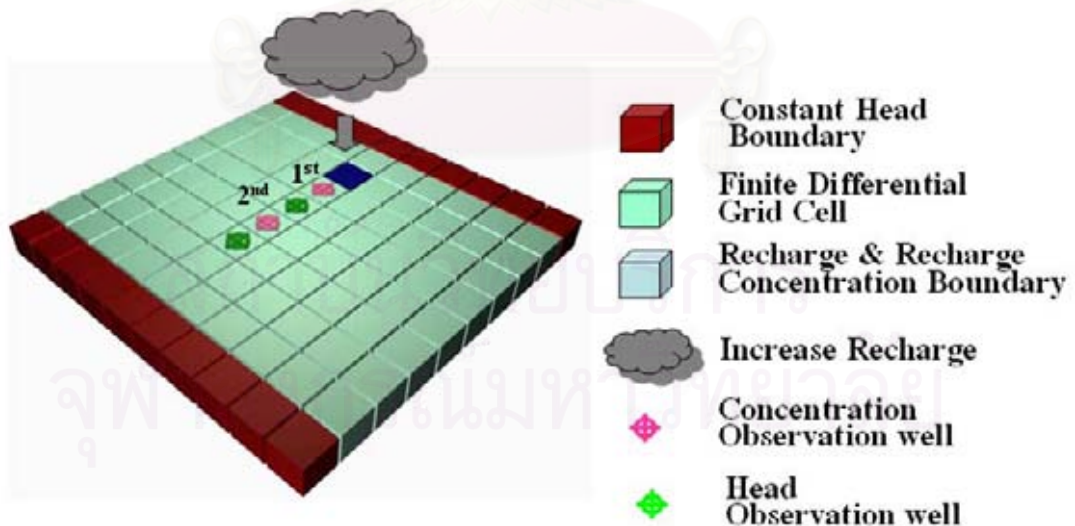
The purpose of study in this condition was to observe how Visual MODFLOW 3.0 calculates the groundwater flow condition and the contaminant distribution.



**Figure 3.11** Simple Scenario Study Condition 1

2. Increasing of the surface recharge with a constant contaminant loading. The scenario was simulated under the transient flow condition. Figure 3.12 represents the simple scenario study of condition 2.

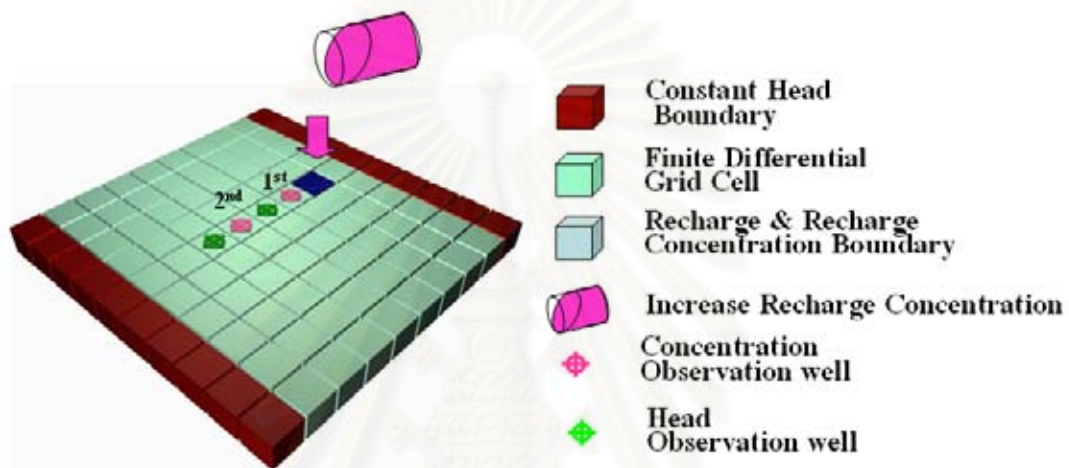
The purpose of study in this condition was to observe how Visual MODFLOW 3.0 calculates the groundwater flow when the flow boundary changes.



**Figure 3.12** Simple Scenario Study Condition 2

- Increasing of the contaminant loading through the recharge of the concentration with a constant flow boundary. The scenario was simulated under the transient flow condition as shown in Figure 3.13.

The purpose of study in this condition was to observe how the Visual MODFLOW 3.0 calculates the distribution of the contaminant when the contaminant transport boundary had been changed.



**Figure 3.13** Simple Scenario Study Condition 3

### 3.4.5 Real scenario study

This section will explain the steps of creating a real scenario of Lead contamination in groundwater.

#### Defined Model Domain

Before creating a model, the position and dimension of the study area must be defined. The area size,  $2.8 \times 2.64 \text{ km}^2$ , was divided into 140 columns and 132 rows which can be generated into small grid cell of  $20 \times 20 \text{ m}^2$ . Also the surface was separated into 5 layers to represent the total depth of 100 m.

The model origin coordinate in the UTM system was 707790 E 1423560 N and the diagonal coordinate was 710570 E 1426180 N.



### Assigned Soil Layer

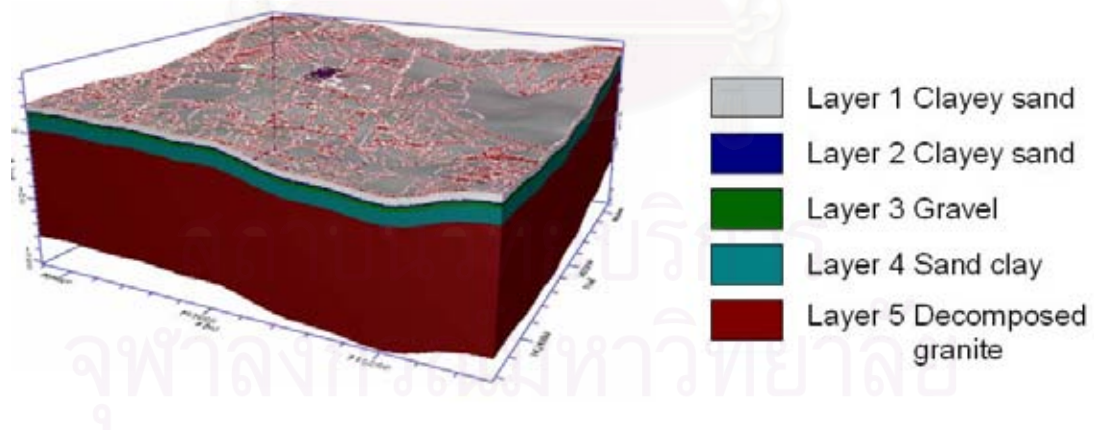
Soil layers in the model were classified by soil characteristics of 5 layers as shown below:

Layer 1 and 2 is sand mixed with clay, fine to coarse (SC). The thicknesses of these layers are 5 m and 1 m, respectively.

Layer 3 is sand mixed with clay, fine to medium. The thickness of this layer is 2.5 m. Layer is 7.3 m.

Layer 5 was decomposed granite with 83.9 m. of thickness.

In the overlaying of soil layer process, the surface elevation of soil in the first layer was assigned; then, the primary layer thickness was input. The surface elevation of lower soil layer can be calculated by subtraction of surface elevation with layer thickness. However, the assign surface elevation process of each soil layer can be accomplished by the Arc view program. Anyway, the overlaying and the thickness of each soil layer was shown in the Figure 3.14



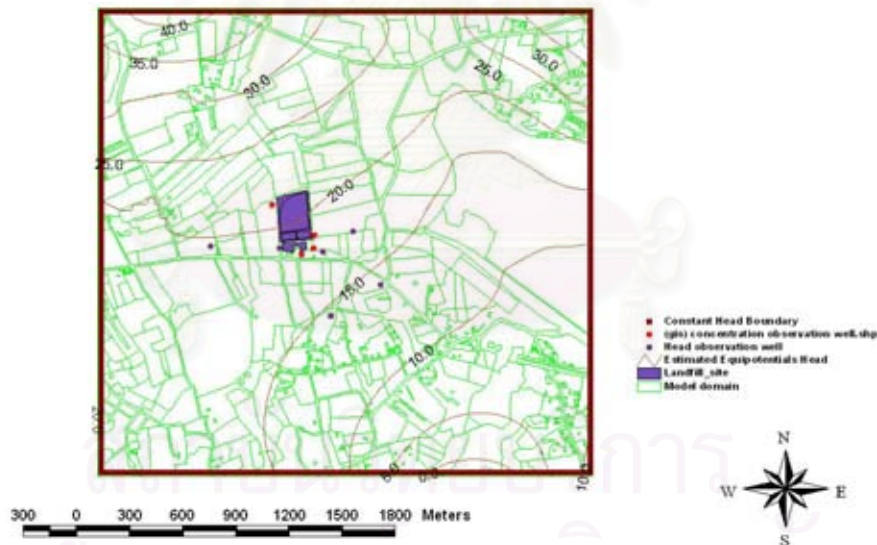
**Figure 3.14** Overlaying and the thickness of soil layer

This information was obtained from Geological Map produced by Department of Mineral Resources. The soil properties such as hydraulic conductivity, specific storage, specific yield and porosity are shown in Appendix D.

### Assigned Constant Head Boundary

The constant head boundary is used to fix the head value in the selected grid cell regardless of the system conditions in the surrounding grid cells. The constant head boundary conditions can have a significant influence over the results of a simulation and may lead to unrealistic predictions, particularly when used in locations which are close to the area of interest.

To assign the constant head boundary, the groundwater level from several head observation wells was required to interpolate and create the estimated equipotential head contour; then, the groundwater contour was extended to the edge of model domain. The extended equipotential head contour was represented in Figure 3.15. Thus, the constant head boundary can be assigned at the edge of the model domain from one groundwater contour to another contour.



**Figure 3.15** Extended equipotential head contour

### Assigned Recharge Boundary

Recharge boundary in this study can be separated into two areas. The recharge in the general area was calculated from the multiplication of the infiltration rate and precipitation information obtained from Department of Meteorology. The general recharge boundary was equal to  $5.9 \times 10^{-5}$  m/day or 21.54 mm/year. However, the

recharge in the landfill area was obtained from the landfill seepage calculation by Visual HELP, which was conducted by the PCD in 1999. The landfill recharge is equal to  $1.06 \times 10^{-3}$  m/day or 386.90 mm/year.

#### Assigned Recharge Concentration Boundary

In this research, the groundwater flow was simulated retrospectively over 20 years. That means the starting date of the model was in 1987, when the landfill was built. However, the first data used for model calibration was from 1999, which was the 13<sup>rd</sup> year the landfill was in operation.

According to the study on the leachate concentration, which the PCD started in 1999, it was found that the average concentration of lead was equaled to 0.1 mg/l. However, the data observed by the PCD was not used throughout the simulation of the contaminant transport process. This is because the concentration of lead in monitoring well 4 was up to 0.199 mg/l in 2001 and up to 0.267 mg/l in 2003. The leachate with very high concentrations of lead led people to believe that there was serious leakage from the landfill during 1987 and 2003. Therefore, in the calibration process, it was assumed that the huge contamination situations occurred twice, in the 11<sup>st</sup> and 13<sup>rd</sup> year, with lead concentrations in groundwater of 2 mg/l and 3 mg/l, respectively.

#### **3.4.6 Model calibration**

After the input-files model was run, model calibration was required to make the deviation between the computed result and observed data to be acceptable. Model calibration involves repeating the model preprocessing through the model postprocessing steps using adjusted input based on the model output.

In this study, the output from the simulation, which is the calculated head and concentration, was calibrated with the previous measurement data taken by the Pollution Control Department from 1999 – 2003.

A statistical analysis was required to verify the fitness between the measured data and calculated data. In this study, the Root Mean Square Error (RMSE) in

equation 3.1 and the correlation coefficient ( $R^2$ ) in equation 3.2 were used to verify the result from the simulation.

The RMSE is one of the most widely employed methods for evaluating the differences between the predicted and observed values in modeling. Ideally, the RMSE should be as small as possible.

$$\text{RMSE} = [ \sum (C_0 - C_p)^2 / N ]^{1/2} \quad \text{..... (3.1)}$$

Where:

- $C_0$  = Observed Value  
 $C_p$  = Predicted Value  
 $N$  = Numbers of measurement

The correlation coefficient ( $R^2$ ) is the statistical parameter that shows the correlation between the predicted and observed values in modeling. Normally, an acceptable correlation coefficient should be over 0.6 (Chaikul, 2004).

$$R^2 = 1 - \frac{\text{SEE}}{\text{SST}} \quad \text{..... (3.2)}$$

Where:

$$\text{SEE} = \sum (C_0 - C_p)^2$$

$$\text{SST} = ( \sum C_0^2 ) - ( \frac{\sum C_p^2}{n} )$$

### 3.4.7 Application study: model prediction and analysis

The last section of this research focused on the application study of MODFLOW 3.0 on remediation scenarios. There were 3 selected remediation methods to solve the problems of groundwater contamination. First is a do-nothing. Second is applying pump-and-treat technique and the last scenario is to put in the constructed vertical cutoff wall to protect the contaminant migration to sensitive areas, based on study of “Cost analyses for selected Groundwater Cleanup Projects”. (USEPA, 2001) These scenarios were compared with each other.

The objective of model prediction and analysis is to represent the advantages of the linked GIS–groundwater model, which is not only a map-based groundwater

model that has capacity to display various types of information within a spatial framework, but also provides capability in terms of an initial decision-making tool.



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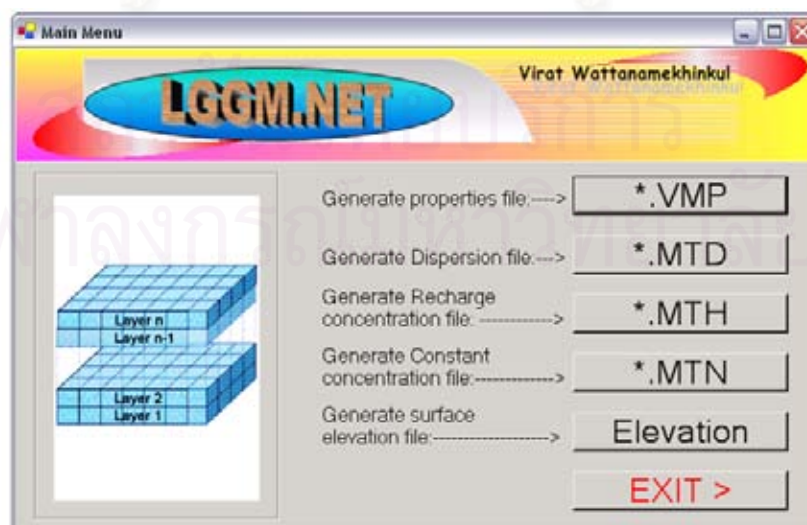
## CHAPTER IV

### MODELING RESULTS

This chapter presents the modeling results, including the results of the model validation, the results from the model calibration, and the application studies which included model prediction and analysis. The results of calibration are reported in terms of a statistical analysis. Finally, the calibrated model was used to predict contaminant migration in the field with three options of remediation: (1) Natural Attenuation, (2) Pump-and-treat, and (3) vertical cutoff wall. Then the efficiency and cost of each option was being compared and analyzed.

#### 4.1 CONVERTER PROGRAMMING RESULT

Since the output format of Arc View GIS is different from the Visual MODFLOW input format, the LGGM.NET Converter Program, the Windows application written and compiled by Microsoft Visual BASIC.NET, was used for converting the Arc View GIS format to be a recognized format for MODFLOW input file. Therefore, the Separated Files Formatting Converter Program of each Visual MODFLOW input file was written as Visual BASIC.NET codes, which are resulting in five compiled modules. The main menu screen of the LGGM.NET converter program is illustrated in Figure 4.1.



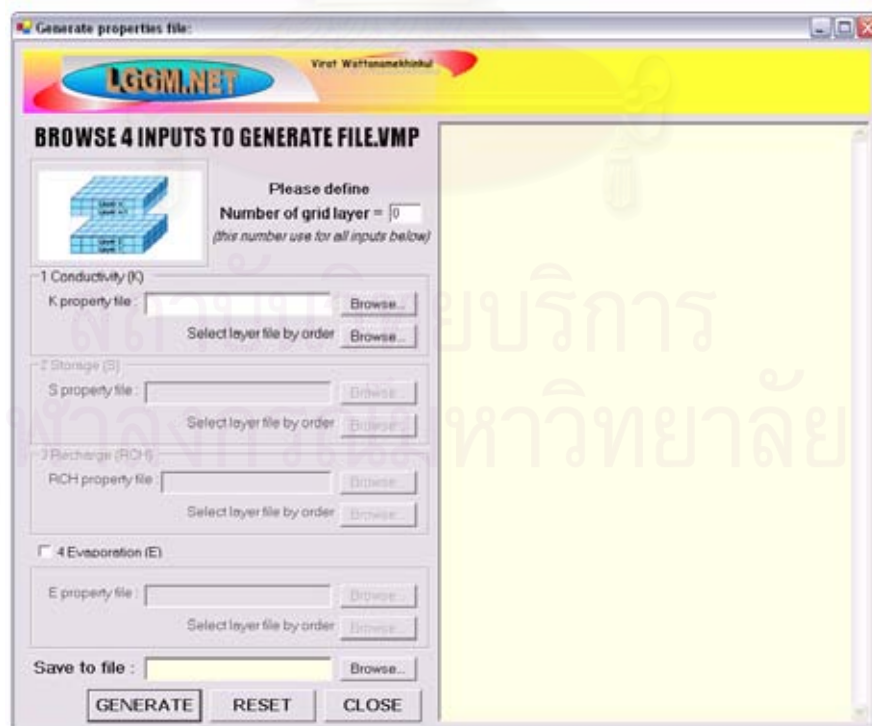
**Figure 4.1** Main menu screen of LGGM.NET

There are six buttons on the main menu screen; the first five buttons have the same functions on generating the Visual MODFLOW files, but the last button was created for exiting from the main menu program. The program source code for each module which linked to each button on main menu program is shown in Appendix A. The operations of each button are explained below.

### \*.VMP Module

The \*.VMP Module button is used to generate the flow properties file of Visual MODFLOW. The properties of concern are Hydraulic conductivity, Storage, Recharge and Evapotranspiration. The \*.VMP dialog as well as the flow properties frame are illustrated in Figure 4.2. The steps for inputting files of hydraulic conductivity are as follows:

- (1) Input the relative property file of hydraulic conductivity to the “K property file” textbox by clicking the Browse button; then select the appropriated file.
- (2) Input the number of model layers in the “Number of grid layer” textbox
- (3) Input the ASCII grid array file of hydraulic conductivity by clicking the second Browse button.



**Figure 4.2** \*.VMP dialog and flow properties frame

The other property input files require the same steps as hydraulic conductivity, with the exception of step (2), which is skipped. However, for the Evapotranspiration property, it can be activated by choosing box “4 Evapotranspiration (E).”

After all the parameter files are inputted, the output file’s name is assigned in the “Save to file:” text box. The assigned name in the output file must be the same as the project’s name that was allocated when the model was created. Then choose “Generate” button to generate the flow properties file.

### **\*.MTD, \*.MTH and \*.MTN Module**

These buttons are used to create transport properties files of Visual MODFLOW. The properties of concern of \*.MTD, \*.MTH, \*.MTN are Dispersion, Recharge concentration, and Constant concentration, respectively. The dialogs are illustrated in Figure 4.3. The steps for inputting files for each property are listed as follows:

- (1) Input the relative property file of hydraulic conductivity to the “K property file” textbox by clicking the browse button; then select the appropriate file.
- (2) Input the number of model layer to the “Number of grid layer” textbox
- (3) Input the ASCII grid array file of hydraulic conductivity by clicking the second browse button.

After all the parameter files are inputted, the output file’s name is assigned in the “Save to file:” text box. The assigned name in the output file must be the same as the project’s name that was allocated when the model was created. Then choose “Generate” button to generate the flow properties file.

### **Elevation Module**

This button is used to generate the surface elevation file for import into Visual MODFLOW. This module does not require property as the other former modules, \*.VMP, \*.MTD, \*.MTH and \*.MTN. It requires only the ASCII grid array file of surface elevation, which is illustrated as an Elevation dialog as seen in Figure 4.3.



After the ASCII grid array file of surface elevation are assigned the output file's name into the "Save to file:" text box, the "Generate" button is then clicked to generate the surface elevation file.

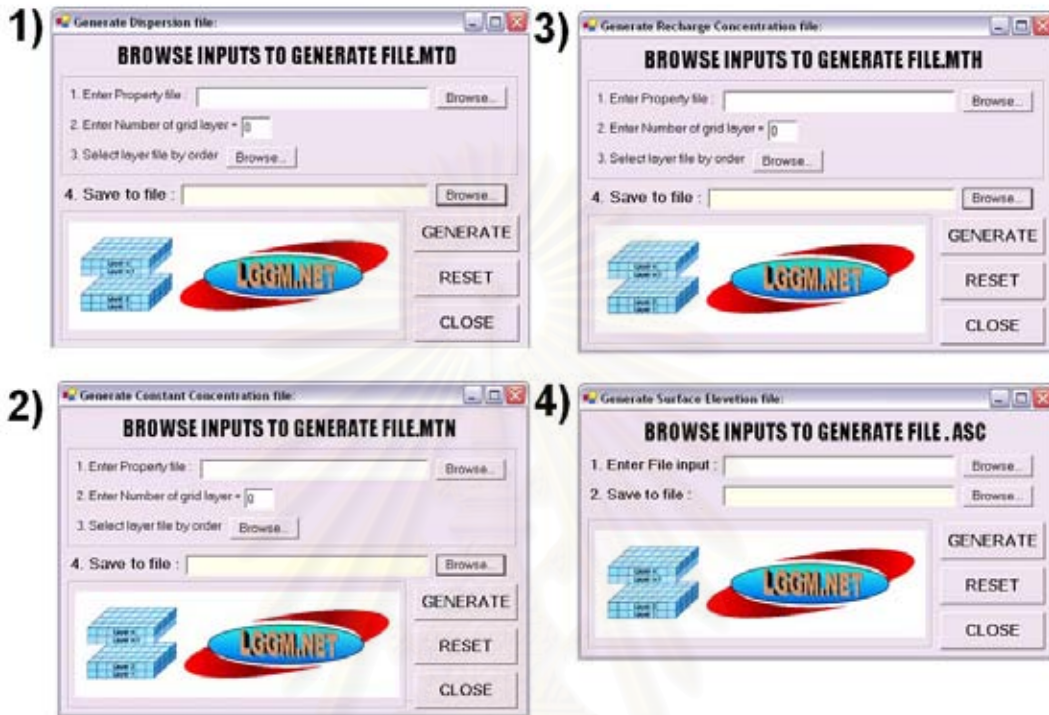


Figure 4.3 \*.MTD, \*.MTH, \*.MTN and Elevation dialog

## 4.2 MODELING RESULTS

This modeling results section firstly presented the results of the three simple scenarios model validation. The results of the typical executed model were compared to the results from the Linked GIS-groundwater model. The results could be used to prove the reliable of Linked GIS-groundwater model approach. The following part presents the results of model calibration with a real scenario. The reliability of calibration results was also shown in this part by using two statistical parameters, which were the Root Mean Square Error (RMSE) and the Correlation Coefficient ( $R^2$ ).

#### 4.2.1 Results of the Model Validation study

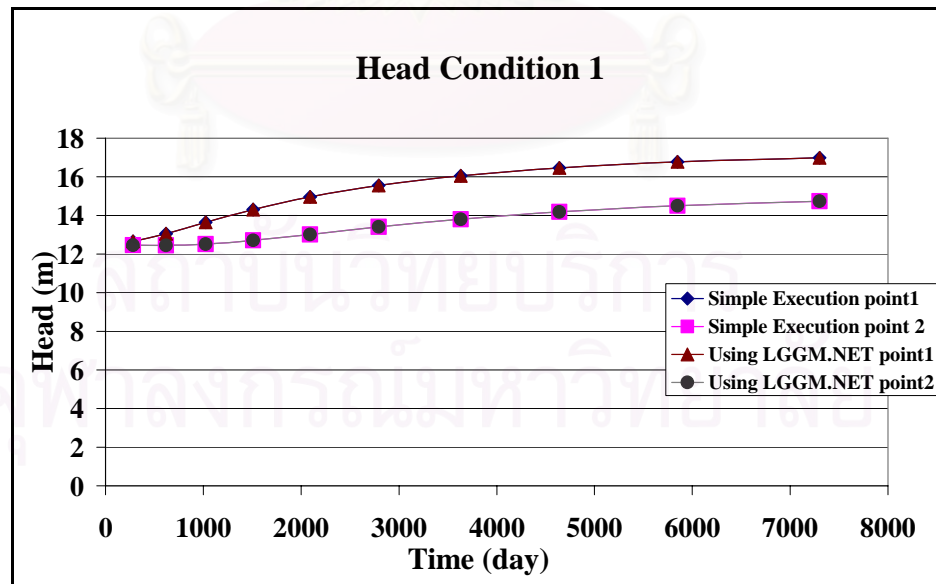
There were three simple conditions used to verify the model's accuracy as follows:

Condition 1: Constant steady state flow with contaminant loading.

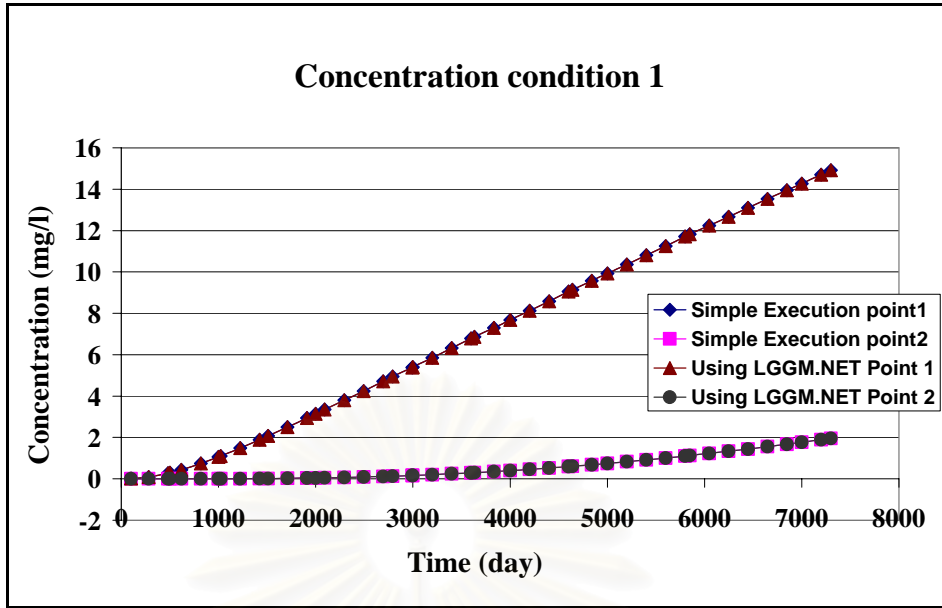
Condition 2: Increasing of the surface recharge with constant contaminant loading.

Condition 3: Increasing of the contaminant loading via the recharge concentration with a constant flow boundary.

The objective of the model validation study was to verify the accuracy between simple model execution and Linked GIS-groundwater model. The result from the simple model execution was plotted against the simulation from the Linked GIS-groundwater model as shown in Figures 4.4 to 4.6. It can be seen that the simple model execution matched the Linked GIS-groundwater model solution in each of the three scenarios.

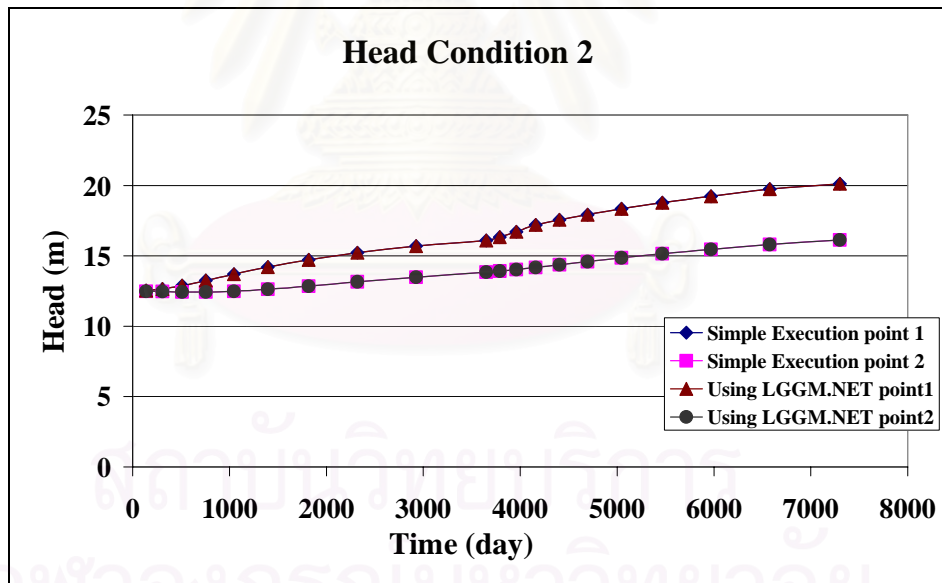


(A)

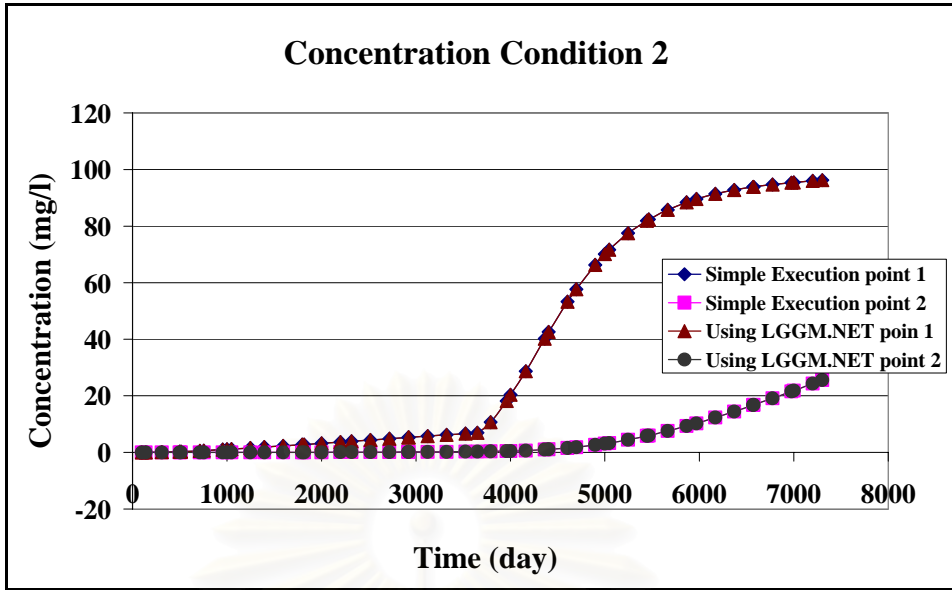


(B)

Figure 4.4 Result of model validation under condition 1: (A) Head; (B) Concentration

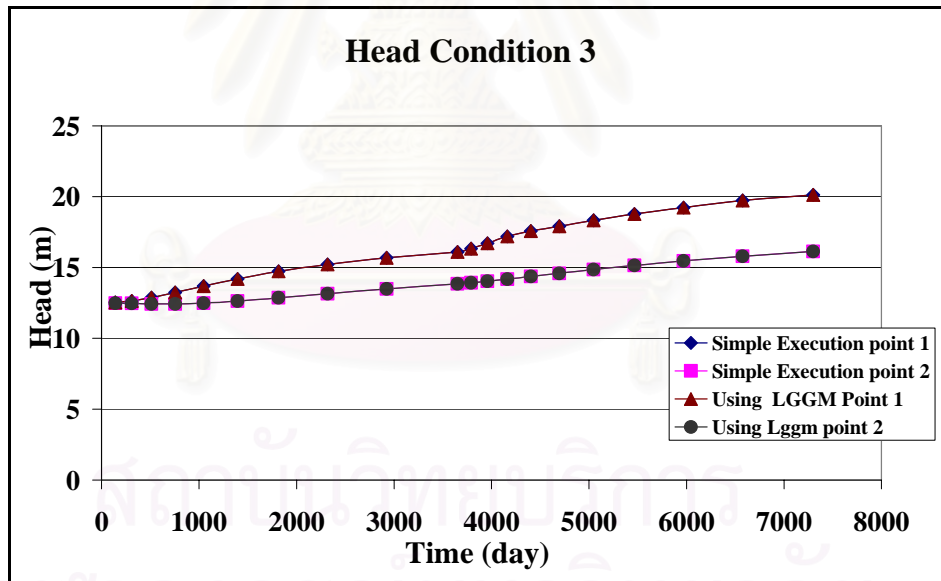


(A)

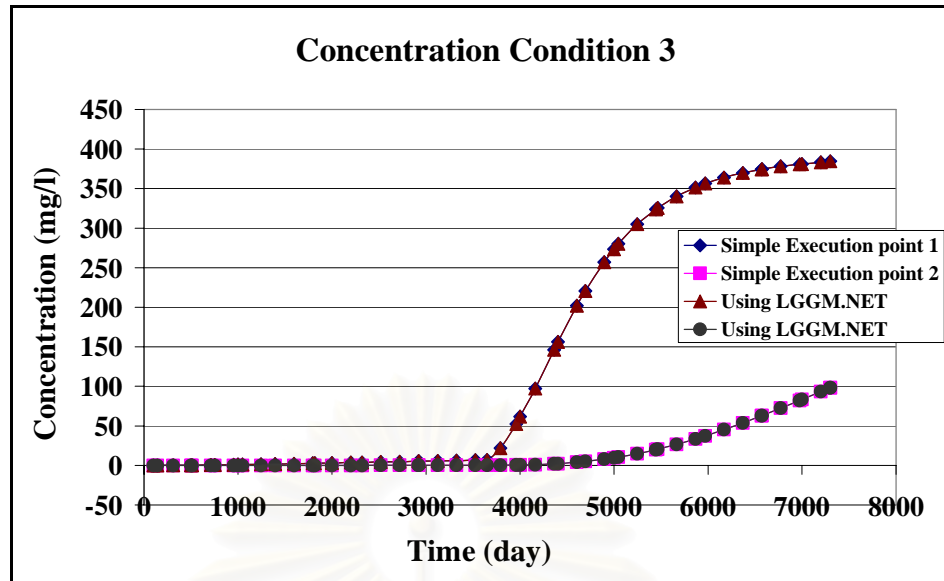


(B)

Figure 4.5 Result of model validation under condition 2: (A) Head; (B) Concentration



(A)



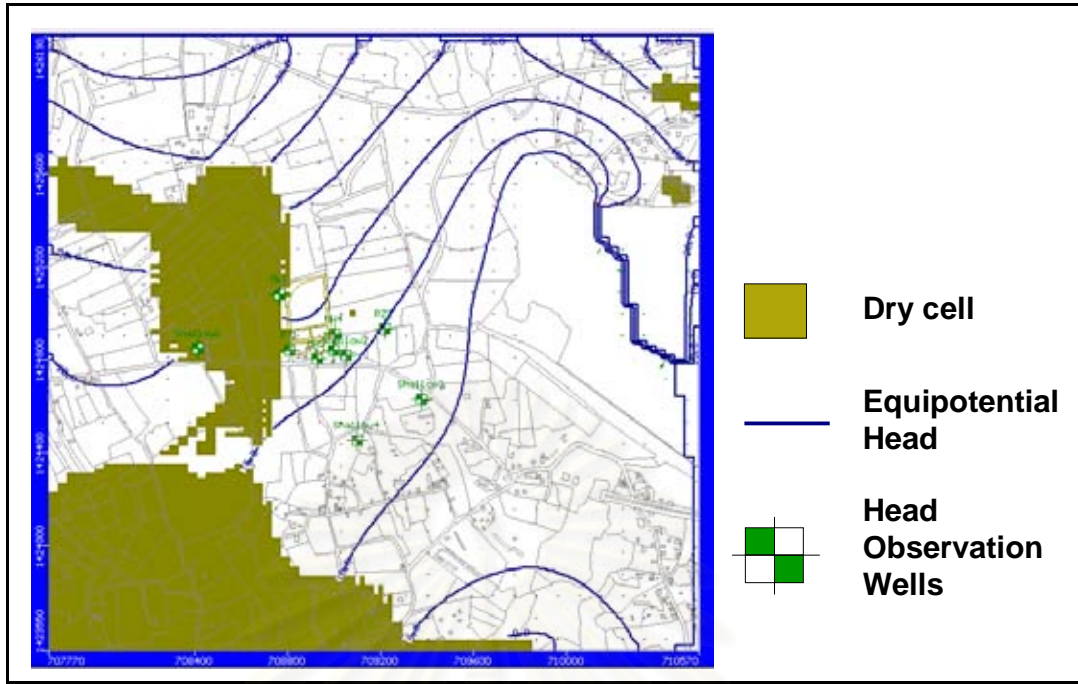
(B)

**Figure 4.6** Result of model validation under condition 3: (A) Head; (B) Concentration

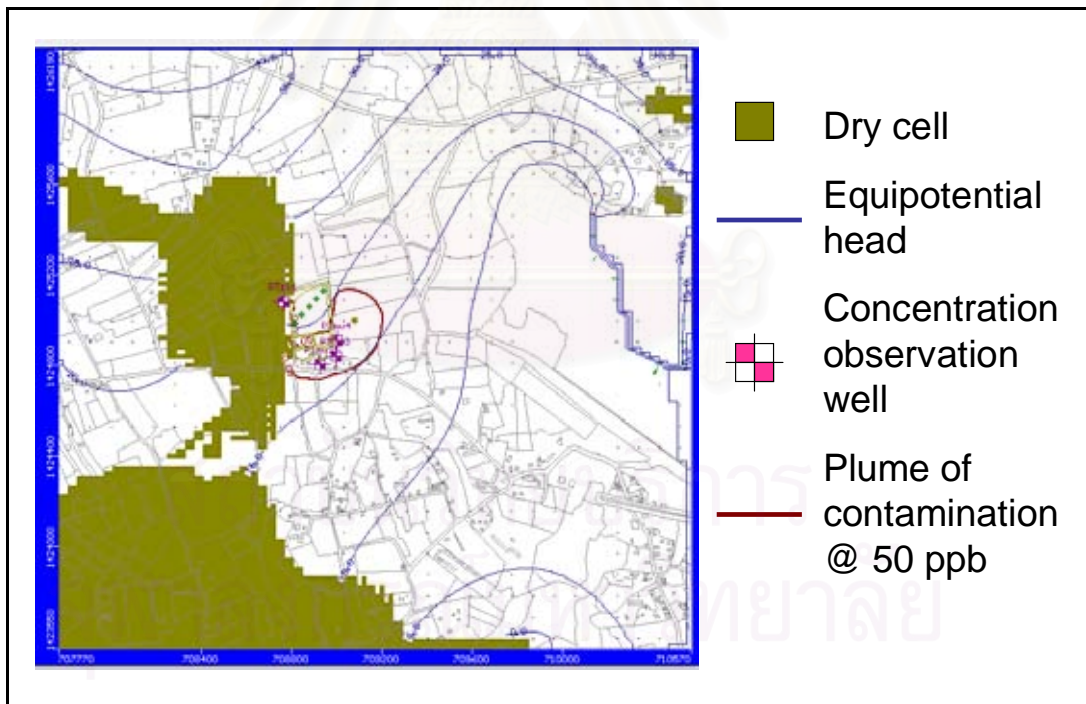
From Figures 4.4 to 4.6, the results of the simple executed were similar to the result of LGGM.NET because the GIS-linked groundwater model did not change the grid parameter value and also it used the same numerical engine of MODFLOW and MT3D. Therefore, the results of model validation in this section are shown that the LGGM.NET is useable and reliable. The comparisons of manual digitize method and LGGM.NET technique to create Visual MODFLOW input files are shown in the Appendix C.

#### 4.2.2 Results of Calibration

After all the parameters were inputted to the simulated real scenario, the result was calibrated by comparing with the real measure data, which were obtained by the Pollution Control Department in 1999 – 2003. The calibrated results of the Equipotentials head and concentration are shown in Figures 4.7 and 4.8.



**Figures 4.7** Calibrated results of equipotentials head



**Figures 4.8** Calibrated results of concentration (plume of contamination) at simulation present days

Dry cells in Figure 4.7 and 4.8 are the finite different grid cell that the water table drops below the cell bottom or assigned head value as a flag to indicate it is dry (such as

$-1.0e^{-30}$ ). During flow simulations it is common for cells to become dry when the water table drops below the bottom of the grid cell.

Figure 4.7 is the result from groundwater flow simulation by MODFLOW model. It can be seen that there are a lot of dry cells because they are high land when compare with neighboring area. Also the thickness of first soil layer in the model was specified at rather low value, 5 meters. Hence, the simulation of groundwater level that is not reach to the first layer soil will become dry cell.

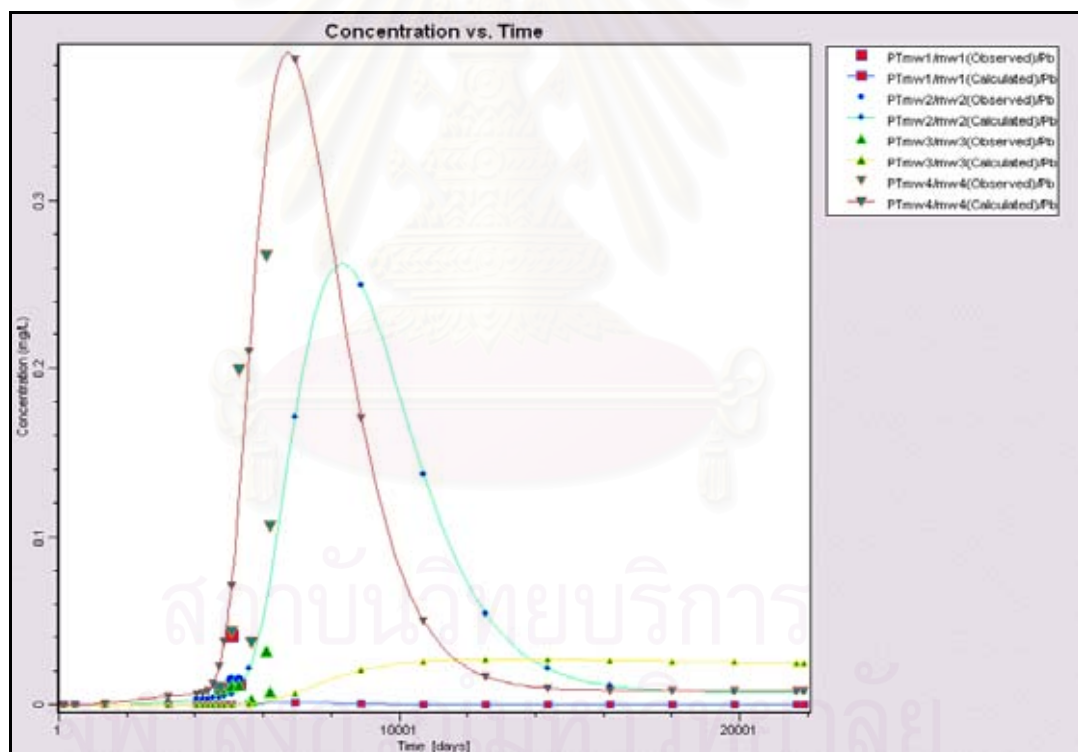
However, it was found that the equipotentials head contour was well distribution with the hydraulic gradient about  $10.8 \times 10^{-3}$ . Also the equipotentials head contour was not appeared in the reservoir area because the water level had been assumed to be a constant head boundary. In summarize, the groundwater flow simulation is consistent with all setting assumption.

In the part of contaminant transport simulation at present, it was found that the plume of contamination that higher than the standard value of lead contamination in groundwater, 50 ppb, covers the area of 250 m<sup>2</sup> and seep into the depth of 8.5 meter. When the time goes by, the plume of contamination is move toward south-west as follow the direction of hydraulic gradient. The results of contaminant transport simulation in each period are shown in the Appendix F. The plume will be continuously smaller when it moves far away from the source because of the effect of physical remediation such as diffusion through the advective and dispersive transport. Furthermore, the significant natural remediation reaction is soil adsorption and biodegradation. However, this research is lack of the information on biodegradation decay rate as well as lead is a heavy metal, which is difficult to degrade by the living thing thus only soil adsorption was assumed to be a remediation reaction of concern.

The calibration result at all head observation wells and concentration observation wells are shown in Table 4.1 and Figure 4.9, respectively.

**Table 4.1** Calibration Result of Head at Head Observation Wells

Well Name	Observation value. (m)	Calculated Value. (m)	Calc.-Obs. (m)
MW2	17.35	16.67038	-0.67962
MW3	16.48	15.94219	-0.53781
MW4	17.41	17.34505	-0.06495
PZ1	19.59	17.31544	-2.27456
PZ2	13.03	14.36146	1.331459
Shallow1	19.13	19.14141	0.011411
Shallow2	13.56	15.84646	2.286464
Shallow3	8.51	11.21473	2.704725
Shallow4	10.15	12.28976	2.139757



**Figure 4.9** Comparison between calculated and observed values of total lead concentrations in groundwater

The specification of a constant head boundary was a significant factor of simulation of groundwater flow and contaminant transport in this research. A constant head boundary can stipulate groundwater flow via the height level of the groundwater



around the model domain. Groundwater can flow in a determined direction, which is a way to control the groundwater contour. When the water direction is fixed, it can be effectively used to specify the route of the contaminant's dispersion as well.

Along with a constant head boundary, hydraulic conductivity was also an important parameter for simulating groundwater flow and contaminant transport. Hydraulic conductivity can limit the characteristics of the groundwater flow. When the hydraulic conductivity is high, groundwater as well as the pollutant can disperse easily. The type of soil in most of study area was sandy clay, which has very low hydraulic conductivity.

Besides the above parameters, there were several imperative factors namely specific storage, specific yield, porosity, dispersion, and distribution coefficient. Nevertheless, the effects of these parameters on the simulation process were much less than the effects of a constant head boundary and hydraulic conductivity.

The significant calibrated values of flow parameters; namely, hydraulic conductivity, specific storage, specific yield, and porosity, as well as the values of transport parameters; namely, the dispersion and distribution coefficient are shown in Table 4.2. Most of the calibrated values were taken from the EnviroBrowser Lite Version 3.0 program. The program provided the values of the optimum range or best estimation of each soil parameter and represented the contaminant properties as well. Moreover, the distribution coefficient value was retrieved from soils data sets of Gerritse (1982) and Rhoads (1992)

**Table 4.2** Calibrated Values for the Important Parameters in this study

Parameter	Calibrated value	Optimum Range	Best Estimate
Hydraulic conductivity (for Aquifer) (m/s)	$1.0 \times 10^{-5}$ – $1.15 \times 10^{-5}$	$9.38 \times 10^{-6}$ – $2.78 \times 10^{-5}$	–
Hydraulic conductivity (for Aquitard ) (m/s)	$1.15 \times 10^{-8}$	$2.55 \times 10^{-12}$ – $2.55 \times 10^{-6}$	–

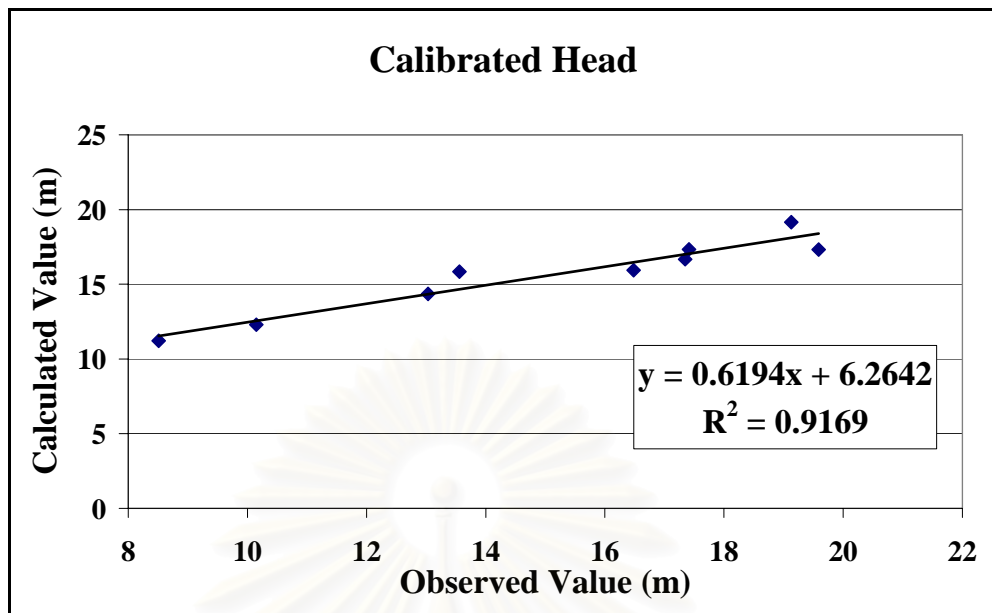
**Table 4.2** Calibrated Values for the Important Parameters in this study (cont.)

Parameter	Calibrated value	Optimum Range	Best Estimate
Specific storage (1/m)	0.001 – 0.1	–	0.01
Specific yield	0.1 – 0.2	0.01 – 0.46	–
Porosity	0.3 – 0.67	–	0.51
Dispersion (m)	0.1 – 0.4	–	0.03 – 0.5
Distribution coefficient (L/mg)	$1.0 * 10^{-3}$	$7.10 \times 10^{-4}$ – $2.3 \times 10^{-3}$	–

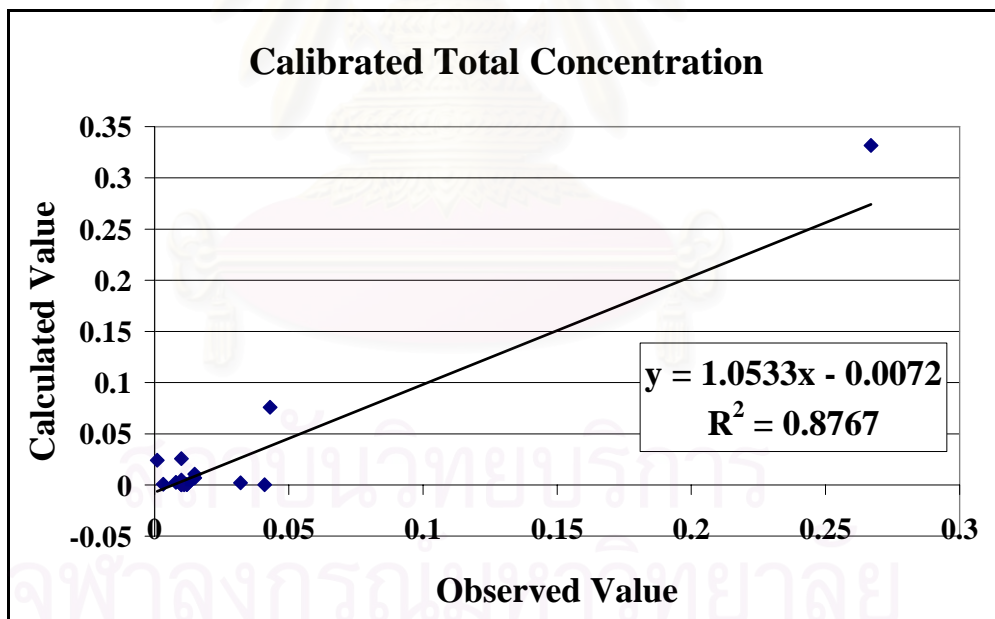
With reference to statistical testing for the calibrated model, the root mean square errors (RMSE) of Head from the groundwater flow and contaminant transport simulation were 1.66 m. and 0.029 mg/l, respectively as shown in Table 4.3. The correlation between the simulated and measured amounts of the total lead concentration was observed in terms of the correlation coefficient ( $R^2$ ). The  $R^2$  of Head from the groundwater flow and contaminant transport simulation was 0.91 and 0.87, respectively as shown in the Figure 4.10 and 4.11.

**Table 4.3** Summary of the Results from Statistical Analysis

Simulation	RMSE	$R^2$	No.of Reference Point
Groundwater Flow (Head)	1.66 (m)	0.91	9
Contaminant Transport (Concentration)	0.029 (mg/l)	0.87	17



**Figure 4.10** Correlation and  $R^2$  between the calculated and observed Head of the Study Area



**Figure 4.11** Correlation and  $R^2$  between the simulated and observed total lead concentrations of the study area

### 4.3 MODEL PREDICTION

After the results from model calibration were assured by statistic testing. The real scenario conditions were applied to predict the three remediation scenarios, natural attenuation, pump-and-treat systems, and vertical cutoff wall. Then the best option was selected by applying GIS analytical technique. The objective was to represent effective result analysis from the method of integrating GIS and groundwater modeling.

#### 4.3.1 Results of Natural attenuation

Normally, any contaminant can be slightly removed or diluted by natural attenuation and become less toxic. The environment cleans itself via biodegradation, diffusive exchange, dispersive transport, advective transport, and adsorption in soil bed.

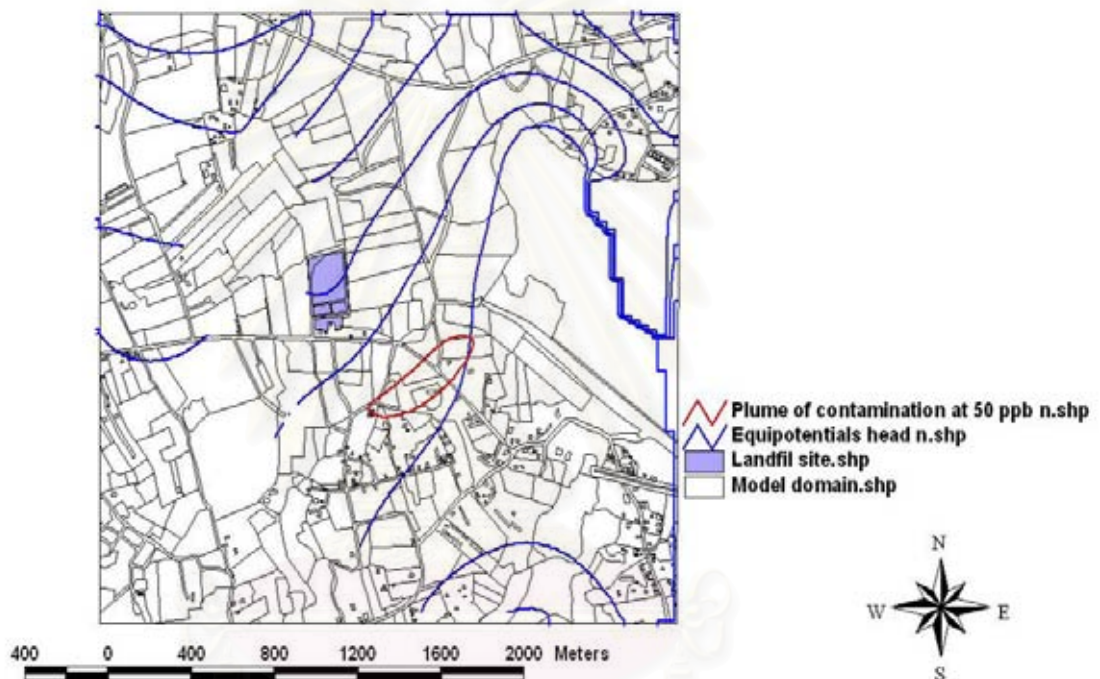
Therefore, in the natural attenuation simulation, it was understood that the leaked contaminant from the landfill was left alone to treat itself naturally. It was supposed that there were only 2 natural actions in its attenuation process, which were soil adsorption and spread through the groundwater transport that included both advective and dispersive transport.

Solute transport dominated by advection yields a sharp plume towards the hydraulic gradient direction. In contrast dominated by dispersion transport, the contaminant plume spreads out in directions that are transverse to the direction of plume migration. The research found that the contaminant plume tends to spreads out because groundwater velocity is very low as well as longitudinal coefficient of hydrodynamic dispersion was set at the high value reach to 0.4 m. However, adsorption process can restrain the spreading of contaminant since some contaminant particle adheres to the particle of soil matrix.

Figure 4.12 shows the result of the natural attenuation simulation. In this model, it was assumed that the leakage of lead form the landfill was 0.01 mg/l throughout the simulation period. It can be seen that about 47 years after severe leaking in the 11<sup>th</sup> and 13<sup>th</sup> years of landfill operation, or 40 years from the present,

the contamination situation changed to 50 ppb over the standard and cover an area of 72,773.47 m<sup>2</sup>, as shown in the plume of contaminant in the Figure 4.12.

However, this model simulation was run under the assumption that there was no more leak after the 13<sup>th</sup> year of the landfill operation. Thus, in the real situation, if there was any huge percolate through the landfill liner or if there was an extreme alteration of the groundwater flow, the actual result might differ from this model simulation.



**Figure 4.12** Results of natural attenuation remediation

### 4.3.2 Results of Pump-and-treat Systems (P&T)

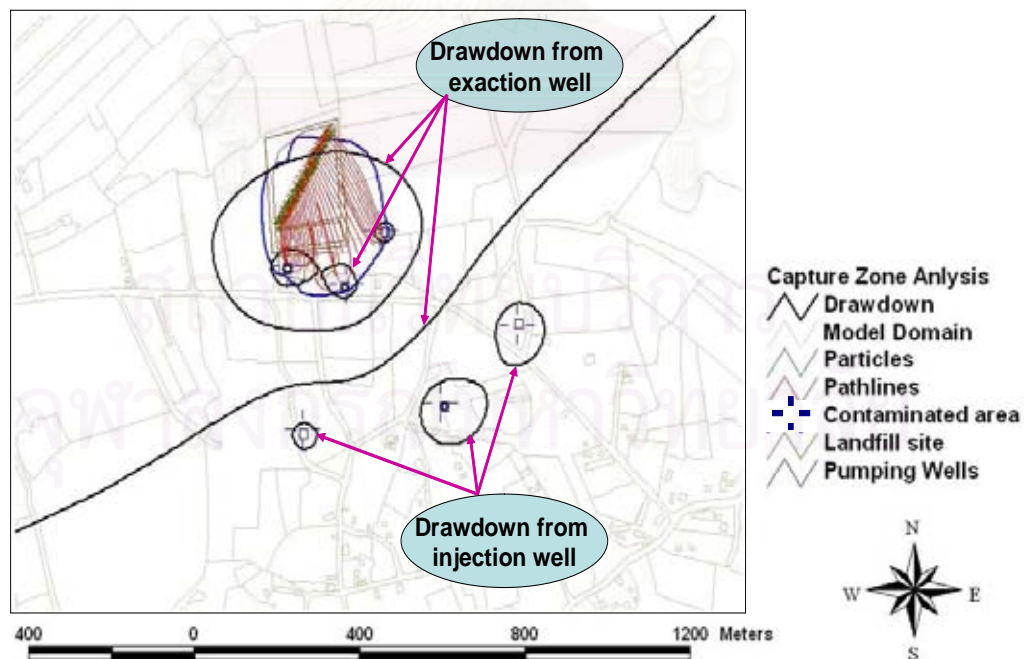
Pump-and-treat Systems involve extracting contaminated groundwater through recovery wells or trenches and treating the groundwater by ex situ (aboveground) processes, such as air stripping, carbon adsorption, biological reactors, or chemical precipitation (USEPA, 2001).

At sites where the contaminant source cannot be removed (e.g., a landfill or bedrock), hydraulic containment is an option to achieve source control. The concept

of remediation design of hydraulic containment is setting up the exaction well for pumping up the polluted groundwater to obstruct the expanding of contamination plume.

The first step in establishing design for pump and treat systems is to determine the desired containment area. After defining the proposed containment area, a capture zone analysis is conducted to design the P&T system. The size of containment area is near by the plume of contamination, which cover the area in diameter of 375 meters. After that, pumping rate was designed to receive the drawdown size equal or larger than the containment area. In this study, the pumping rate of  $68.85 \text{ m}^3/\text{day}$  was calculated by the method as shown in the Appendix E.

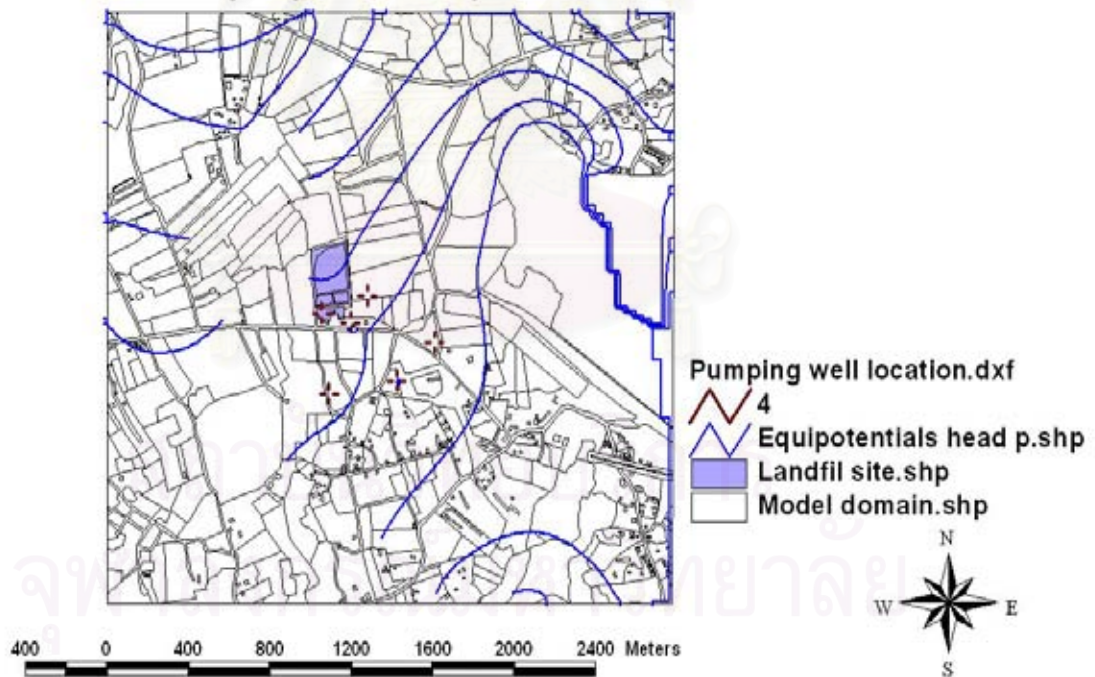
The screen of pumping well was specified into the depth of 8.5 meters from surface elevation, the same depth with Pb contaminant layer in the aquifer. Then, exaction well was separated into 3 wells with the pumping rate  $25 \text{ m}^3/\text{day}$  each so that the capture zone can be cover most of contamination area. Figure 4.13 shows the size of plume contamination in soil layer 3 that the most soil was contaminated, and displays drawdown or capture zone received from pumping rate designing.



**Figure 4.13** Compared area of contamination versus drawdown form pumping well

The other important step of Pump-and-treat process is above ground treatment plant. There are several suitable treatment technologies for eliminating heavy metal; namely, ion exchange, settling, and metals precipitation. However in the study of groundwater contamination from leachate, it was concerned on various kinds of pollutants including non aqueous phase and organic compound. Thus, the integration of treatment systems or more complex remediation process was required.

The simulation of this remediation scenario as follow the above discussion can be concluded that the contamination plume was absolutely eliminated. After the use of the pump-and-treat system for 3 years, lead concentration stayed below the standard level as shown in the Figure 4.14. A majority factor on efficiency of pump-and-treat technique is a pumping rate, which high enough to create the capture zone cover the area of plume transportation. The capture zone can introduce advection transport as well as it can force the direction of contaminant's pathlines or steam line to flow into the extraction well.



**Figure 4.14** Location of each pumping well and results of Pump-and treat systems remediation

### 4.3.3 Results of vertical cutoff wall

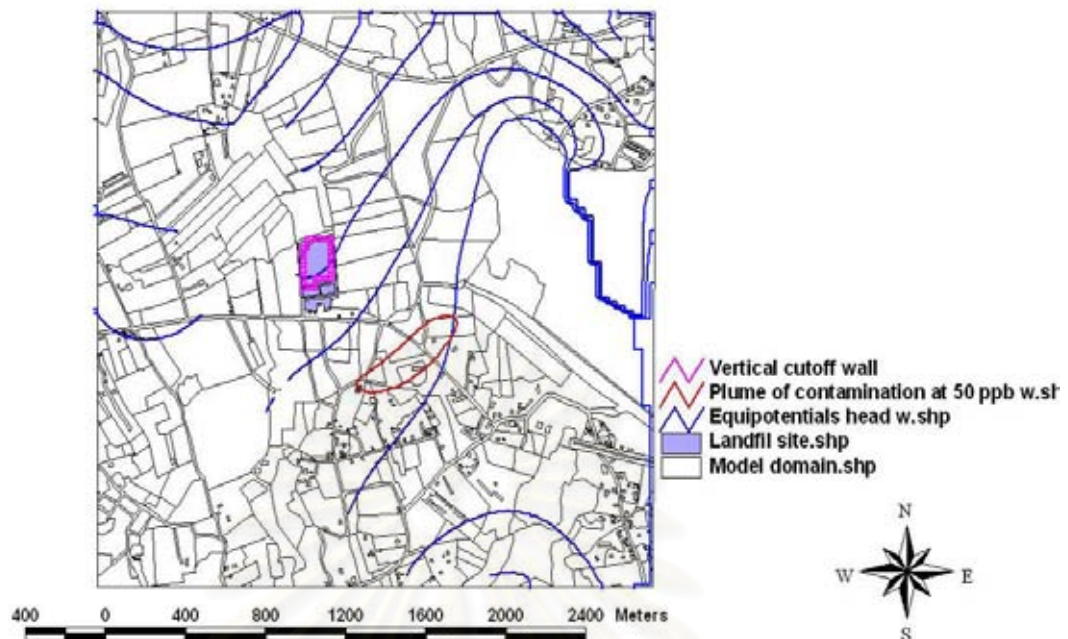
A vertical cutoff wall is an in situ (below-ground) treatment zone of reactive material that degrades or immobilizes contaminants as groundwater flows through it. A vertical cutoff wall is installed as permanent, semi-permanent, or replaceable units across the flow path of a contaminated plume.

In this study, significant criteria of vertical cutoff wall designing are aquifer characteristics, which are important information to assist in hydrogeologic modeling performed to locate and design the barrier. From the simulation result of contamination plume at present, it can be seen that the plume was seep into the soil layer 3, 8 meter deep from the ground surface. Thus, in this study, the vertical cutoff wall scenario was designed to be 895 meter length and 8.5 meter depth. The vertical cutoff wall was built around the source to block the contaminant migration in groundwater. The overlay of the wall and results of the model execution are shown in Figure 4.15. However, the contamination characteristic is important information because it will be used to select appropriate reactive media, conduct, and design the thickness of the wall.

When consider on a contaminant in this study, the most suitable reactive media should be composed of limestone. The alkaline property of limestone can react with Pb to be more precipitation; also, some Pb can adsorb with the reactive media. However, not only lead is contaminant of landfill leachate. Thus, the selecting of appropriated reactive media should be depended on the composition of landfill leachate.

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**Figure 4.15** Results of remediation by vertical cutoff wall.

From the Figure 4.15, it can be seen that plume of contamination still appears in the model. This is because vertical cutoff wall remediation only blocks the leaked contaminant from that point on, but cannot eliminate the pollution that had already leaked since 1987. Therefore, the plume of contamination covers the area of 70,268.42 m<sup>2</sup>, which is close that of the remediation by natural attenuation. However, a vertical cutoff wall can provide protection from a leakage disaster that might occur in the future.

#### 4.4 RESULTS OF MODEL PREDICTION ANALYSIS

After predicting the results of each remediation scenario using the GIS technique with clip theme of contamination plumes and theme of land utilization, it could be shown the areas potentially contaminated with lead in the groundwater. According to Figure 4.12, the Natural attenuation method would let the lead contaminant spread 355.47 m<sup>2</sup> into the residential area, but that size would be reduced to 220.49 m<sup>2</sup> under installation of vertical cutoff wall. However, for Pump and Treat, whole pollutants could be eliminated; therefore, there would be no damage to the

residential area. Nevertheless, the sizes of potentially contaminated area for each remediation were shown in Table 4.4.

**Table 4.4:** Contaminated area size of after treatment by each method

<b>Affected area (m<sup>2</sup>)</b>	<b>Natural attenuation</b>	<b>Pump and treat</b>	<b>Vertical cutoff wall</b>
Animal Farm	659.69	-	657.97
Bush/Shrub	1,548.55	-	978.67
Cassava	12,435.99	-	12,895.08
Coconut	15,789.69	-	15,608.84
Garden	24,471.40	-	23,722.49
Idle land	13,057.71	-	12,237.94
Residential	355.47	-	220.49
Unclassified	4,454.97	-	3,946.95
Sum Area	72,773.47	-	70,268.42

#### 4.5 RESEARCH LIMITATIONS

During the model's development, the monitoring data were analyzed to determine how the system functions. Because of inherent limitations in the detail and accuracy of the monitoring data and because of the essentially infinite number of factors which might influence water quality, the final model was a simplified representation of an imperfectly known system. Therefore, models were always wrong in the details, but provided a good reproduction in the general behavior of the system. Even physically based models, whose parameters were measured in the field, were not likely to approximate the measured response of the hydrologic system without additional parameter "adjustments," which constituted the calibration process. The final result of a successful modeling effort was a simplified representation of the system which was neither unique nor exact. This meant that a different model could always be developed which did a better job of reproducing the measured behavior of the system.

Not only limitation of general behavior of the model itself, but also any other restriction was list below.

1. Most of the obtained data was only area around the landfill site. Also, the gathering information from various governmental agencies was not the same standards because different drilling of monitoring well methods. Moreover, during the well boring process, the soil kind and the soil characteristic were not profoundly examined. Therefore, the model domain had only adequate information of soil.
2. Due to the limitation of continuous data received from the PCD, the available information to calibrate the groundwater flow was merely around landfill site. Furthermore, there is only information in 1999 as well as the only 6 data sets of lead contamination in groundwater for the 5 years period. Moreover, the site also lacked of the down gradient monitoring wells that was far away from the landfill to consider the contamination spreading.
3. There were a few field parameters assumed due to the limited information. The constant concentration parameter was assumed to be zero throughout the entire layer of the model domain due to the concentration in soil sample in the northern part from the landfill were very small. Biochemical and geochemical reactions were neglected since the degradation and transformation of lead by microbial and photolysis in nature occurred at a very low rates.
4. In the groundwater flow simulation, the water level of Huai Chak Nok reservoir was assumed to be the constant head boundary instead of the river boundary because the characteristics of the reservoir. The water can continuously percolate into the ground like the properties of the constant head boundaries.
5. The linked GIS-groundwater model approach involved a set of data-transfer, and all the model input and output had to be stored twice (Ming and Donald, 2001). Once in the GIS database and once in the ASCII files that were read and written by the simulation model. Also, running the sequence of data transfer programs was slow, and much debugging may be needed to ensure that data is transferred correctly from the GIS to the model.

#### 4.6 RECOMMENDATIONS

The development of a groundwater flow and contaminant transport model resulted in the identification of a number of areas where additional data could improve the model performance and capabilities. Changes in groundwater monitoring would be required to achieve the optimum results from the model developed here. Additional monitoring will also be required to develop models with more spatial detail or the ability to predict the impacts of accidental spills or other point sources of pollutants.

Increase the frequency of water quality sampling in wells should continue so that changes in water quality can be identified at the earliest possible time. Because of the natural variability demonstrated by the historical data, a large number of samples will be required for timely identification of long-term changes in water quality. Sampling of wells on an annual basis will not be sufficient. A groundwater sampling scheme should be developed based on an analysis of the historical water quality data.

With regard to the model simulation of three remediation scenarios, each method had its own advantages and disadvantages. For example, pump-and-treat method provided the best efficiency but was very expensive. In contrast to vertical cutoff wall and natural attenuation, they were at lower cost but less effectiveness. However, in comparison vertical cutoff wall to natural attenuation, the remediation efficiency was no significantly different. Therefore, it might be primarily concluded that the vertical cutoff wall might not be a suitable treatment procedure.

To improve the efficiency of linked GIS-groundwater models, a link pattern should be developed to be groundwater model embedded in the GIS. This pattern can be directly input and transfer data to the groundwater model without repeating data storage or creating several temporal data sets (Watkins, McKinney, and Maidment, 1996). Moreover, it can save the time for model developing as well as it can reduce the mistake of data transferring, and keep the same ability on output analysis from model by using GIS technique.

The process of GIS analysis should also be developed as a part of the spatial decision-support system (SDSS), which could provide decision-makers with more useful and timely information.



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## CHAPTER V

### CONCLUSIONS AND SUGGESTIONS

#### 5.1 Conclusions

As a preliminary step in this research, an alternated program using to link the GIS with groundwater modeling, LGGM.NET, was written by Visual Basic.NET to be used within a Windows Operation System. It was designed to have 1 main module to connect among 5 sub-modules. The function of the main module is to support the sub-modules, which are classified into 5 compiled modules, for converting the GIS file into a Visual MODFLOW file.

Next step, a simple scenario simulation was predicted and analyzed to confirm the reliability of LGGM.NET when it was used as a Linked GIS-groundwater modeling approach. Since the plot of simple execution and LGGM.NET execution were a completely matched for all three conditions, LGGM.NET was deemed a functional transferring program. Moreover, the process of obtaining results from this preliminary study provided an understanding of the model and methods for inputting and creating more complicated scenarios.

According to the research objective 1, to investigate the method of integrating the GIS (Specifically Arc View 3.3) and MODFLOW (Visual MODFLOW 3.0 interface), it could be concluded that this integrating process could be done by creating a new program to convert the GIS data into an ASCII grid file and convert the attribute data format into a Visual MODFLOW file format. When this was performed, the model was simply executed. The output from the executed model can directly export from a Visual MODFLOW into a GIS coverage file.

To achieve research objective 2, to represent the advantage of result analysis from the method of integrating the GIS and Visual MODFLOW, the model was executed with the real data. The sanitary landfill of the Pattaya municipality was the chosen project area for this study. The predicted groundwater level and concentration was compared with measured data taken by the Pollution Control Department from 1999 - 2003. The first statistical parameter that was selected for calibrating the model, the root mean square error (RMSE), showed that errors were approximately 1.66 m

for the simulation of the groundwater level and 0.029 mg/l for the simulation of the contaminant transport. Furthermore, a strong correlation between the predicted and observed groundwater level and concentrations was observed from the modeling.

Altogether, through this real scenario simulation, it was found that the model could reasonably predict observed concentrations, as measured by statistical analysis, and thus it could be used in other application studies.

The outcome from the simulation of the three remediation scenarios, natural attenuation, pump-and-treat systems, and vertical cutoff wall, found that the most effective remediation method was the pump-and-treat system. The contamination of lead in groundwater was disappeared within 3 years of pump-and-treat operation. The other scenarios, Natural attenuation and vertical cutoff wall were also less effective than the pump-and-treat systems. The plume of contamination after treatment by Natural attenuation and vertical cutoff wall covered areas of 72,773.47 m<sup>2</sup> and 70,268.4 m<sup>2</sup>, respectively.

The key advantage of the Linked GIS-groundwater model in this study is developing the model's ability on spatial analysis to be more effective when using as a spatial decision-support system.

## **5.2 Suggestions**

A groundwater model embedded into the GIS should be developed to reduce the problem of the linked GIS-groundwater model, which is the generation of temporal data during file converting process. An embedded groundwater model would use the intrinsic model capabilities in the GIS. The advantage of this approach is that no data conversion would be required. Since the user would directly interface with the GIS and model, there would be no generated temporal files. There can be at least two approaches for embedding the model in raster base GIS: 1) to modify the GIS source code to build intrinsic groundwater flow and transport functions and 2) to write macro programs to perform iterative sequences of map algebra calculations, which are analogous to block-centered finite-difference methods (Watkins, McKinney, and Maidment, 1996).

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## **APPENDICES**

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## APPENDIX A

Source code for Main Menu Program

```

Public Class MainF
    Inherits System.Windows.Forms.Form
    Private Sub vmpBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles vmpBtn.Click
    Private Sub mtdBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles mtdBtn.Click
    Private Sub mthBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles mthBtn.Click
    Private Sub mtnBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles mtnBtn.Click
    'close main form
    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button2.Click
    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button1.Click
    Private Shared myTimer As New System.Windows.Forms.Timer
    Private Shared alarmCounter As Integer = 1
    Private Shared exitFlag As Boolean = False

    ' This is the method to run when the timer is raised.
    Private Sub TimerEventProcessor(ByVal myObject As Object, _
ByVal myEventArgs As EventArgs)
        myTimer.Stop()

        ' Displays a message box asking whether to continue running
the timer.
        If alarmCounter < 5 Then
            ' Restarts the timer and increments the counter.

```

```

        alarmCounter += 1
        myTimer.Enabled = True
    Else
        ' Stops the timer.
        exitFlag = True
    End If
End Sub

Private Sub MainF_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
    ' Adds the event and the event handler for the method that
will
    ' process the timer event to the timer.
    Dim wel As New welcome
    wel.Show()

    AddHandler myTimer.Tick, AddressOf TimerEventProcessor

    ' Sets the timer interval to 5 seconds.
    myTimer.Interval = 1000
    myTimer.Start()

    ' Runs the timer, and raises the event.
    While exitFlag = False
        ' Processes all the events in the queue.
        Application.DoEvents()
    End While

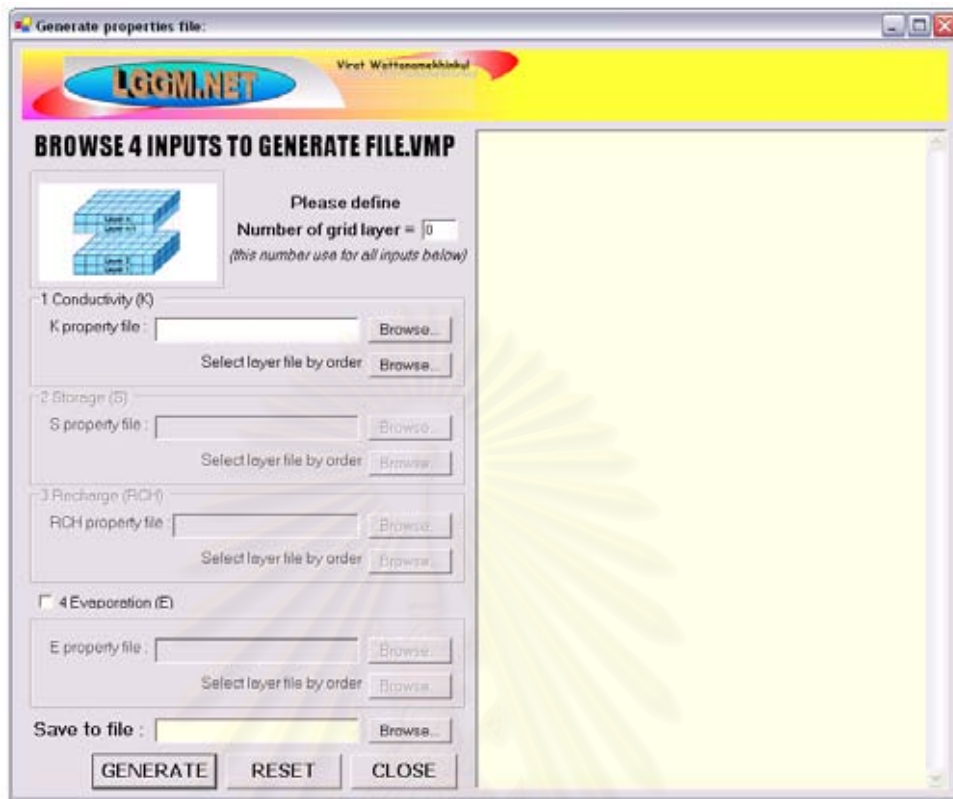
    wel.Close()

End Sub
End Class

```

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## Source code for generate File.VMP



```
Imports System.IO
Imports System.IO.File

Public Class Form1
    Inherits System.Windows.Forms.Form
    Dim myfile, globrow, globcol As String
    Private Sub Form1_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
    Private Sub TextBox3_TextChanged(ByVal sender As System.Object, ByVal
e As System.EventArgs)
    Private Sub genBtn_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles genBtn.Click
    Private Sub resetBtn_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles resetBtn.Click
    Private Sub closeBtn_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles closeBtn.Click
    Private Sub Button9_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button9.Click
    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
    Private Sub Button3_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button3.Click
    Private Sub Button4_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button4.Click
    Private Sub Button5_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button5.Click
    Private Sub Button6_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button6.Click
```

```

Private Sub Button7_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button7.Click
Private Sub Button8_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button8.Click

Function conduct(ByVal propcond As String, ByVal layers As String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, splpath(-1), spl() As String

    'read property file
    myreader = New StreamReader(propcond)
    Dim i As Int16 = 0
    Dim j As Int16 = 0
    Dim proprow(-1) As String
    ReDim proprow(99)
    Do
        mystr = myreader.ReadLine()
        proprow(i) = mystr
        i += 1
    Loop Until myreader.Peek = -1
    ReDim Preserve proprow(i - 1)

    'path files input conductivity
    Dim path2read As New FileStream("c:\dummy.txt", FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(path2read)
    ReDim splpath(99)

    'loop read path of conduct
    For i = 1 To Convert.ToInt16(layers)
        splpath(Convert.ToInt16(layers) - i) = myreader.ReadLine()
    Next
    ReDim Preserve splpath(i - 1)

    Dim stread As New FileStream(splpath(1), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(stread)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    nocols = spl(9) 'cols
    globcol = spl(9)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    norows = spl(9) 'rows
    globrow = spl(9)

    Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
    Dim mywriter As New StreamWriter(stwrite)

    mywriter.WriteLine(layers)
    mywriter.WriteLine(nocols)
    mywriter.WriteLine(norows)
    mywriter.WriteLine(proprow.Length - 1)
    For i = 1 To proprow.Length - 1
        'mywriter.WriteLine(proprow(i).Replace(", ", " "))
        'start adding scientific
        Dim dummystr(proprow.Length), ss(proprow.Length) As
String

        Dim doub(proprow.Length) As Double
        'ReDim dummystr(proprow.Length)

```



```

        dummystr = proprow(i).Split(New Char() {","})
        ReDim doub(dummystr.Length)
        ReDim ss(dummystr.Length)
        For j = 1 To dummystr.Length - 1
            doub(j) = Convert.ToDouble(dummystr(j))
            ss(j) = String.Format("{1:e}", Math.Round(doub(j)),
doub(j))
        Next
        mywriter.WriteLine(dummystr(0) & " " & ss(1) & " " & ss(2)
& " " & ss(3))
        'end adding scientific
    Next
    mywriter.WriteLine() 'blank
    mywriter.Flush()

    For i = 0 To Convert.ToInt16(layers) - 1
        Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
        myreader = New StreamReader(gridread)
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        Do
            mywriter.WriteLine(myreader.ReadLine())
        Loop Until myreader.Peek = -1
        mywriter.WriteLine() 'blank
        mywriter.Flush()
        gridread.Close() 'add close file stream here
    Next

    myreader.Close() 'and add close file stream here
    mywriter.Close()
    path2read.Close()
    stread.Close()
    stwrite.Close()

End Function

Function storage(ByVal propsto As String, ByVal layers As String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, splpath(-1), spl() As String

    'read property file
    myreader = New StreamReader(propsto)
    Dim i As Int16 = 0
    Dim j As Int16 = 0
    Dim proprow(-1) As String
    ReDim proprow(99)
    Do
        mystr = myreader.ReadLine()
        proprow(i) = mystr
        i += 1
    Loop Until myreader.Peek = -1
    ReDim Preserve proprow(i - 1)

    'path files input storage
    Dim path2read As New FileStream("c:\dummy.txt", FileMode.Open,
FileAccess.Read)

```

```

myreader = New StreamReader(path2read)
ReDim splpath(99)

'loop detect path of conduct
For i = 1 To Convert.ToInt16(layers)
    myreader.ReadLine()
Next
'loop read path of storage
For i = 1 To Convert.ToInt16(layers)
    splpath(Convert.ToInt16(layers) - i) = myreader.ReadLine()
Next

ReDim Preserve splpath(i - 1)

Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
Dim mywriter As New StreamWriter(stwrite)

mywriter.WriteLine(proprow.Length - 1)
For i = 1 To proprow.Length - 1
    'mywriter.WriteLine(proprow(i).Replace(",", " "))
    'start adding scientific
    Dim dummystr(proprow.Length), ss(proprow.Length) As
String
    Dim doub(proprow.Length) As Double
    dummystr = proprow(i).Split(New Char() {","})
    ReDim doub(dummystr.Length)
    ReDim ss(dummystr.Length)
    For j = 1 To dummystr.Length - 1
        doub(j) = Convert.ToDouble(dummystr(j))
        ss(j) = String.Format("{1:e}", Math.Round(doub(j)),
doub(j))
    Next
    mywriter.WriteLine(dummystr(0) & " " & ss(1) & " " & ss(2)
& " " & ss(3) & " " & ss(4))
    'end adding scientific
Next
mywriter.WriteLine() 'blank
mywriter.Flush()

For i = 0 To Convert.ToInt16(layers) - 1
    Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(gridread)
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    Do
        mywriter.WriteLine(myreader.ReadLine())
    Loop Until myreader.Peek = -1
    mywriter.WriteLine() 'blank
    gridread.Close() 'add close file stream here
Next

myreader.Close() 'and add close file stream here
mywriter.Close()
path2read.Close()
'stread.Close()

```

```
stwrite.Close()
```

```
End Function
```

```
Function recharge(ByVal proprec As String, ByVal layers As String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, splpath(-1), spl() As String

    'read property file
    myreader = New StreamReader(proprec)
    Dim i As Int16 = 0
    Dim j As Int16 = 0
    Dim k As Int16 = 0
    Dim proprow(-1) As String
    ReDim proprow(99)
    Do
        mystr = myreader.ReadLine()
        proprow(i) = mystr
        i += 1
    Loop Until myreader.Peek = -1
    ReDim Preserve proprow(i - 1)

    'path files input storage
    Dim path2read As New FileStream("c:\dummy.txt", FileMode.Open,
    FileAccess.Read)
    myreader = New StreamReader(path2read)
    ReDim splpath(99)

    'loop detect path of conduct and sto
    For i = 1 To (Convert.ToInt16(layers) * 2)
        myreader.ReadLine()
    Next
    'loop read path of storage
    For i = 1 To Convert.ToInt16(layers)
        splpath(Convert.ToInt16(layers) - i) = myreader.ReadLine()
    Next

    ReDim Preserve splpath(i - 1)

    Dim stwrite As New FileStream(myfile, FileMode.Append,
    FileAccess.Write)
    Dim mywriter As New StreamWriter(stwrite)

    mystr = proprow(proprow.Length - 1)
    spl = mystr.Split(New [Char]() {","})
    'max of pro_no
    mywriter.WriteLine(spl(0))
    'prop group of each pro_no
    Dim max As Int16 = Convert.ToInt16(spl(0))
    For i = 1 To max
        mywriter.WriteLine(max - (max - i) & " 1.000000 Index")

        Dim count As Int16 = 0
        For j = 1 To proprow.Length - 1
            mystr = proprow(j)
            spl = mystr.Split(New [Char]() {","})
            If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
                count += 1
            End If
        Next
    Next
End Function
```

```

'quantity of pro_no
mywriter.WriteLine(count & " rchr entries")

For j = 1 To proprow.Length - 1
    mystr = proprow(j)
    spl = mystr.Split(New [Char]() {","})
    If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
        'each pro_no
        'start adding scientific
        Dim ss(proprow.Length) As String
        Dim doub(proprow.Length) As Double
        ReDim doub(spl.Length)
        ReDim ss(spl.Length)
        For k = 1 To spl.Length - 1
            doub(k) = Convert.ToDouble(spl(k))
            ss(k) = String.Format("{1:e}",
Math.Round(doub(k)), doub(k))
        Next
        mywriter.WriteLine(spl(0) & " " & ss(1) & " " &
ss(2) & " " & ss(3))
        'end adding scientific
    End If
Next

Next
mywriter.WriteLine() 'blank
mywriter.Flush()

For i = 0 To Convert.ToInt16(layers) - 1
    Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(gridread)
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    Do
        mywriter.WriteLine(myreader.ReadLine())
    Loop Until myreader.Peek = -1
    mywriter.WriteLine() 'blank
    gridread.Close() 'add close file stream here
Next

myreader.Close() 'and add close file stream here
mywriter.Close()
path2read.Close()
'stread.Close()
stwrite.Close()

End Function

Function evaporate(ByVal propeva As String, ByVal layers As
String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, splpath(-1), spl() As String

    'read property file
    myreader = New StreamReader(propeva)

```

```

Dim i As Int16 = 0
Dim j As Int16 = 0
Dim k As Int16 = 0
Dim proprow(-1) As String
ReDim proprow(99)
Do
    mystr = myreader.ReadLine()
    proprow(i) = mystr
    i += 1
Loop Until myreader.Peek = -1
ReDim Preserve proprow(i - 1)

'path files input storage
Dim path2read As New FileStream("c:\dummy.txt", FileMode.Open,
FileAccess.Read)
myreader = New StreamReader(path2read)
ReDim splpath(99)

'loop detect path of conduct sto rec
For i = 1 To (Convert.ToInt16(layers) * 3)
    myreader.ReadLine()
Next
'loop read path of storage
For i = 1 To Convert.ToInt16(layers)
    splpath(Convert.ToInt16(layers) - i) = myreader.ReadLine()
Next

ReDim Preserve splpath(i - 1)

Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
Dim mywriter As New StreamWriter(stwrite)

'duplicate form rch
mystr = proprow(proprow.Length - 1)
spl = mystr.Split(New [Char]() {","})
'max of pro_no
mywriter.WriteLine(spl(0))

'prop group of each pro_no
Dim max As Int16 = Convert.ToInt16(spl(0))
For i = 1 To max
    mywriter.WriteLine(max - (max - i) & " 1.000000 Index")

    Dim count As Int16 = 0
    For j = 1 To proprow.Length - 1
        mystr = proprow(j)
        spl = mystr.Split(New [Char]() {","})
        If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
            count += 1
        End If
    Next

    'quantity of pro_no
    mywriter.WriteLine(count & " evap entries")

    For j = 1 To proprow.Length - 1
        mystr = proprow(j)
        spl = mystr.Split(New [Char]() {","})
        If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
            'each pro_no

```

```

        'start adding scientific
        Dim ss(proprow.Length) As String
        Dim doub(proprow.Length) As Double
        ReDim doub(spl.Length)
        ReDim ss(spl.Length)
        For k = 1 To spl.Length - 1
            doub(k) = Convert.ToDouble(spl(k))
            ss(k) = String.Format("{1:e}",
Math.Round(doub(k)), doub(k))
        Next
        mywriter.WriteLine(spl(0) & " " & ss(1) & " " &
ss(2) & " " & ss(3) & " " & ss(4))
        'end adding scientific
    End If
Next

Next
mywriter.WriteLine() 'blank
mywriter.Flush()

'1 group of eva
'mywriter.WriteLine("1")
'mywriter.WriteLine("1 1.000000 Index")

'mystr = proprow(proprow.Length - 1)
'spl = mystr.Split(New [Char]() {","})
'quantity of time
'mywriter.WriteLine(spl(0) & " evap entries")

'Dim j, k As Int16
'For j = 1 To proprow.Length - 1
'    mystr = proprow(j)
'    'each pro_no
'    'start adding scientific
'    spl = mystr.Split(New [Char]() {","})
'    'Dim text As String = "1 " & spl(1) & " " & spl(2) & " "
& spl(3) & " " & spl(4)
'    'mywriter.WriteLine(text)
'    Dim ss(spl.Length) As String
'    Dim doub(spl.Length) As Double
'    'dummystr = proprow(i).Split(New Char() {","})
'    For k = 1 To spl.Length - 1
'        doub(k) = Convert.ToDouble(spl(k))
'        ss(k) = String.Format("{1:e}", Math.Round(doub(k)),
doub(k))
'    Next
'    mywriter.WriteLine(spl(0) & " " & ss(1) & " " & ss(2) &
" " & ss(3))
'    'end adding scientific
'Next

'mywriter.WriteLine() 'blank
'mywriter.Flush()

For i = 0 To Convert.ToInt16(layers) - 1
    Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(gridread)
    myreader.ReadLine()
    myreader.ReadLine()

```

```

myreader.ReadLine()
myreader.ReadLine()
myreader.ReadLine()
myreader.ReadLine()
Do
    mywriter.WriteLine(myreader.ReadLine())
Loop Until myreader.Peek = -1
mywriter.WriteLine() 'blank
gridread.Close() 'add close file stream here
Next

myreader.Close() 'and add close file stream here
mywriter.Close()
path2read.Close()
stwrite.Close()
End Function

Function gennull()
    'gennull
    Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
    Dim mywriter As New StreamWriter(stwrite)

    '1 group of eva
    mywriter.WriteLine("0")
    mywriter.WriteLine()
    Dim h, i, j As Int16
    For h = 1 To Convert.ToInt16(TextBox3.Text)
        For i = 1 To globcol
            For j = 1 To globrow
                mywriter.Write("1 ")
            Next
            mywriter.Write(vbCrLf)
        Next
        mywriter.WriteLine()

    Next

    mywriter.WriteLine() 'blank
    mywriter.Flush()

    mywriter.Close()
    stwrite.Close()
End Function

Private Sub CheckBox1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
CheckBox1.CheckedChanged
    If CheckBox1.Checked Then
        GroupBox4.Enabled = True
    Else
        GroupBox4.Enabled = False
    End If
End Sub

End Class

```

### Source code for generate File.MTD

```
Imports System.IO
Imports System.IO.File

Public Class Form2
Inherits System.Windows.Forms.Form
Dim myfile, globrow, globcol As String

Private Sub Form2_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
Private Sub TextBox3_TextChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles TextBox3.TextChanged
Private Sub genBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles genBtn.Click
Private Sub resetBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles resetBtn.Click
Private Sub Button9_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button9.Click
Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button1.Click
Private Sub Button2_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button2.Click
Function mtdFunc(ByVal propcond As String, ByVal layers As String)
Dim myreader As StreamReader
Dim mystr, norows, nocols, splpath(-1), spl() As String

'read property file
myreader = New StreamReader(propcond)
Dim i As Int16 = 0
Dim j As Int16 = 0
Dim proprow(-1) As String
ReDim proprow(99)
Do
```



```

        mystr = myreader.ReadLine()
        proprow(i) = mystr
        i += 1
    Loop Until myreader.Peek = -1
    ReDim Preserve proprow(i - 1)

    'path files input mtd
    Dim path2read As New FileStream("c:\dummy2.txt",
    FileMode.Open, FileAccess.Read)
    myreader = New StreamReader(path2read)
    ReDim splpath(99)

    'loop read path of mtd
    For i = 1 To Convert.ToInt16(layers)
        splpath(Convert.ToInt16(layers) - i) =
myreader.ReadLine()
    Next
    ReDim Preserve splpath(i - 1)

    Dim stread As New FileStream(splpath(1), FileMode.Open,
    FileAccess.Read)
    myreader = New StreamReader(stread)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    nocols = spl(9) 'cols
    globcol = spl(9)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    norows = spl(9) 'rows
    globrow = spl(9)

    Dim stwrite As New FileStream(myfile, FileMode.Append,
    FileAccess.Write)
    Dim mywriter As New StreamWriter(stwrite)

    mywriter.WriteLine(layers)
    mywriter.WriteLine(nocols)
    mywriter.WriteLine(norows)
    mywriter.WriteLine(proprow.Length - 1)
    For i = 1 To proprow.Length - 1
        'mywriter.WriteLine(proprow(i).Replace(",", " "))
        'start adding scientific
        Dim dummystr(proprow.Length), ss(proprow.Length) As
String
        Dim doub(proprow.Length) As Double
        'ReDim dummystr(proprow.Length)
        dummystr = proprow(i).Split(New Char() {","})
        ReDim doub(dummystr.Length)
        ReDim ss(dummystr.Length)
        For j = 1 To dummystr.Length - 1
            doub(j) = Convert.ToDouble(dummystr(j))
            ss(j) = String.Format("{1:e}", Math.Round(doub(j)),
doub(j))
        Next
        mywriter.WriteLine(dummystr(0) & " " & ss(1))
        'end adding scientific
    Next
    mywriter.WriteLine() 'blank
    mywriter.Flush()

    For i = 0 To Convert.ToInt16(layers) - 1

```

```

        Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
        myreader = New StreamReader(gridread)
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        myreader.ReadLine()
        Do
            mywriter.WriteLine(myreader.ReadLine())
        Loop Until myreader.Peek = -1
        mywriter.WriteLine() 'blank
        mywriter.Flush()
        gridread.Close() 'add close file stream here
    Next

    myreader.Close() 'and add close file stream here
    mywriter.Close()
    path2read.Close()
    stread.Close()
    stwrite.Close()

End Function

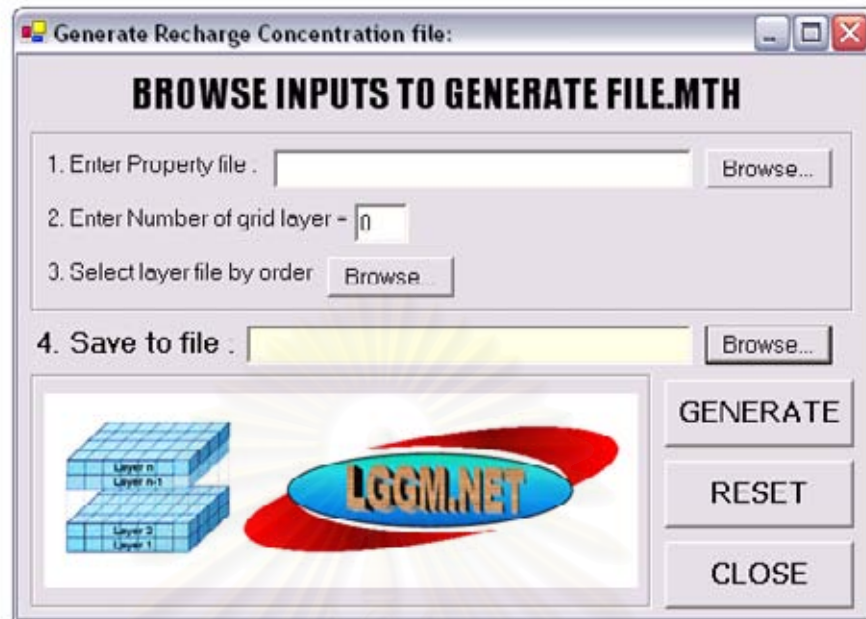
Private Sub closeBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles closeBtn.Click
    'close form
    Form2.ActiveForm.Close()
End Sub

End Class

```

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### Source code for generate File.MTH



```
Imports System.IO
Imports System.IO.File

Public Class Form3
Inherits System.Windows.Forms.Form
    Dim myfile, globrow, globcol As String
    Private Sub Form3_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
    Private Sub TextBox3_TextChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles TextBox3.TextChanged
    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button1.Click
    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button2.Click

    Function mthFunc(ByVal propcond As String, ByVal layers As
String)
        Dim myreader As StreamReader
        Dim mystr, norows, nocols, splpath(-1), spl(), nodata As
String

        'read property file
        myreader = New StreamReader(propcond)
        Dim i As Int16 = 0
        Dim j As Int16 = 0
        Dim k As Int16 = 0
        Dim m As Int16 = 0
        Dim proprow(-1) As String
        ReDim proprow(99)
        Do
            mystr = myreader.ReadLine()
            proprow(i) = mystr
            i += 1
        Loop Until myreader.Peek = -1
        ReDim Preserve proprow(i - 1)
```

```

'path files input mth
Dim path2read As New FileStream("c:\dummy3.txt",
FileMode.Open, FileAccess.Read)
myreader = New StreamReader(path2read)
ReDim splpath(1)
'loop read path of mth
For i = 0 To Convert.ToInt16(layers) - 1
    splpath(i) = myreader.ReadLine()
    'splpath(Convert.ToInt16(layers) - i) =
myreader.ReadLine()
Next

path2read.Close()
myreader.Close()

ReDim Preserve splpath(i - 1)

Dim stread As New FileStream(splpath(0), FileMode.Open,
FileAccess.Read)
myreader = New StreamReader(stread)
mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
nocols = spl(9) 'cols
globcol = spl(9)
mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
norows = spl(9) 'rows
globrow = spl(9)

stread.Close()
myreader.Close()

Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
Dim mywriter As New StreamWriter(stwrite)

'write propoties
mywriter.WriteLine(layers)
mywriter.WriteLine(globcol)
mywriter.WriteLine(globrow)
mywriter.WriteLine() 'blank
mywriter.Flush()

Dim x As Int16
'for loop to all layers
For x = 0 To splpath.Length - 1
    Dim stread2 As New FileStream(splpath(x), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(stread2)
    mystr = myreader.ReadLine()
    mystr = myreader.ReadLine()
    mystr = myreader.ReadLine()
    mystr = myreader.ReadLine()
    mystr = myreader.ReadLine()
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    nodata = spl(2) 'NO_Data

    i = 0
    j = 0
    k = 0

```

```

Dim cell(-1, -1) As String
ReDim cell(globrow + 1, globcol + 1)
Do
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    For j = 0 To globcol
        cell(i, j) = spl(j)
    Next
    i += 1
Loop Until myreader.Peek = -1

For i = 0 To globrow
    For j = 0 To globcol
        If cell(i, j) <> nodata Then
            'check prop no
            For k = 0 To proprow.Length - 1
                spl = proprow(k).Split(New [Char]()
{"", ""}))

                Dim ss(spl.Length) As String
                Dim doub(spl.Length) As Double
                If spl(0) = cell(i, j) Then
                    mywriter.WriteLine(k)
                    mywriter.WriteLine(j)
                    mywriter.WriteLine(i)
                    mywriter.WriteLine(1)
                    For m = 1 To spl.Length - 1
                        doub(m) =
Convert.ToDouble(spl(m))
                        ss(m) = String.Format("{1:e}",
Math.Round(doub(m)), doub(m))
                    Next
                    mywriter.WriteLine(" " & ss(1) & "
" & ss(2) & " " & ss(3))
                End If
            Next
        End If
    Next
Next
stead2.Close()
myreader.Close()
Next

myreader.Close() 'and add close file stream here
mywriter.Close()
stead.Close()
stwrite.Close()

End Function

Private Sub Button9_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button9.Click
    'save to file
    If SaveF1.ShowDialog = DialogResult.OK Then
        TextBox5.Text = SaveF1.FileName
        myfile = SaveF1.FileName
    End If
End Sub

Private Sub closeBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles closeBtn.Click
    'close form

```

```

        Form3.ActiveForm.Close()
    End Sub

    Private Sub resetBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles resetBtn.Click
        'reset and clear text
        File.Delete("c:\dummy3.txt")
        'clear textbox
        TextBox2.Text = ""
        TextBox3.Text = "0"
        TextBox5.Text = ""
    End Sub

    Private Sub genBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles genBtn.Click
        'press generate
        Try
            Call mthFunc(TextBox2.Text, TextBox3.Text)

            File.Delete("c:\dummy3.txt")
            MessageBox.Show("COMPLETED! See file at path " & myfile,
"Result", MessageBoxButtons.OK, MessageBoxIcon.Information)

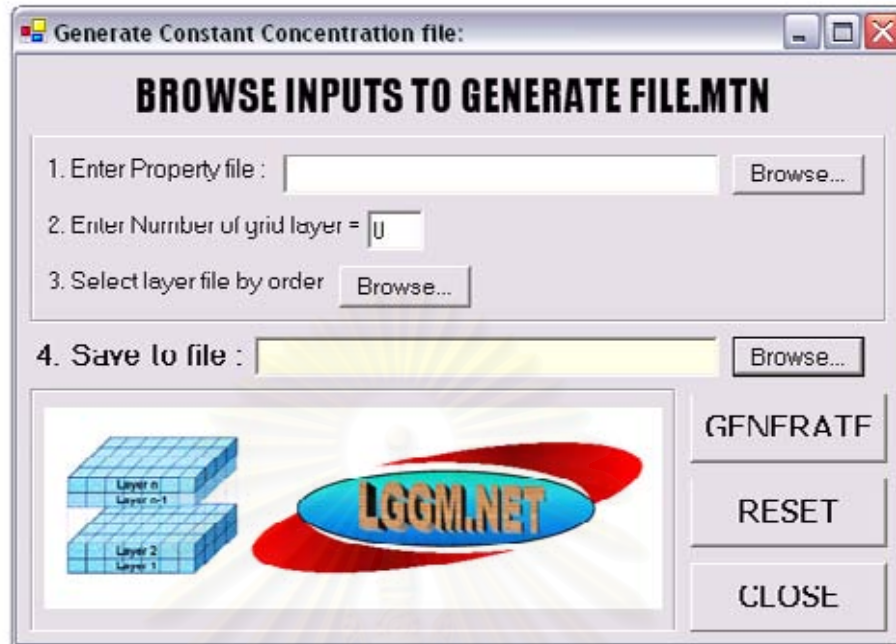
            Catch ex As Exception
                MessageBox.Show("Wrong Action!", "Error",
MessageBoxButtons.OK, MessageBoxIcon.Error)
            End Try

            'clear textbox
            TextBox2.Text = ""
            TextBox3.Text = "0"
            TextBox5.Text = ""
        End Sub
    End Class

```

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### Source code for generate File.MTN



```
Imports System.IO
Imports System.IO.File

Public Class Form4
Inherits System.Windows.Forms.Form
    Dim myfile, globrow, globcol As String
    Private Sub Form4_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        Private Sub TextBox3_TextChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles TextBox3.TextChanged
            Private Sub genBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles genBtn.Click
                Private Sub resetBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles resetBtn.Click
                    Private Sub closeBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles closeBtn.Click
                        Private Sub Button9_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button9.Click
                            Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button1.Click
                                Private Sub Button2_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button2.Click

Function mtnFunc(ByVal proprec As String, ByVal layers As String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, splpath(-1), spl() As String

    'read property file
    myreader = New StreamReader(proprec)
    Dim i As Int16 = 0
    Dim k As Int16 = 0
    Dim proprow(-1) As String
    ReDim proprow(99)
    Do
        mystr = myreader.ReadLine()
        proprow(i) = mystr
```

```

        i += 1
    Loop Until myreader.Peek = -1
    ReDim Preserve proprow(i - 1)

    'path files input conductivity
    Dim path2read As New FileStream("c:\dummy4.txt",
    FileMode.Open, FileAccess.Read)
    myreader = New StreamReader(path2read)
    ReDim splpath(99)

    'loop read path of conduct
    For i = 1 To Convert.ToInt16(layers)
        splpath(Convert.ToInt16(layers) - i) =
myreader.ReadLine()
    Next
    ReDim Preserve splpath(i - 1)

    Dim stread As New FileStream(splpath(1), FileMode.Open,
    FileAccess.Read)
    myreader = New StreamReader(stread)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    nocols = spl(9) 'cols
    globcol = spl(9)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    norows = spl(9) 'rows
    globrow = spl(9)

    Dim stwrite As New FileStream(myfile, FileMode.Append,
    FileAccess.Write)
    Dim mywriter As New StreamWriter(stwrite)

    mystr = proprow(proprow.Length - 1)
    spl = mystr.Split(New [Char]() {","})
    'quantity of pro_no add 0 pro_no
    mywriter.WriteLine(Convert.ToInt16(spl(0)))
    mywriter.WriteLine(nocols)
    mywriter.WriteLine(norows)
    'max of pro_no
    mywriter.WriteLine(Convert.ToInt16(spl(0)) + 1)
    mywriter.WriteLine("-1 1.000000 Index")
    mywriter.WriteLine("1 cncn entries")
    mywriter.WriteLine("0 -1.000000 0.000000 0.000000")

    'prop group of each pro_no
    Dim max As Int16 = Convert.ToInt16(spl(0))
    For i = 1 To max
        mywriter.WriteLine(max - (max - i) & " 1.000000 Index")
        Dim j As Int16 = 0
        Dim count As Int16 = 0
        For j = 1 To proprow.Length - 1
            mystr = proprow(j)
            spl = mystr.Split(New [Char]() {","})
            If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
                count += 1
            End If
        Next

        'quantity of pro_no
        mywriter.WriteLine(count & " cncn entries")
    
```



```

For j = 1 To proprow.Length - 1
    mystr = proprow(j)
    spl = mystr.Split(New [Char]() {","})
    If Convert.ToInt16(spl(0)) = (max - (max - i)) Then
        'start adding scientific
        Dim ss(spl.Length) As String
        Dim doub(spl.Length) As Double
        For k = 1 To spl.Length - 1
            doub(k) = Convert.ToDouble(spl(k))
            ss(k) = String.Format("{1:e}",
Math.Round(doub(k)), doub(k))
        Next
        mywriter.WriteLine(spl(0) & " " & ss(1) & " " &
ss(2) & " " & ss(3))
        'end adding scientific
    End If
Next

Next
mywriter.WriteLine() 'blank
mywriter.Flush()

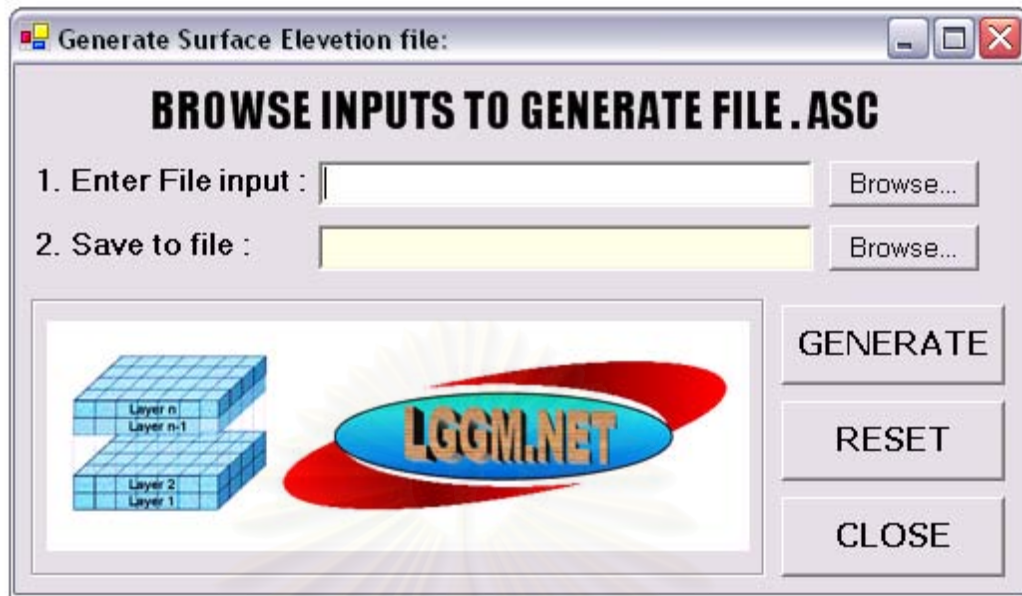
For i = 0 To Convert.ToInt16(layers) - 1
    Dim gridread As New FileStream(splpath(i), FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(gridread)
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    myreader.ReadLine()
    Do
        mywriter.WriteLine(myreader.ReadLine())
    Loop Until myreader.Peek = -1
    mywriter.WriteLine() 'blank
    gridread.Close() 'add close file stream here
Next

myreader.Close() 'and add close file stream here
mywriter.Close()
path2read.Close()
stread.Close()
stwrite.Close()

End Function
End Class

```

**Source code for generate Surface Elevation**



```
Imports System.IO
Imports System.IO.File

Public Class Form5
    Inherits System.Windows.Forms.Form

    Dim myfile, globrow, globcol As String
    Private Sub genBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles genBtn.Click
    Private Sub resetBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles resetBtn.Click
    Private Sub closeBtn_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles closeBtn.Click
    Private Sub Button9_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button9.Click
    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Button1.Click

Function xxxFunc(ByVal propcond As String)
    Dim myreader As StreamReader
    Dim mystr, norows, nocols, spl(), striz As String
    Dim xcorner, ycorner, cellsize, nodata, x, y As Single
    Dim z As Double

    Dim i As Int16 = 0
    Dim j As Int16 = 0
    Dim k As Int16 = 0

    Dim stread As New FileStream(TextBox2.Text, FileMode.Open,
FileAccess.Read)
    myreader = New StreamReader(stread)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    nocols = spl(9) 'cols
    globcol = spl(9)
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    norows = spl(9) 'rows
```

```

globrow = spl(9)

mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
xcorner = Convert.ToSingle(spl(5))
mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
ycorner = Convert.ToSingle(spl(5))
mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
cellsize = Convert.ToSingle(spl(6))
mystr = myreader.ReadLine()
spl = mystr.Split(New [Char]() {" "})
nodata = Convert.ToSingle(spl(2)) 'NO_Data

Dim stwrite As New FileStream(myfile, FileMode.Append,
FileAccess.Write)
Dim mywriter As New StreamWriter(stwrite)

i = 0
j = 0
k = 0
Dim cell(-1, -1) As String
ReDim cell(globrow + 1, globcol + 1)
Do
    mystr = myreader.ReadLine()
    spl = mystr.Split(New [Char]() {" "})
    For j = 0 To globcol
        cell(i, j) = spl(j)
    Next
    i += 1
Loop Until myreader.Peek = -1

For i = 0 To globrow
    For j = 0 To globcol
        If cell(i, j) <> "" Then
            y = (ycorner + (cellsize / 2) + (cellsize *
(globrow - i))) - 20
            x = (xcorner + (cellsize / 2) + (cellsize * (j -
1))) + 20

            z = Convert.ToDouble(cell(i, j))
            striz = String.Format("{1:f6}", Math.Round(z), z)
            mywriter.WriteLine(x & "," & y & "," & striz)
        End If
    Next
Next

' DO 50 I = 1, NROW
'     Y = Y11CORNER + CELLSIZE / 2 + CELLSIZE * (NROW
- i)
'         READ (7,*) (Z(J), J = 1,NCOL)
'         DO 40 J = 1, NCOL
'             X(j) = X11CORNER + CELLSIZE / 2 + CELLSIZE *
(j - 1)
'             WRITE (8,*) X(J), Y, Z(J)
'40:         CONTINUE()
'50:         CONTINUE()

myreader.Close() 'and add close file stream here
mywriter.Close()
stead.Close()

```

```
stwrite.Close()
```

```
End Function
```

```
End Class
```



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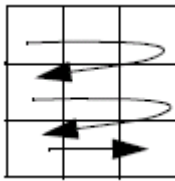
## APPENDIX B

### VISUAL MODFLOW 3.0 INPUT FILES STRUCTURE

#### File.VMP

#### VMP - Flow Property File Format

For each property (conductivity, storage, recharge, and evapotranspiration), the .VMP file contains a property value list followed by one integer array for each model layer. The integers in the arrays reference the property numbers in the property value list.



Looking down on the top of the model, the **Index array** for each layer is written starting in the top left and ending in the bottom right  
 Each element = integer flag = property index  
 Each line = one model row

Number\_of\_layers

Number\_of\_rows

Number\_of\_columns

Number\_of\_conductivity\_properties (NK)

1 KX1 KY1 KZ1

...

NK KXNK KYNK KZNK

BLANK LINE

Conductivity\_Index\_ArrayBottom\_layer

BLANK LINE

...

Conductivity\_Index\_ArrayTop\_layer

BLANK LINE

Number\_of\_storage\_properties (NS)

1 SS1 SY1 Effective\_porosity1 Total\_Porosity1

...

NS SSNS SYNS Effective\_PorosityNS Total\_PorosityNS

BLANK LINE

Storage\_Index\_ArrayBottom\_layer

BLANK LINE

...

Storage\_Index\_ArrayTop\_layer

BLANK LINE

Number\_of\_recharge\_properties (NR)

for each recharge property

Property\_number Recharge\_multiplier Index

Number\_of\_recharge\_timesteps rchr entries

Property\_number Recharge\_value1 Start\_time1 Stop\_time1

Property\_number Recharge\_value2 Start\_time2 Stop\_time2

...

Property\_number Recharge\_valuensteps Start\_timensteps Stop\_timensteps

BLANK LINE

Recharge\_Index\_ArrayBottom\_layer

BLANK LINE

...

Recharge\_Index\_ArrayTop\_layer

BLANK LINE

Number\_of\_evapotranspiration\_properties (NE)

for each evapotranspiration property

Property\_number Evapo\_multiplier Index

Number\_of\_evapo\_timesteps evap entries

Property\_number Evapo\_value1 Evapo\_depth1 Start\_time1 Stop\_time1

Property\_number Evapo\_value2 Evapo\_depth2 Start\_time2 Stop\_time2

...

Property\_number Evapo\_valuensteps Evapo\_depthnsteps Start\_timensteps

Stop\_timensteps

BLANK LINE

Evapo\_Index\_ArrayBottom\_layer

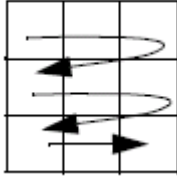
BLANK LINE

...

Evapo\_Index\_ArrayTop\_layer

**File.MTN****MTN – Constant Concentration Boundary File Format**

For each property (Constant Concentration), the .MTN file contains a property value list followed by one integer array for each model layer. The integers in the arrays reference the property numbers in the property value list.



Looking down on the top of the model, the **Index array** for each layer is written starting in the top left and ending in the bottom right  
 Each element = integer flag = property index  
 Each line = one model row

Number\_of\_layers

Number\_of\_rows

Number\_of\_columns

Number\_of\_constant concentration \_properties (NR)

for each constant concentration property

Property\_number constant concentration \_multiplier Index

Number\_of\_ constant concentration \_timesteps cncn entries

Property\_number constant concentration \_value1 Start\_time1 Stop\_time1

Property\_number constant concentration \_value2 Start\_time2 Stop\_time2

...

Property\_number constant concentration \_valuensteps Start\_timensteps

Stop\_timensteps

BLANK LINE

Constant Concentration \_Index\_ArrayBottom\_layer

BLANK LINE

...

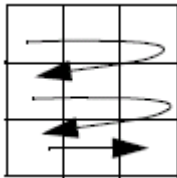
Constant Concentration \_Index\_ArrayTop\_layer

BLANK LINE

## File.MTD

### MTD –Dispersion Property File Format

For each property (Dispersion), the .MTD file contains a property value list followed by one integer array for each model layer. The integers in the arrays reference the property numbers in the property value list.



Looking down on the top of the model, the **Index array** for each layer is written starting in the top left and ending in the bottom right  
 Each element = integer flag = property index  
 Each line = one model row

Number\_of\_layers

Number\_of\_rows

Number\_of\_columns

Number\_of\_dispersion\_properties (ND)

1\_value1

2\_value2

...

ND\_value N

BLANK LINE

Dispersion\_Index\_ArrayBottom\_layer

BLANK LINE

...

Dispersion\_Index\_ArrayTop\_layer

BLANK LINE



## File.MTH

### **MTH – Recharge Concentration Boundary Conditions File Format**

Visual MODFLOW only saves Recharge Concentration boundary condition data for grid cells where boundary conditions are assigned. The row, column, and layer indices in this file are slightly different than those displayed on the Reference cube and written to the MODFLOW files. In the . MTH file,

**Rows** are numbered from **0** to **NR-1**, beginning in the lower left-hand corner of the model (where NR is number of grid rows in the model)

**Columns** are numbered from **0** to **NC-1**, beginning in the lower left-hand corner of the model (where NC is number of grid columns in the model), and

**Layers** are numbered from **0** to **NL-1**, beginning at the bottom most layer of the model.

This contrasts with the MODFLOW files and the Reference cube, where cell (1,1,1) is located in the upper left corner of the top layer (when looking at the model in plan view on the screen). The format of the data saved depends on the type of boundary condition in the grid cell.

Number\_of\_Layers

Number\_of\_Columns

Number\_of\_Rows

BLANK LINE

For each Recharge Concentration boundary grid cell:

Layer

Column

Row

1 (*Code for Recharge Concentration boundary type*)

Start\_Time1 Stop\_Time1 Recharge Concentration\_1

.

Layer

Column

Row

1 (*Code for Recharge Concentration boundary type*)

Start\_TimeNE Stop\_timeNE HeadNE

## ELEVATION

### Importing Surfaces

A numerical model using layers with constant elevations often cannot represent true hydrogeologic conditions caused by variable layer thickness and surface topography. In order to accommodate these conditions, Visual MODFLOW can import and interpolate external data files (Surfer™ .GRD or ASCII .TXT format) to create variable bottom and top elevations for each layer.

To import and interpolate data from an external file select the [**Import Surface**] option from the left-hand toolbar. The following **Import Surface** window will appear.

The **Import Data** frame is used to select the type of data file that will be imported.

The **From ASCII (x,y,z)** option indicates the layer elevation data will be imported from an ASCII text file with three columns of data containing the X-coordinate, Y-coordinate and Z-elevation. This data file cannot contain any header information and each column of data must be space or comma separated.



Surface Elevation (Digital elevation map): ncols 10 nrows 10 xllcorner 0 yllcorner 0 cellsize 10 NODATA_value -9999 0 1 0	
--	--

1.2 Properties text files

Condition 1:

Hydraulic conductivity: "Pro_no","Kx","Ky","Kz" 1,0.11,0.11,0.13 2,0.14,0.14,0.16	Storage: "Pro_no","Ss","Sy","Ep","Tp" 1,0.0001,0.2,0.15,0.3 2,0.1,0.2,0.4,0.5	Recharge: "Pro_no","RCH","Tst","Tsp" 1,100,0,8000 2,250,0,100 2,251,100,8000
Evaporation: "Pro_no","E","D","Tst","Tp" 1,281,14,0,731 2,22,12,731,8000	Dispersion: "Pro_no","Dispersion" 1,10	Recharge Concentration: "Pro_no","Tst","Tsp","RC" 1,0,8000,21 2,0,8000,5000
Constant concentration: "Pro_no","Conc","Tst","Tsp" 1,0.03,0,8000 2,44,0,24 2,34,24,8000		

Condition 2:

Hydraulic conductivity: "Pro_no","Kx","Ky","Kz" 1,0.11,0.11,0.13 2,0.14,0.14,0.16	Storage: "Pro_no","Ss","Sy","Ep","Tp" 1,0.0001,0.2,0.15,0.3 2,0.1,0.2,0.4,0.5	Recharge: "Pro_no","RCH","Tst","Tsp" 1,100,0,8000 2,500,0,100 2,501,100,8000
--	--	--

Evaporation: "Pro_no","E","D","Tst","Tp" 1,281,14,0,731 2,22,12,731,8000	Dispersion: "Pro_no","Dispersion" 1,10	Recharge Concentration: "Pro_no","Tst","Tsp","RC" 1,0,8000,21 2,0,8000,5000
Constant concentration: "Pro_no","Conc","Tst","Tsp" 1,0.03,0,8000 2,44,0,24 2,34,24,8000		

**Condition 3:**

Hydraulic conductivity: "Pro_no","Kx","Ky","Kz" 1,0.11,0.11,0.13 2,0.14,0.14,0.16	Storage: "Pro_no","Ss","Sy","Ep","Tp" 1,0.0001,0.2,0.15,0.3 2,0.1,0.2,0.4,0.5	Recharge: "Pro_no","RCH","Tst","Tsp" 1,100,0,8000 2,500,0,100 2,501,100,8000
Evaporation: "Pro_no","E","D","Tst","Tp" 1,281,14,0,731 2,22,12,731,8000	Dispersion: "Pro_no","Dispersion" 1,10	Recharge Concentration: "Pro_no","Tst","Tsp","RC" 1,0,8000,21 2,0,8000,10000
Constant concentration: "Pro_no","Conc","Tst","Tsp" 1,0.03,0,8000 2,44,0,24 2,34,24,8000		

**2. Output File**

**2.1 File.vmp Condition 1:**

From manual assign in Visual MODFLOW	From LGGM.NET
2	2
10	10
10	10
2	2
1 1.100000e-001 1.100000e-001 1.300000e-001	1 1.100000e-001 1.100000e-001 1.300000e-001
2 1.400000e-001 1.400000e-001 1.600000e-001	2 1.400000e-001 1.400000e-001 1.600000e-001
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1

1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
2	2
1 1.000000e-004 2.000000e-001 1.500000e-001	1 1.000000e-004 2.000000e-001 1.500000e-001
3.000000e-001	3.000000e-001
2 1.000000e-001 2.000000e-001 4.000000e-001	2 1.000000e-001 2.000000e-001 4.000000e-001
5.000000e-001	5.000000e-001
1111111111	1111111111
1111111111	1111111111
1111211111	1111211111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
2	2
1 1.000000 Index	1 1.000000 Index
1 rchr entries	1 rchr entries
1 1.000000e+002 0.000000e+000 8.000000e+003	1 1.000000e+002 0.000000e+000 8.000000e+003
2 1.000000 Index	2 1.000000 Index
2 rchr entries	2 rchr entries
2 2.500000e+002 0.000000e+000 1.000000e+002	2 2.500000e+002 0.000000e+000 1.000000e+002
2 2.510000e+002 1.000000e+002 8.000000e+003	2 2.510000e+002 1.000000e+002 8.000000e+003
1111111111	1111111111
1111111111	1111111111
1111211111	1111211111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
1111111111	1111111111
2	2
1 1.000000 Index	1 1.000000 Index
1 evap entries	1 evap entries

1 2.810000e+002 1.400000e+001 0.000000e+000	1 2.810000e+002 1.400000e+001 0.000000e+000
7.310000e+002	7.310000e+002
2 1.000000 Index	2 1.000000 Index
1 evap entries	1 evap entries
2 2.200000e+001 1.200000e+001 7.310000e+002	2 2.200000e+001 1.200000e+001 7.310000e+002
8.000000e+003	8.000000e+003
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1

**2.1 File.vmp Condition 2:**

From manual assign in Visual MODFLOW	From LGGM.NET
2	2
10	10
10	10
2	2
1 1.100000e-001 1.100000e-001 1.300000e-001	1 1.100000e-001 1.100000e-001 1.300000e-001
2 1.400000e-001 1.400000e-001 1.600000e-001	2 1.400000e-001 1.400000e-001 1.600000e-001
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
2	2
1 1.000000e-004 2.000000e-001 1.500000e-001	1 1.000000e-004 2.000000e-001 1.500000e-001
3.000000e-001	3.000000e-001
2 1.000000e-001 2.000000e-001 4.000000e-001	2 1.000000e-001 2.000000e-001 4.000000e-001

5.000000e-001	5.000000e-001
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
2	2
1 1.000000 Index	1 1.000000 Index
1 rchr entries	1 rchr entries
1 1.000000e+002 0.000000e+000 8.000000e+003	1 1.000000e+002 0.000000e+000 8.000000e+003
2 1.000000 Index	2 1.000000 Index
2 rchr entries	2 rchr entries
2 25.000000e +002 0.000000e+000 1.000000e+002	2 5.000000e+002 0.000000e+000 1.000000e+002
2 5.010000e +002 1.000000e+002 8.000000e+003	2 5.010000e+002 1.000000e+002 8.000000e+003
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
2	2
1 1.000000 Index	1 1.000000 Index
1 evap entries	1 evap entries
1 2.810000e+002 1.400000e+001 0.000000e+000	1 2.810000e+002 1.400000e+001 0.000000e+000
7.310000e+002	7.310000e+002
2 1.000000 Index	2 1.000000 Index
1 evap entries	1 evap entries
2 2.200000e+001 1.200000e+001 7.310000e+002	2 2.200000e+001 1.200000e+001 7.310000e+002
8.000000e+003	8.000000e+003
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1









**2.2 File.mtd Condition 3:**

From manual assign in Visual MODFLOW	From LGGM.NET
1	1
10	10
10	10
1	1
1 1.000000e+001	1 1.000000e+001
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1

**2.3 File.mth Condition 1:**

From manual assign in Visual MODFLOW	From LGGM.NET
1	1
10	10
10	10
0	0
4	4
7	7
1	1
0.000000e+00 8.000000e+03 5.000000e+03	0.000000e+00 8.000000e+03 5.000000e+03

**2.3 File.mth Condition 2:**

From manual assign in Visual MODFLOW	From LGGM.NET
1	1
10	10
10	10
0	0
4	4
7	7
1	1
0.000000e+00 8.000000e+03 5.000000e+03	0.000000e+00 8.000000e+03 5.000000e+03



**2.4 File.mtn Condition 2:**

From manual assign in Visual MODFLOW	From LGGM.NET
1	1
10	10
10	10
3	3
-1 1.000000 Index	-1 1.000000 Index
1 cncn entries	1 cncn entries
0 -1.000000 0.000000 0.000000	0 -1.000000 0.000000 0.000000
1 1.000000 Index	1 1.000000 Index
1 cncn entries	1 cncn entries
1 3.000000e-002 0.000000e+000 8.000000e+003	1 3.000000e-002 0.000000e+000 8.000000e+003
2 1.000000 Index	2 1.000000 Index
2 cncn entries	2 cncn entries
2 4.400000e+001 0.000000e+000 2.400000e+001	2 4.400000e+001 0.000000e+000 2.400000e+001
2 3.400000e+001 2.400000e+001 8.000000e+003	2 3.400000e+001 2.400000e+001 8.000000e+003
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 2 1 1 1 1 1	1 1 1 1 2 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1

**2.4 File.mtn Condition 3:**

From manual assign in Visual MODFLOW	From LGGM.NET
1	1
10	10
10	10
3	3
-1 1.000000 Index	-1 1.000000 Index
1 cncn entries	1 cncn entries
0 -1.000000 0.000000 0.000000	0 -1.000000 0.000000 0.000000
1 1.000000 Index	1 1.000000 Index
1 cncn entries	1 cncn entries
1 3.000000e-002 0.000000e+000 8.000000e+003	1 3.000000e-002 0.000000e+000 8.000000e+003
2 1.000000 Index	2 1.000000 Index
2 cncn entries	2 cncn entries
2 4.400000e+001 0.000000e+000 2.400000e+001	2 4.400000e+001 0.000000e+000 2.400000e+001

















85.0000000	15.0000000	0.0000000	85.0000000	15.0000000	0.0000000
95.0000000	15.0000000	0.0000000	95.0000000	15.0000000	0.0000000
5.0000000	5.0000000	0.0000000	5.0000000	5.0000000	0.0000000
15.0000000	5.0000000	0.0000000	15.0000000	5.0000000	0.0000000
25.0000000	5.0000000	0.0000000	25.0000000	5.0000000	0.0000000
35.0000000	5.0000000	0.0000000	35.0000000	5.0000000	0.0000000
45.0000000	5.0000000	0.0000000	45.0000000	5.0000000	0.0000000
55.0000000	5.0000000	0.0000000	55.0000000	5.0000000	0.0000000
65.0000000	5.0000000	0.0000000	65.0000000	5.0000000	0.0000000
75.0000000	5.0000000	0.0000000	75.0000000	5.0000000	0.0000000
85.0000000	5.0000000	0.0000000	85.0000000	5.0000000	0.0000000
95.0000000	5.0000000	0.0000000	95.0000000	5.0000000	0.0000000



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## APPENDIX D

### RAW DATA

#### 1. Meteorological Data

The meteorological data of the study area

Computer Section Climatology Division  
Meteorological Department 11-May-05

Monthly Rainfall (MM), Rain-days and Daily Maximum

STATION : 459203 Phatthaya\*  
PROVINCE : Chon Buri

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1986_Amt.	0	3.7	12.9	71.2	203.3	52.5	42.6	27.5	170.3	247.4	30.9	3.9	866.2
R-day	0	2	2	4	9	9	17	10	16	24	5	3	101
Max.	0	3.3	7.4	65.4	96.8	24.5	15.7	6.8	43.3	45.8	18.7	2.6	96.8
1987_Amt.	0	2.2	88.8	127.5	66	123.3	29.1	74.1	82.9	269.2	228.6	0	1091.7
R-day	0	1	4	6	11	18	8	12	16	20	21	0	117
Max.	0	2.2	81.8	50	23.7	51	11.6	24.8	26	47.9	52.2	0	81.8
1988_Amt.	0	42.8	2	144.3	138.2	178.6	210.5	153.5	238.6	279.3	25.1	0	1412.9
R-day	0	5	1	14	15	13	14	18	18	18	3	0	119
Max.	0	33.3	2	27.6	21.1	99.4	48.6	33.8	51.5	89.1	24.1	0	99.4

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1989_Amt.	135.2	21.3	68.1	2.6	52.8	59.4	69.9	57.4	284.1	188.2	35.4	0	974.4
R-day	5	5	2	1	10	6	12	8	17	13	3	0	82
Max.	88.2	17.4	68	2.6	24.8	19.4	15.5	27.2	57	37.4	24.6	0	88.2
1990_Amt.	1.5	17.6	54.6	61.3	349.3	12.3	22	55.1	104	304.7	89.3	0	1071.7
R-day	1	3	7	5	11	3	8	10	17	16	7	0	88
Max.	1.5	11	31.1	24.8	69.3	7.3	9.3	25.9	25.2	76.8	46.4	0	76.8
1991_Amt.	T	5.8	18.4	130.5	164.2	95.8	124.7	79	339	297.8	0.6	5.4	1261.2
R-day	0	3	3	4	15	15	16	15	19	23	1	1	115
Max.	T	4.9	9.1	60.2	34.4	27.1	51	25.2	117.1	74.7	0.6	5.4	117.1
1992_Amt.	5.9	16.5	0	27.6	27.8	44.9	243.1	55.5	158.4	266	16	7	868.7
R-day	5	3	0	2	8	15	16	14	13	21	3	2	102
Max.	3.5	12.6	0	27.5	11.5	8	76.6	10.5	41	64.8	7.7	5.2	76.6
1993_Amt.	16.9	4.5	107.2	78.6	80.8	82.9	47	114	142.8	245	19.6	0.1	939.4
R-day	5	2	10	4	11	9	9	16	19	22	4	1	112
Max.	9.8	3.9	53	54	29.2	20.6	17.1	34.5	31.7	58.9	12.3	0.1	58.9
1994_Amt.	0	17	77.2	17.7	136.3	253.2	21.5	54.5	161.6	117.4	1	55.5	912.9
R-day	0	1	10	3	15	18	11	12	15	10	1	2	98
Max.	0	17	41.8	9.2	31.1	70.8	5.8	17	64.3	44.1	1	48.6	70.8
1995_Amt.	33.6	0.4	30.3	88	181.1	73.9	65.9	232	371.7	299.8	72.1	T	1448.8
R-day	2	1	6	5	15	9	15	19	21	16	5	0	114
Max.	23.2	0.4	23.4	44.7	69.3	43	25.5	60.1	43.7	105.8	31.7	T	105.8
1996_Amt.	5.3	6.3	11.7	29.6	194.8	298.6	202.2	74.8	326.6	266.4	81.8	3.3	1501.4
R-day	2	1	4	7	11	16	18	11	22	20	8	1	121
Max.	4.9	6.3	4.2	8.2	52.5	53.9	75.1	31.7	81.7	48.5	52.6	3.3	81.7
1997_Amt.	0	4.5	48.8	44.9	51.8	0.5	72.3	23.8	236.7	176	56.5	0	715.8
R-day	0	1	6	6	8	1	12	9	16	17	5	0	81



YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Max.	0	4.5	25.5	22.4	19	0.5	40.6	14.2	82	41.4	35.7	0	82
1998_Amt.	9.7	14.3	0.2	33.8	162.6	153.3	158.9	157.8	220.4	146.9	25.7	15.4	1099
R-day	1	2	1	4	15	13	16	19	20	15	9	3	118
Max.	9.7	10.9	0.2	17.1	30.5	88.3	35	59.1	28.6	28	10.2	11.2	88.3
1999_Amt.	3.8	1.9	44.6	33.7	341.3	97.9	40.4	108.6	224.6	308.3	46.9	0.2	1252.2
R-day	4	3	5	11	17	9	13	11	15	20	8	1	117
Max.	3	0.9	33	16.2	113.3	39.6	13.6	35.2	52.1	108.2	18.2	0.2	113.3
2000_Amt.	12.9	38	42.6	114.8	14.6	190	76.4	34.7	94.8	198.3	17.7	0.2	835
R-day	1	4	4	14	6	17	13	9	16	21	4	1	110
Max.	12.9	14.3	35.7	24.8	5.4	76.4	21.2	8.4	24	38.2	16.1	0.2	76.4
2001_Amt.	9.7	8	197.6	20.7	125.6	118.5	6.8	231.2	263.8	278.8	64.3	6	1331
R-day	6	2	12	6	10	13	5	13	18	25	3	1	114
Max.	5.6	7.6	56.2	9.8	23	67	2.6	128.7	61.4	47	49.5	6	128.7
2002_Amt.	0	4.5	39.8	103.8	177.7	81.8	108.6	81.8	139	135.4	135	31.6	1039
R-day	0	2	3	8	13	11	13	16	10	10	9	5	100
Max.	0	4.3	20.2	29.5	41.2	25	45	18	44	44.4	59.4	13.2	59.4
2003_Amt.	0	7.6	159.3	83.8	103.4	311.1	217	53.6	104.1	177.5	0	0	1217.4
R-day	0	3	11	5	13	12	14	12	16	16	0	0	102
Max.	0	5.8	56.8	39	31.4	189.4	44.6	17.6	25	26.6	0	0	189.4
2004_Amt.	68.4	38.4	29.7	16.8	214.6	114.7	105.6	62.6	242	57.7	18.6	0	969.1
R-day	4	5	5	4	13	9	14	11	19	9	1	0	94
Max.	52	22.8	15.4	11.8	38.2	48	32.9	14.4	55.5	15.2	18.6	0	55.5
MEAN_Amt.	15.9	13.4	54.4	64.8	146.6	123.3	98.1	91.1	205.5	224.2	50.8	6.8	1094.9
MEAN R-day	1.9	2.6	5.1	5.9	11.9	11.4	12.8	12.9	17	17.7	5.3	1.1	105.6
EXT. Max.	88.2	33.3	81.8	65.4	113.3	189.4	76.6	128.7	117.1	108.2	59.4	48.6	189.4



Bore Hole No.	Depth from ground level (m.)	soil classification	water content (%)	wet unit weight (t/m <sup>3</sup> )	Total Organic Content (%)	sieve analysis (% finer)					porosity test	specific gravity	Note
						No. 3/8"	No. 4	No. 10	No. 40	No. 200			
	7.50-7.70	SC											
	7.70-7.90	SC	13.40	2.15	0.77		100	80	54	43	0.30	2.70	
	7.90-8.35	SC											
	9.00-9.45	SC											
	10.50-10.70	SC											
	10.70-10.90	SC	12.70	2.10	0.37		100	75	45	33	0.29	2.63	
	10.90-11.20	SC											
	12.00-12.45	SC											
	13.50-13.67	SC											
	15.00-15.13	SC											
	16.50-16.55	SC											No Recovery
	18.00-18.10	SM											
	19.50-19.50	Granite											

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### Results of Hydraulic Testing

Name	Easting UTM - meters	Northing	Land Surface Elevation (meters)	Total Depth (meters)	Screen Interval(meters)		Hydraulic Conductivity (meters/day)
					Top	Bottom	
<b>Pattaya Landfill Site</b>							
<b>1. Aquifer Pump Test</b>							
MW1	708764	1425082	-4.70	5.00	-6.70	-9.70	0.447
MW2	708927.5	1424804	-10.98	7.00	-14.98	-17.98	0.788
MW3	708996.8	1424841	-11.83	14.00	-20.33	-21.33	0.014
MW4	709002	1424909	-10.16	6.60	-13.76	-16.76	1.455
Average							0.676
<b>2. Permeability Test</b>							
BH-3			-10.68	2.03	-12.18	-12.71	0.1160
BH-3			-10.68	6.20	-16.38	-16.88	0.0001
BH-3			-10.68	10.20	-20.38	-20.88	0.0020
BH-3			-10.68	13.20	-23.18	-23.88	0.0097

**Summary of Groundwater Monitoring Data for the Pattaya Landfill site**

Name	Easting Northing UTM - meters		Land Surface Elevation (meters)	Top of Casing Elevation (meters)	Screen Interval(meters) <sup>1</sup>		Depth to Water Reading (meters BLS) <sup>2</sup>	Groundwater Elevation (meters)	Date of Reading
					Top	Bottom			
<i>Monitoring well/Piezometer.</i>									
MW1	708764	1425082	-4.7	-3.77	-6.7	-9.7	-2.2	-5.98	01-Jul-99
MW2	708988	1424864	-10.98	-10.13	-14.98	-17.998	-3.72	-13.85	01-Jul-99
MW3	708997	1424841	-11.83	-10.98	-20.33	-21.33	-3.74	-14.72	01-Jul-99
MW4	709002	1424909	-10.16	-9.29	-13.76	-16.76	-4.5	-13.787	01-Jul-99
PZ1	708808	1424839	-9.26	-8.47	-19.76	-20.76	-3.17	-11.61	11-Jun-99
PZ2	709219	1424933	-14.43	-13.47	-26.97	-27.97	-5.65	-19.12	11-Jun-99
Leachate	708969	1424933	-5.9	-4.7	NA	NA	-2.6	-7.3	01-Jul-99
W1(W)	708415	1424849	-4.19	NA	NA	NA	NA	-12.07	01-May-99
W2(S)	709049	1424819	-12.56	NA	NA	NA	NA	-17.64	01-May-99
W3(SE)	709376	1424629	-21.36	NA	NA	NA	-1.96	-22.69	01-Jul-99

Name	Easting UTM - meters	Northing	Land Surface Elevation (meters)	Top of Casing Elevation (meters)	Screen Interval(meters) <sup>1</sup>		Depth to Water Reading (meters BLS) <sup>2</sup>	Groundwater Elevation (meters)	Date of Reading
					Top	Bottom			
W4(S) <i>Soil Boring</i>	709059	1424470	-21.49	NA	NA	NA	-2.9	-23.89	01-Jul-99
BH-1			-10.68	NA	NA	NA	NA		29-Apr-99
BH-2			-5.85	NA	NA	NA	NA		29-Apr-99
BH-2/1			-5.9	NA	NA	NA	NA		29-Apr-99
BH-3			-10.68	NA	NA	NA	-1.56	-12.24	01-Apr-99
BH-17/1			-9.87	NA	NA	NA	-2.2	-12.07	24-Nov-98
BH-17/2			-6.6	NA	NA	NA	-1	-7.6	24-Nov-98

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### 3. PATTAYA MUNICIPALITY LANDFILL INFORMATION

Information of disposal site ranking, method of analysis and preservatives of water sample and groundwater and leachate quality (Pollution Control Department, 1999)

#### Summary of Total Scored for Disposal Site Ranking

Municipality Disposal Site	Risk Factor				Total
	Surface Water	Ground- water	Socio- Economic	Waste Quantity & Disposal Procedure	
<b>1. North East</b>					
<b>1) Ubon Ratchathani M.</b>	<b>29</b>	<b>61</b>	<b>53</b>	<b>56</b>	<b>199</b>
<b>2) Khonkhen M.</b>	<b>15</b>	<b>59</b>	<b>34</b>	<b>56</b>	<b>164</b>
3) Chaiyaphum M.	21	46	38	53	<b>158</b>
4) Udon Thani M.	14	50	38	47	<b>149</b>
5) Nakhon Ratchathani M.	5	55	39	47	<b>146</b>
6) Nong Khai M.	5	45	47	46	<b>143</b>
7) Banphai M.	5	50	40	40	<b>135</b>
8) Pak Chong M.	6	54	23	40	<b>123</b>
9) Chum Phea M.	34	32	30	25	<b>121</b>
10) Muangphol M.	5	18	7	22	<b>52</b>
<b>2. East</b>					
<b>1) Muang Pattaya</b>	<b>57</b>	<b>64</b>	<b>46</b>	<b>66</b>	<b>233</b>
2) Mabtapud M.	28	64	40	37	<b>169</b>
3) Chonburi M.	20	56	34	49	<b>159</b>
4) Rayong M.	30	57	40	31	<b>158</b>
<b>5) Banbung M.</b>	<b>33</b>	<b>64</b>	<b>29</b>	<b>28</b>	<b>154</b>
6) Phanus Nikhom M.	32	49	30	38	<b>149</b>
7) Muang Klaeng M.	22	62	25	24	<b>133</b>
8) Sansuk M.	5	50	25	43	<b>123</b>
9) Sriracha M.	7	55	25	19	<b>106</b>
10) Laem Chabang M.	24	24	3	24	<b>75</b>

Note : M. = Municipality

### Method of Analysis and Preservatives of Water

Parameter	Method of Analysis	Container	Preservative
<b>A. Field Test</b>			
Static Water			
1. Level	Water Level Meter	-	-
2. pH	Water Quality Checker	Polyethylene 1000 ml.	Cooling at 4 °C
3. Temperature	Water Quality Checker	-	-
4. Conductivity	Water Quality Checker	Polyethylene 1000 ml.	Cooling at 4 °C
5. Salinity	Water Quality Checker	Polyethylene 1000 ml.	Cooling at 4 °C
6. Turbidity	Water Quality Checker	Polyethylene 1000 ml.	Cooling at 4 °C
7. Appearance	Visual Inspection	-	-
<b>B. Laboratory Test</b>			
1. Acidity	Titrimetric Method	Polyethylene 1000 ml.	Cooling at 4 °C
2. Alkalinity	Titrimetric Method	Polyethylene 1000 ml.	Cooling at 4 °C
3. Color	Nessler Tube	Polyethylene 1000 ml.	Cooling at 4 °C
4. Chloride	Argentometric	Polyethylene 1000 ml.	Cooling at 4 °C
5. Sulfide	Iodometric	Polyethylene 1000 ml.	2N Zinc Acetate & 6 N NaOH until pH > 9
6. Total Solids	Gravimetric	Polyethylene 1000 ml.	Cooling at 4 °C
7. Total Dissolved Solids	Filtration & Gravimetric	Polyethylene 1000 ml.	Cooling at 4 °C
8. DO	Azide modification	BOD Bottle 300 ml.	MnSO <sub>4</sub> , AIA & H <sub>2</sub> SO <sub>4</sub>
9. COD	Dichromate Reflux	Polyethylene 1000 ml.	H <sub>2</sub> SO <sub>4</sub> until pH < 2
10. BOD	Incubation & Azide modification	Polyethylene 1000 ml.	Cooling at 4 °C
11. TOC	Combustion-Infared	Polyethylene 1000 ml.	Cooling at 4 °C



**Method of Analysis and Preservatives of Water (cont.)**

<b>Parameter</b>	<b>Method of Analysis</b>	<b>Container</b>	<b>Preservative</b>
12. Sulfate	Turbidimetric Method	Polyethylene 1000 ml.	Cooling at 4 °C
13. Total Hardness	Titrimetric Method	Polyethylene 1000 ml.	Cooling at 4 °C
14. NO <sub>3</sub> -N	Cadmium Reduction	Polyethylene 1000 ml.	Cooling at 4 °C
15. NH <sub>3</sub> -N	Distillation & Titration	Polyethylene 1000 ml.	H <sub>2</sub> SO <sub>4</sub> until pH < 2
16. Mn	Atomic Absorption	Polyethylene 1000 ml.	HNO <sub>3</sub> until pH < 2
17. Fe	Atomic Absorption	Polyethylene 1000 ml.	HNO <sub>3</sub> until pH < 2
18. Hg, Pb, Cd, Ni, Total Cr, Cr <sup>+6</sup>	Atomic Absorption	Polyethylene 1000 ml.	HNO <sub>3</sub> until pH < 2
19. VOCs	Gas Chromatography/ Mass Spectrometry	Amber Bottle 1000 ml.	Cooling at 4 °C

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### Water Quality Analysis at Pattaya Disposal Site

Parameter	Unit	Sample								Standards	
		MW1	MW2	MW3	MW4	GW1	GW2	GW3	SW1	Groundwater *	Surface Water **
<i>Field Test</i>											
1 Static water level	m	-5.98	-13.85	-14.72	-13.79	-	-	-	-	-	-
2 pH	-	6.2	7.4	6.0	7.3	5.2	4.7	5.3	5.8	6.5-9.2	5.0-9.0
3 Conductivity	mmho/cm	0.5	15	1.9	12	0.9	0.1	4.3	3.5	-	-
4 Turbidity	NTU	20	91	16	214	10	10	10	10	20	-
5 Temperature	°C	30.1	32.3	30.8	32.1	29.8	30.9	30.5	30.2	-	natural
6 Salinity	PPT	0.2	8.7	0.9	6.9	0.3	0.0	2.1	1.7	-	-
7 Appearance	-	slightly turbid	pale yellow	slightly turbid	yellowish	clear	clear	clear	clear	-	-
<i>Lab Analysis</i>											
1 Color	Color unit	20	2,500	30	1,000	20	20	70	-	15	natural
2 Acidity	mg/l	12	549	147	204	9	4	13	-	-	-
3 Alkalinity	mg/l	307	5,150	307	4,300	148	11	233	37	-	-

**Water Quality Analysis at Pattaya Disposal Site**

Parameter	Unit	Sample								Standards	
		MW1	MW2	MW3	MW4	GW1	GW2	GW3	SW1	Groundwater *	Surface Water **
4 TS	mg/l	1,320	6,950	1,460	5,280	691	170	3,190		1,200	-
5 TDS	mg/l	266	4,740	1,390	4,350	688	169	3,188		-	-
6 Chloride	mg/l	52	1,760	330	1,370	225	10	825	1,000	600	-
7 DO	mg/l								3.3	-	≥4
8 BOD	mg/l								2	-	≤2
9 COD	mg/l								64	-	-
10 TOC	mg/l	0.50	1.38	9.20	1.15					-	-
11 Total hardness	mg/l					170	27	670		500	-
12 Sulfate	mg/l					7.0	<0.01	76		250	-
13 Sulfide	mg/l	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	-	-
14 Mn	mg/l	0.53	0.15	1.25	1.08	0.26	0.02	0.38	1.29	0.5	≤1.0
15 NH <sub>3</sub> -N	mg/l	<0.005	378	8.2	486	0.13	0.13	21	0.94	-	≤0.5

## Water Quality Analysis at Pattaya Disposal Site (cont.)

Parameter	Unit	Sample								Standards	
		MW1	MW2	MW3	MW4	GW1	GW2	GW3	SW1	Groundwater *	Surface Water **
16 NO <sub>3</sub> -N	mg/l	0.06	0.05	0.27	0.58	0.12	0.24	0.37	0.09	10	≧5.0
17 Fe	mg/l	72	10	5.27	22.4	0.56	<0.01	<0.01		1.0	-
18 Ni	mg/l	<0.001	0.02	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-	≧0.1
19 Cd	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	≧0.05
20 Pb	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	≧0.05
21 Cr <sup>+6</sup>	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	≧0.05
22 Total Cr	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	-
23 Hg	mg/l	0.002	0.008	0.021	<0.001	<0.001	0.014	0.015	0.008	0.001	≧0.002
24 VOC <sub>s</sub>	mg/l	nil	nil	nil	nil						

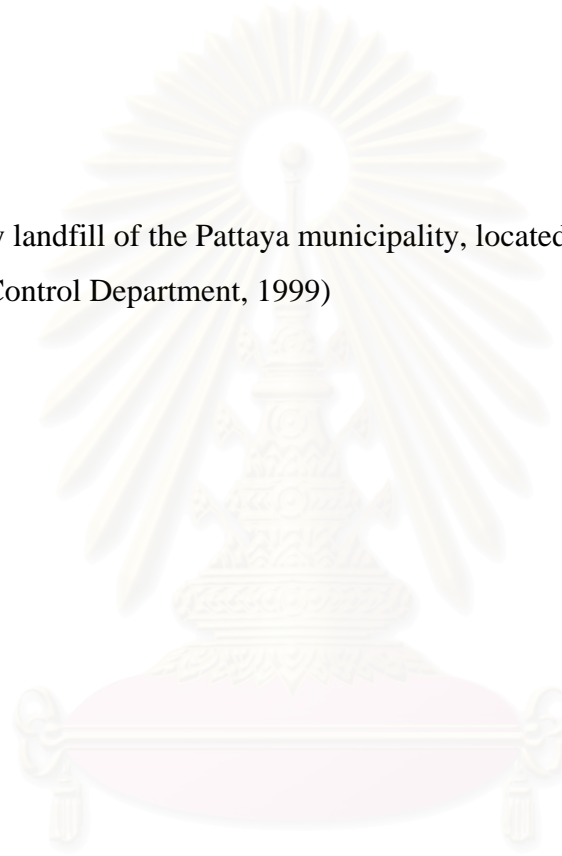
Notes ; MW : Monitoring Wells , GW : Groundwater , SW : Surface water

\* : Maximum allowable limit for drinking purpose

\*\* : For human consumption and agriculturate purpose

#### 4. Observed Groundwater Quality

The observed groundwater quality of the sanitary landfill of the Pattaya municipality, located in Tampon Huai Yai, Amphoe Banglamung, Chonburi province from 1999-2003 (Pollution Control Department, 1999)



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**The observed groundwater quality of the sanitary landfill of the Pattaya municipality at monitoring well 1**

Parameter	Unit	ND	Groundwater Standard	Maximum Permit	2000	2001		2002		2003	
					20-Jun	23-Jan	25-Dec			13-Mar	
Depth	m	-	-	-	-	-	No water in monitoring well	No data observed	No data observed	monitoring well was destroyed due to development of area	
pumping out water	litre	-	-	-	-	-					
temperature	Celsius	-	-	-	30.5	Error					
pH	-	-	-	6.5 - 9.2	7.40	Error					
Conductivity	mS/cm	-	-	-	0.0518	Error					
SO <sub>4</sub> <sup>2-</sup>	mg/l	< 0.5	-	250	7	173					
Cd	microgram/l	< 0.05	< 3	10	ND	ND					
Cr	microgram/l	< 0.15	< 50	-	142	7.4					
Hg	microgram/l	< 0.05	< 1	1	Error	Error					
Mn	microgram/l	< 10	< 500	500	1,600	110					
Ni	microgram/l	< 1.0	< 20	-	69	71					
Pb	microgram/l	< 0.45	<10	50	41	12					

**The observed groundwater quality of the sanitary landfill of the Pattaya municipality at monitoring well 2**

Parameter	Unit	ND	Groundwater Standard	Maximum Permit	2000	2001		2002		2003			
					20-Jun	23-Jan	25-Dec			13-Mar			
Depth	m	-	-	-	-	-	-	-	No water in monitoring well	No data observed	monitoring well was destroyed due to development of area		
pumping out water	litre	-	-	-	-	-	-						
temperature	Celsius	-	-	-	30.4	Error	30.6						
pH	-	-	-	6.5 - 9.2	7.54	Error	7.20						
Conductivity	mS/cm	-	-	-	1.229	Error	1.098						
SO <sub>4</sub> <sup>2-</sup>	mg/l	< 0.5	-	250	8	185	18.6						
Cd	microgram/l	< 0.05	< 3	10	ND	ND	ND						
Cr	microgram/l	< 0.15	< 50	-	19	4.8	11						
Hg	microgram/l	< 0.05	< 1	1	Error	Error	ND						
Mn	microgram/l	< 10	< 500	500	90	1,600	180						
Ni	microgram/l	< 1.0	< 20	-	41	28	52						
Pb	microgram/l	< 0.45	<10	50	15	15	1.4						

**The observed groundwater quality of the sanitary landfill of the Pattaya municipality at monitoring well 3**

Parameter	Unit	ND	Groundwater Standard	Maximum Permit	2000	2001		2002		2003		
					20-Jun	23-Jan	25-Dec			13-Mar		
Depth	m	-	-	-	-	-	-	-	No water in monitoring well	No data observed	-	-
pumping out water	litre	-	-	-	-	-	-	-			-	-
temperature	Celsius	-	-	-	29.0	Error	30.9	29.9			32.2	
pH	-	-	-	6.5 - 9.2	7.08	Error	6.97	6.40			6.36	
Conductivity	mS/cm	-	-	-	0.234	Error	0.243	0.260			Error	
SO <sub>4</sub> <sup>2-</sup>	mg/l	< 0.5	-	250	25	177	24.9	185			25.4	
Cd	microgram/l	< 0.05	< 3	10	0.28	ND	ND	ND			ND	
Cr	microgram/l	< 0.15	< 50	-	7.7	21	2.0	2.0			ND	
Hg	microgram/l	< 0.05	< 1	1	Error	Error	2.2	Error			Error	
Mn	microgram/l	< 10	< 500	500	3,300	4,600	970	953			810	
Ni	microgram/l	< 1.0	< 20	-	42	91	25	28			30	
Pb	microgram/l	< 0.45	<10	50	11	12	3.2	32	7.9			



**The observed groundwater quality of the sanitary landfill of the Pattaya municipality at monitoring well 4**

Parameter	Unit	ND	Groundwater Standard	Maximum Permit	2000	2001		2002		2003	
					20-Jun	23-Jan	25-Dec			13-Mar	
Depth	m	-	-	-	-	-	-			-	-
pumping out water	litre	-	-	-	-	-	-			-	-
temperature	Celsius	-	-	-	30.7	Error	30.7	No data observed	No data observed	30.7	32.5
pH	-	-	-	6.5 - 9.2	7.56	Error	7.29			7.54	7.50
Conductivity	mS/cm	-	-	-	0.76	Error	1.178			0.972	Error
SO <sub>4</sub> <sup>2-</sup>	mg/l	< 0.5	-	250	56	34	6.59			260	91.4
Cd	microgram/l	< 0.05	< 3	10	ND	0.79	0.18			ND	ND
Cr	microgram/l	< 0.15	< 50	-	40	418	40			72	30
Hg	microgram/l	< 0.05	< 1	1	Error	Error	ND			Error	Error
Mn	microgram/l	< 10	< 500	500	5,800	11,000	9,200			27,498	7,400
Ni	microgram/l	< 1.0	< 20	-	43	282	106			71	105
Pb	microgram/l	< 0.45	<10	50	43	199	37			267	106



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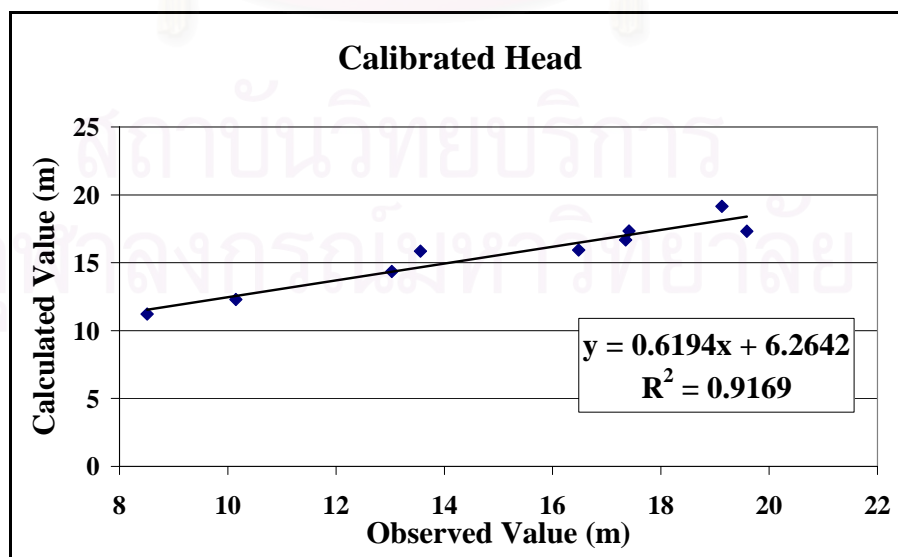
## APPENDIX E

**STATISTICAL ANALYSIS AND  
REMEDATION STUDY CALCULATION RESULT**

The data and result of statistical analysis of Head at Head Observation Wells

Well Name	Observation value.	Calculated Value.	Calc.-Obs.	(Calc.- Obs.) <sup>2</sup>
MW2	17.35	16.67	-0.68	0.46
MW3	16.48	15.94	-0.54	0.29
MW4	17.41	17.35	-0.06	0.00
PZ1	19.59	17.32	-2.27	5.17
PZ2	13.03	14.36	1.33	1.77
Shallow1	19.13	19.14	0.01	0.00
Shallow2	13.56	15.85	2.29	5.23
Shallow3	8.51	11.21	2.70	7.32
Shallow4	10.15	12.29	2.14	4.58
<b>Sum</b>				24.82
<b>Sum/N</b>				2.76
<b>RMSE</b>				1.66

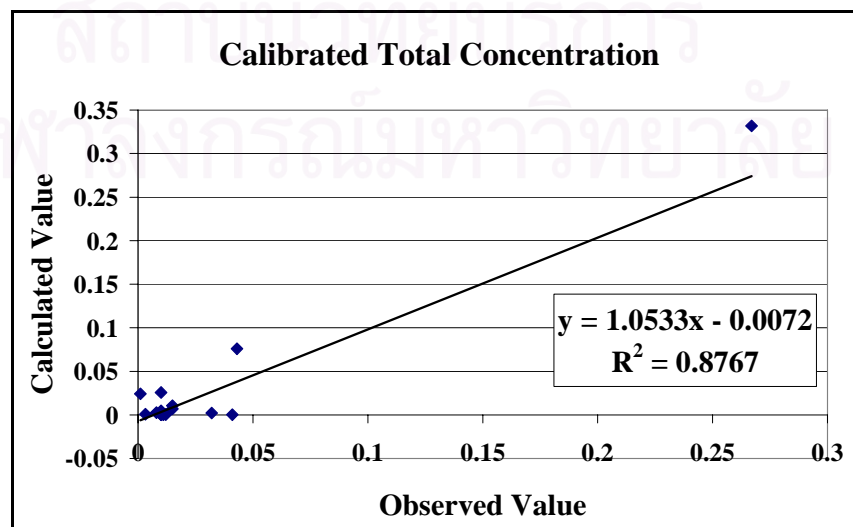
The Correlation and  $R^2$  between the calculated and observed Head of the Study Area



The data and result of statistical analysis of Concentration at Observation Wells

Well/Point Name	Times	Observation value.	Calculated Value.	Calc.- Obs.	(Calc.- Obs.) <sup>2</sup>
PTmw1/mw1	4745	0.010	0.000	-0.010	0.0001
PTmw2/mw2	4745	0.010	0.005	-0.005	0.0000
PTmw3/mw3	4745	0.010	0.000	-0.010	0.0001
PTmw4/mw4	4745	0.010	0.026	0.016	0.0002
PTmw1/mw1	5099	0.041	0.000	-0.041	0.0017
PTmw2/mw2	5099	0.015	0.007	-0.008	0.0001
PTmw3/mw3	5099	0.011	0.000	-0.011	0.0001
PTmw4/mw4	5099	0.043	0.076	0.033	0.0011
PTmw1/mw1	5316	0.012	0.000	-0.012	0.0001
PTmw2/mw2	5316	0.015	0.011	-0.004	0.0000
PTmw3/mw3	5316	0.012	0.000	-0.012	0.0001
PTmw4/mw4	5316	0.199	0.128	-0.071	0.0051
PTmw2/mw2	5652	0.001	0.024	0.023	0.0005
PTmw3/mw3	5652	0.003	0.001	-0.002	0.0000
PTmw4/mw4	5652	-	-	0.187	-
PTmw3/mw3	6095	0.032	0.002	-0.030	0.0009
PTmw4/mw4	6095	0.267	0.332	0.065	0.0042
PTmw3/mw3	6207	0.008	0.002	-0.006	0.0000
PTmw4/mw4	6207	-	-	0.245	-
<b>Sum</b>					0.0144
<b>Sum/N</b>					0.0008
<b>RMSE</b>					0.0291

The Correlation and  $R^2$  between the simulated and observed total lead concentrations of the study area



## Calculation of Pump & Treat System remediation

Equations for the dividing streamlines that separate the capture zone of a single well from the rest of an isotropic, confined aquifer with a uniform regional hydraulic gradient are given in (USEPA, 1997):

$$w = Q/2Ti$$

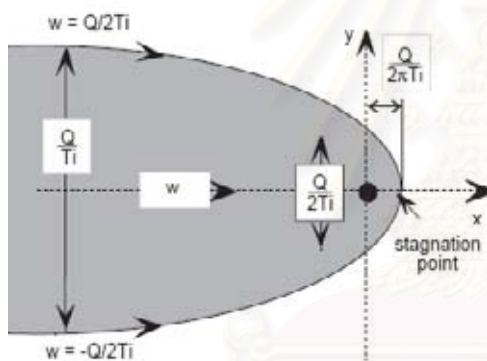
where

$$T = \text{Transmissivity (m}^2\text{/s)}$$

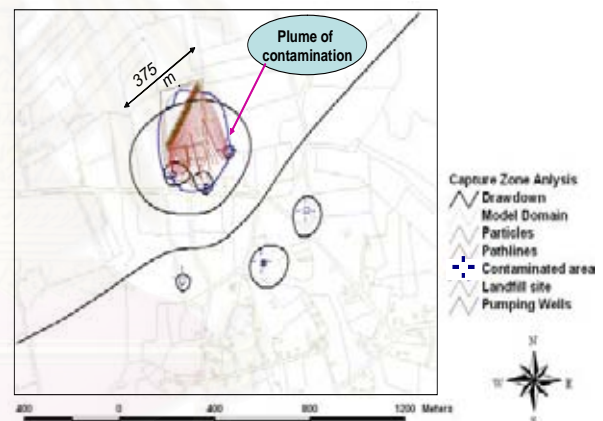
$$= \text{Hydraulic conductivity, K (m/s) * Aquifer thickness, b (m)}$$

$$Q = \text{pumping rate (m}^3\text{/s)}$$

$$i = \text{initial uniform hydraulic gradient}$$



**Figure 1** Capture zone of a single pumping well in a uniform medium



**Figure 2** Area of contamination and drawdown from pumping well

Thus that,

$$\begin{aligned} Q &= 2WTi = 2WKbi \\ &= 2 * 375 \text{ (m)} * 1 \text{ (m/day)} * 8.5 \text{ (m)} * 10.8 * 10^{-3} \\ &= 68.85 \text{ (m}^3\text{/day)} \end{aligned}$$

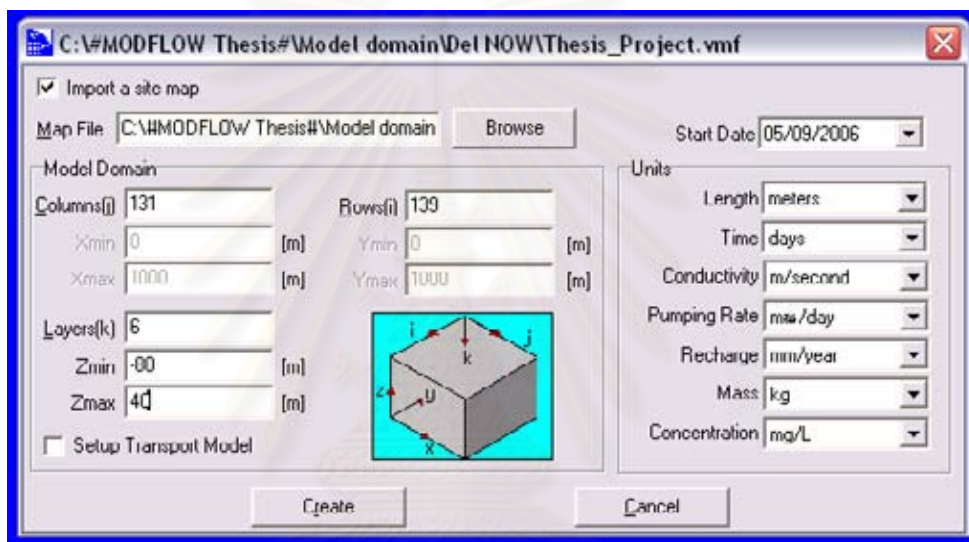
The total pumping rate should not be less than 68.85 m<sup>3</sup>/day. So that, we can design the pumping system by divided pump into 3 stations and each station has pumping rate 25 m<sup>3</sup>/day as shown in the Figure 2.

## APPENDIX F

### VISUAL MODFLOW DATA SETS FOR REAL SCENARIO STUDY AND PREDICTION SIMULATION RESULTS

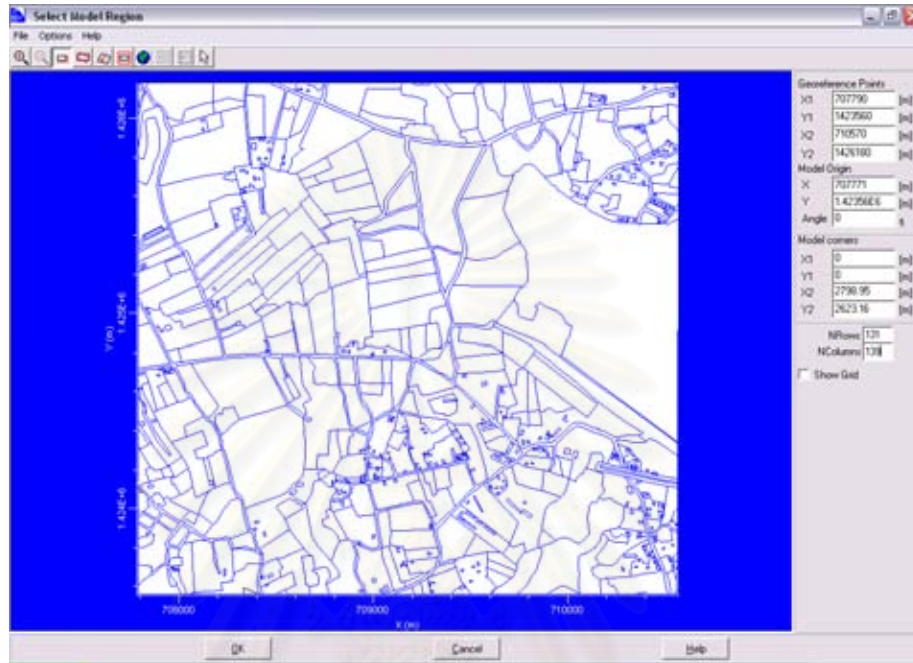
#### Section 1: Generating a New Model

The first module will take you through the steps necessary to generate a new model data set using the Visual MODFLOW modeling environment. Then enter the dimensions of the **Model Domain** and specify the **Units** for the model.



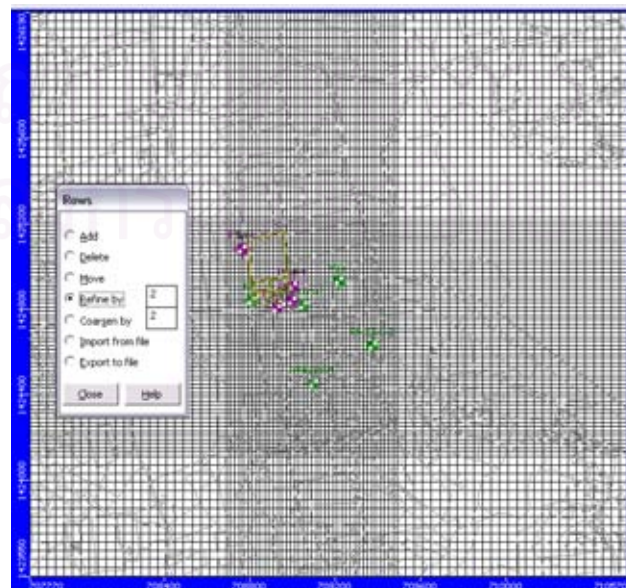
สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

A **Select Model Region** window will appear prompting you to define the extents of the model area. Visual MODFLOW will read the minimum and maximum co-ordinates from the site map (**Sitemap.dxf**) and suggest a default location that is centered in the model domain.



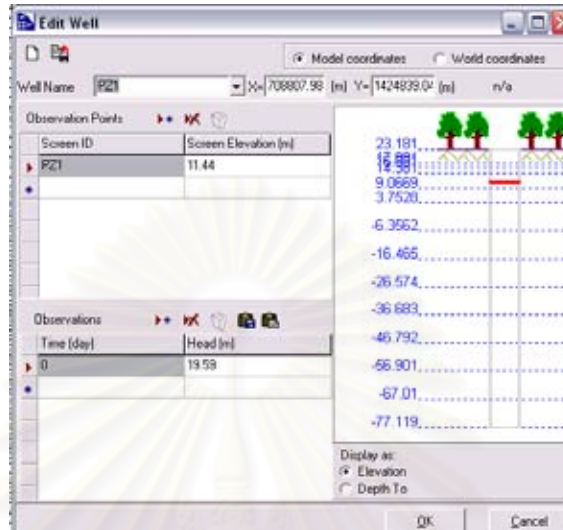
## Section 2: Refining the Model Grid

The **Grid** screen provides a complete assortment of graphical tools for refining the model grid, importing layer surface elevations, optimizing (smoothing) the grid spacing, contouring the layer surface elevations, and delineating inactive grid zones.



### Section 3: Adding Head Observation Wells

The purpose of this section will be to guide you through the steps necessary to assign Head Observation wells to the model.



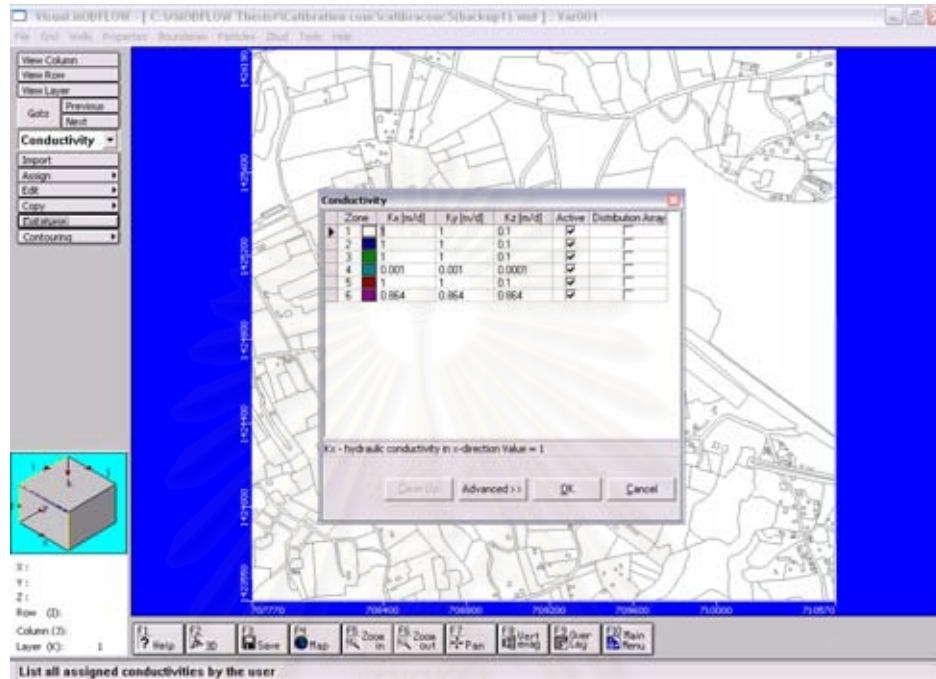
Summary of the observation head (Pollution Control Department, 1999- 2003)

Well Name	UTM E	UTM N	Screen Depth (m)	Observation Head (m) (07/02/1999)
MW1	708764	1425082	24.50	25.22
MW2	708928	1424804	16.22	17.35
MW3	708997	1424841	10.87	16.48
MW4	709002	1424909	17.44	17.41
PZ1	708808	1424839	11.44	19.59
PZ2	709219	1424933	4.23	13.03
Le_well	708969	1424933	20.00	23.90
Shallow1	708415	1424849	15.00	19.13
Shallow2	709049	1424819	10.00	13.56
Shallow3	709376	1424629	8.00	8.51
Shallow4	709097	1424453	12.00	10.15



## Section 4: Assigning Flow Properties

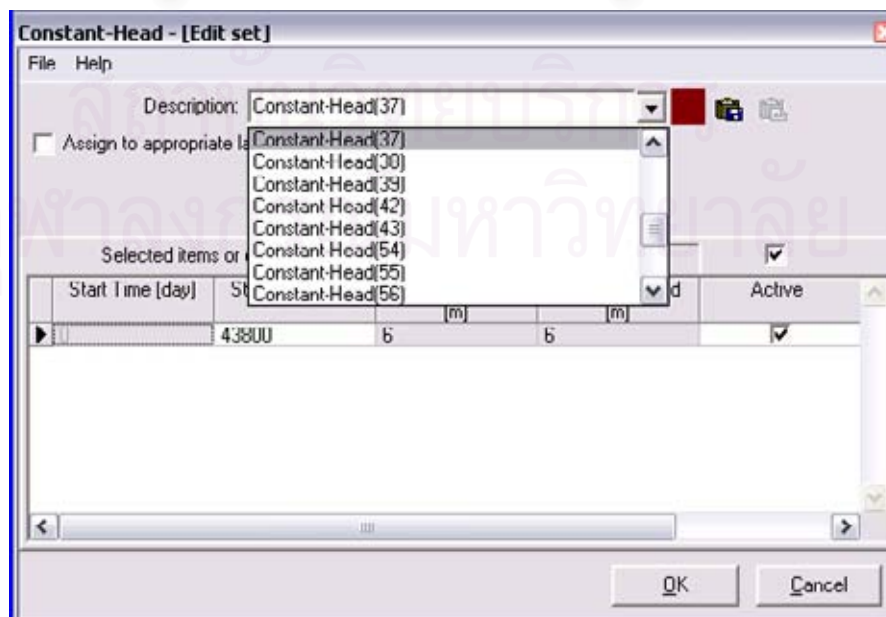
This section will guide you through the steps necessary to design a model with layers of highly contrasting hydraulic conductivities.



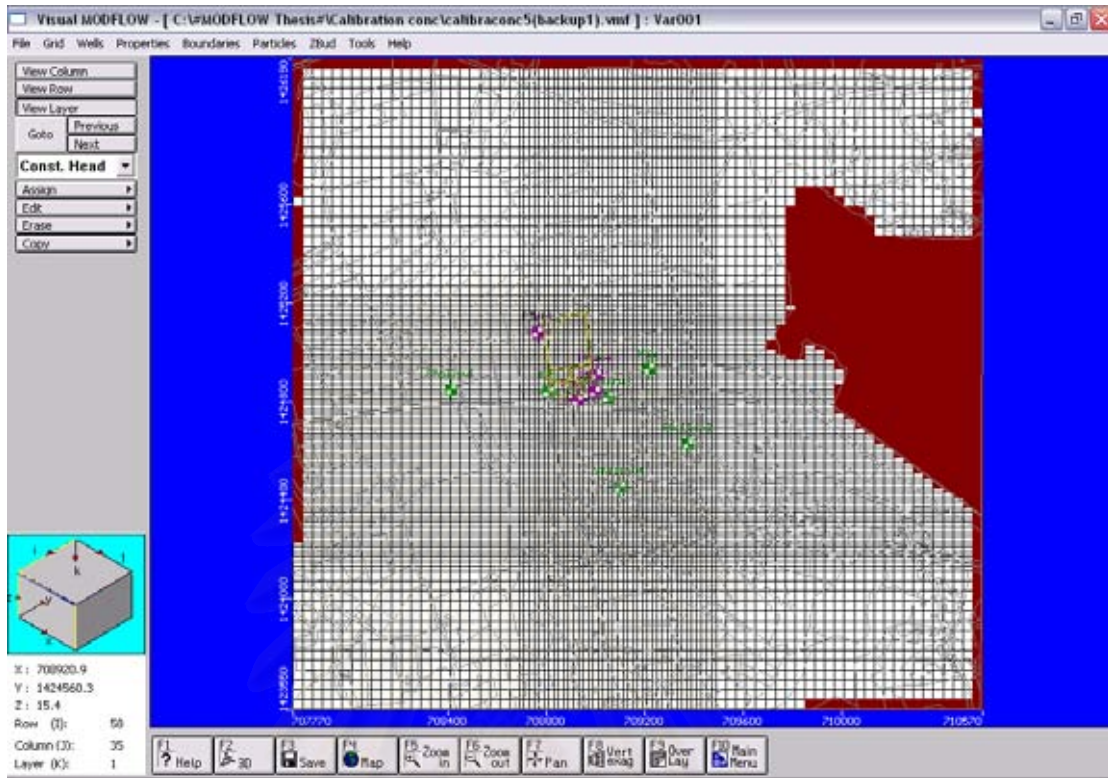
## Section 5: Assigning Flow Boundary Conditions

In Visual MODFLOW the boundary conditions for the groundwater flow and mass transport model are assigned and edited in the **Boundaries** module of the **Input** section.

### Constant Head Boundary:




**Assign Constant Head Boundary around model domain:**



**Recharge Boundary:**

**Edit Recharge**

Property #  

Multiply values by:

Copy schedule from:

Start Time [day]	Stop Time [day]	Recharge [m/d]
<input type="text" value="0"/>	<input type="text" value="43800.00"/>	<input type="text" value="0.00106"/>

### Constant Concentration Boundary:

Start Time (day)	Stop Time (day)	Pb (mg/L)
0	4000	0.01
4000	4300	2
4300	4500	0.01
4500	4600	3
4600	43800	0.01

### Section 6: Setting Up the Transport Model

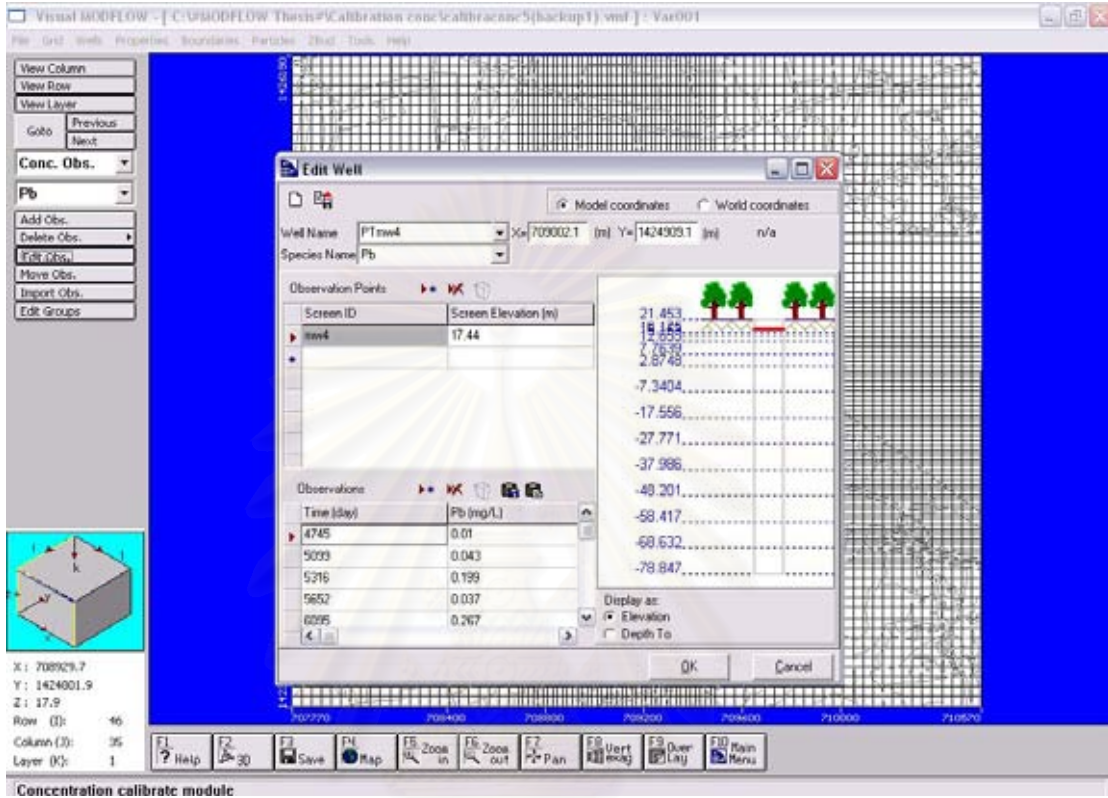
Due to the number of different Mass Transport numeric engines available and the different simulation capabilities associated with each one, Visual MODFLOW stores all of the transport characteristics for a model (e.g. numeric engine, observations, properties, and boundary conditions) in a compressed file called a Transport Variant.

To select the desired Numeric Engine for the Mass Transport model, select **Setup/ Numeric Engines/Transport** from the **Main Menu**. The following **Select Transport Variant** window will appear.

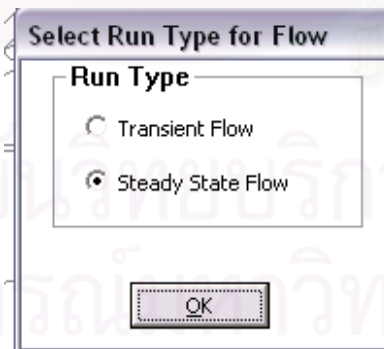
Designation	Component Description	Mobile	SCONC(mg SPE)/mg
Pb	Component 001	yes	0 1E-3

### Section 7: Adding Concentration Observation Wells

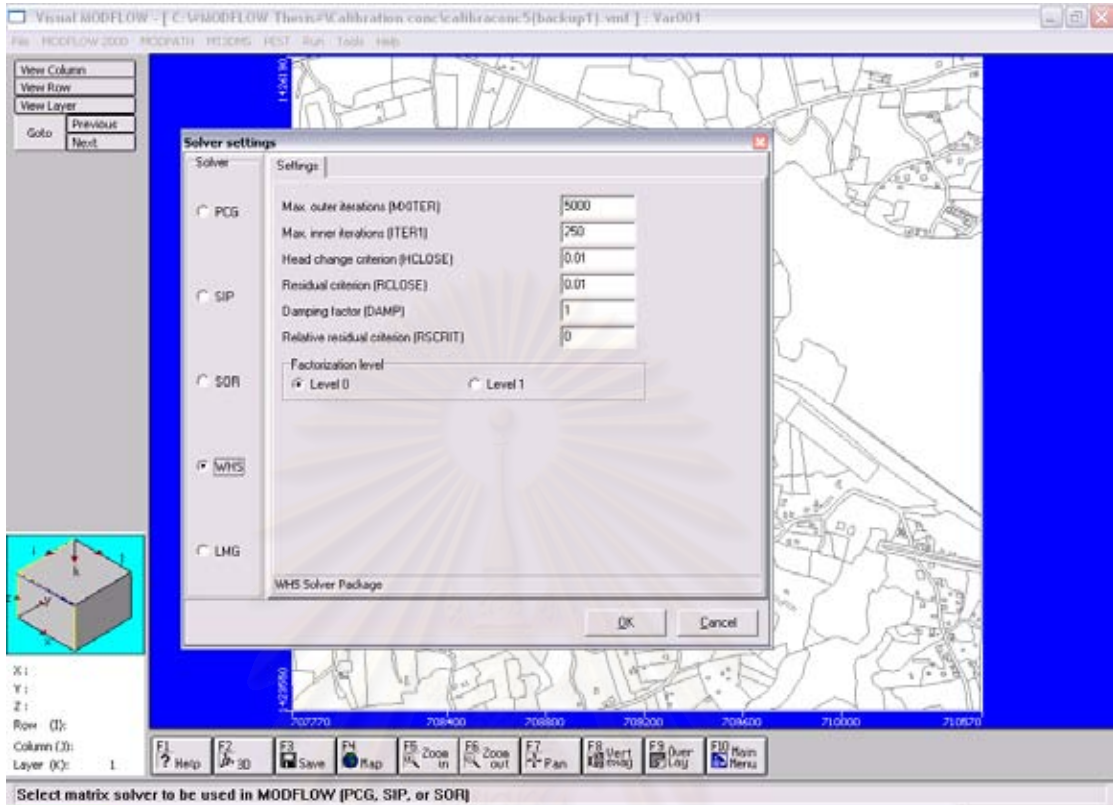
Concentration observation well data can be entered by selecting **Wells/ Conc. Observation Wells** from the top menu bar.



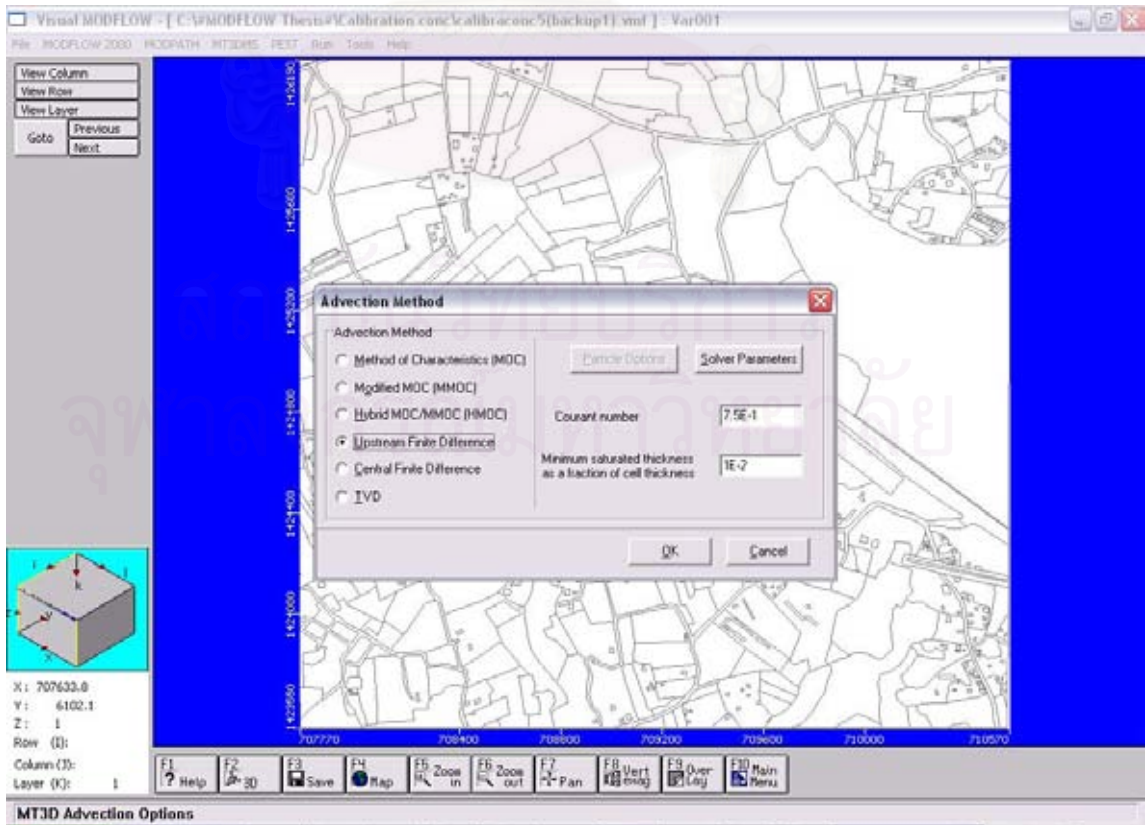
### Section 8: MODFLOW Run Options



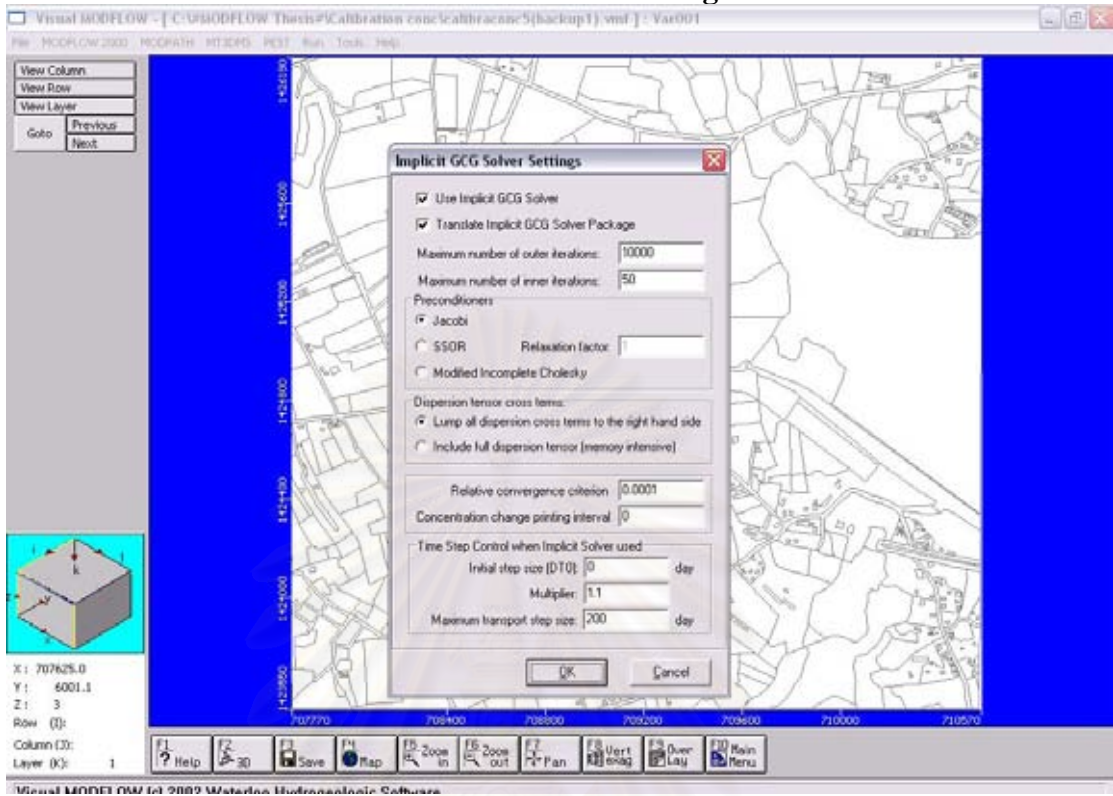
### MODFLOW Solver Options:



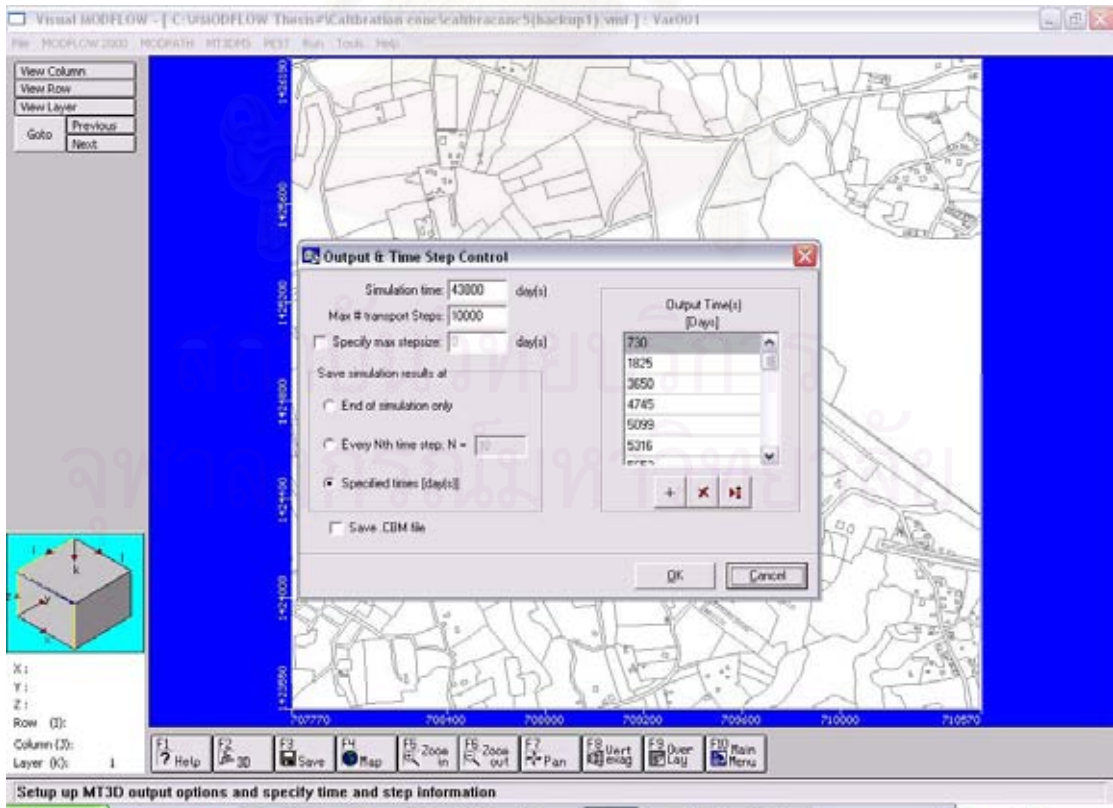
### Section 9: MT3DMS Run Options



**MT3DMS Solver Settings:**

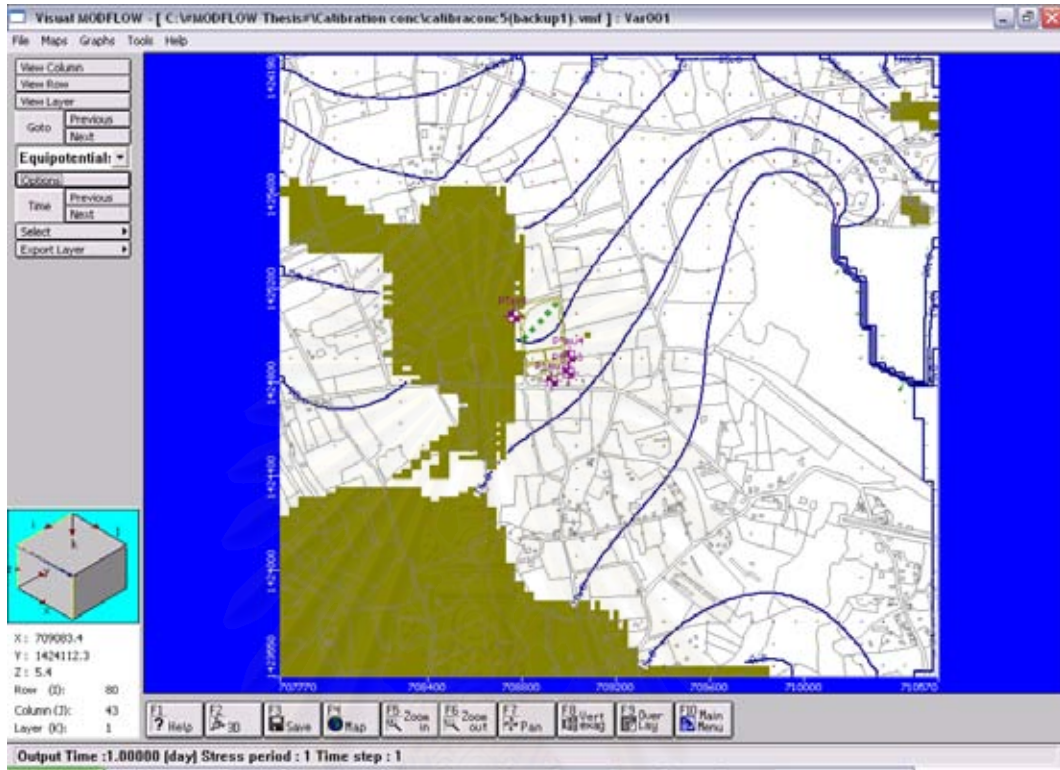


**MT3DMS Output Times:**

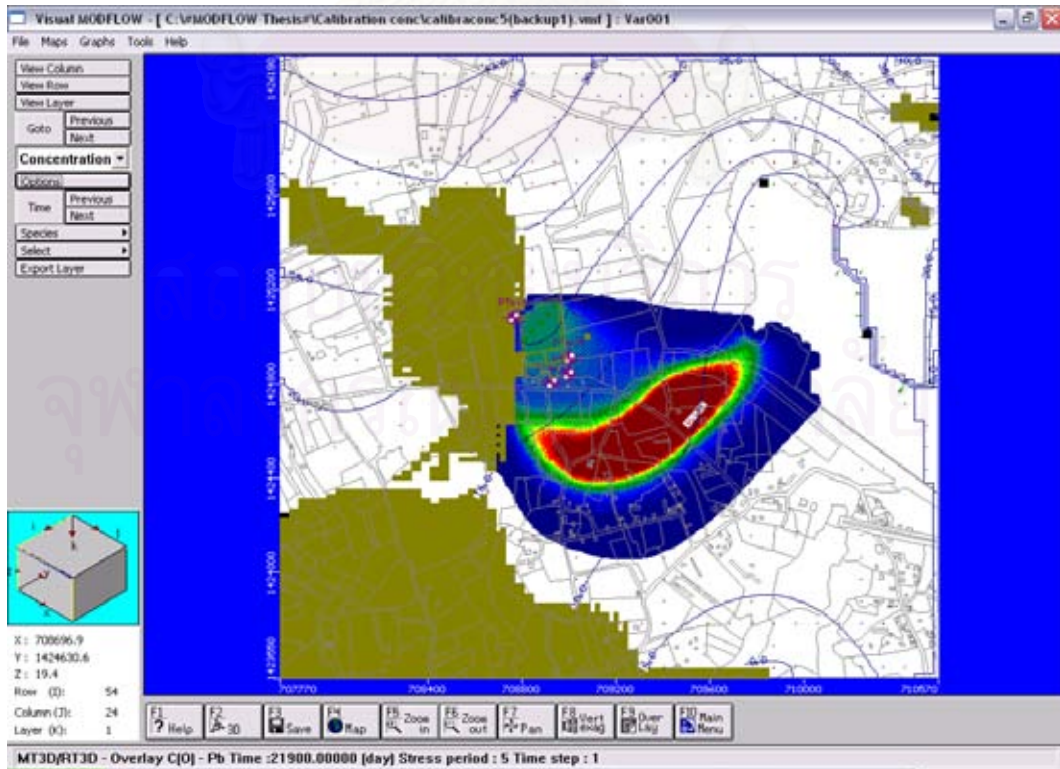


## Output Visualization

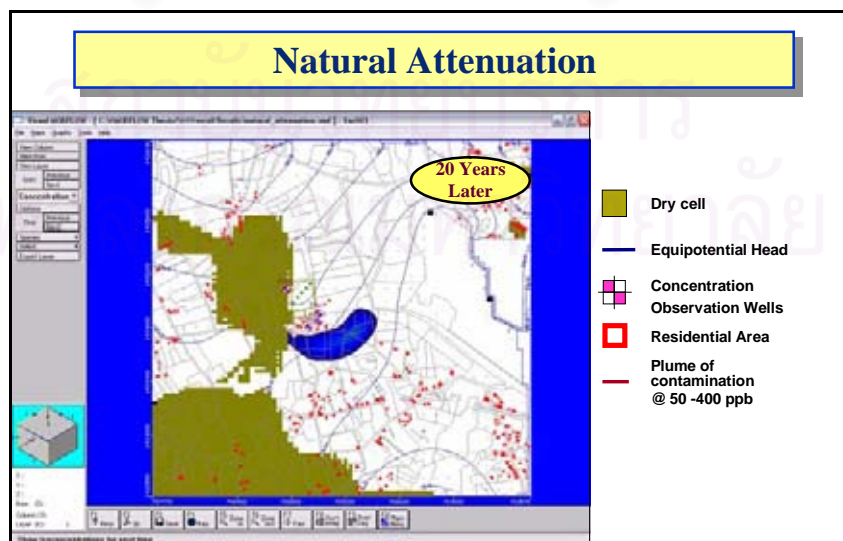
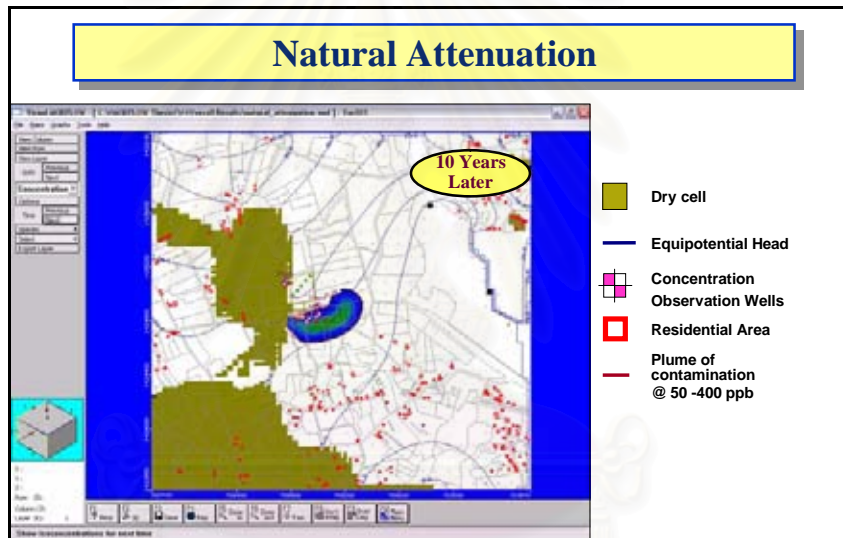
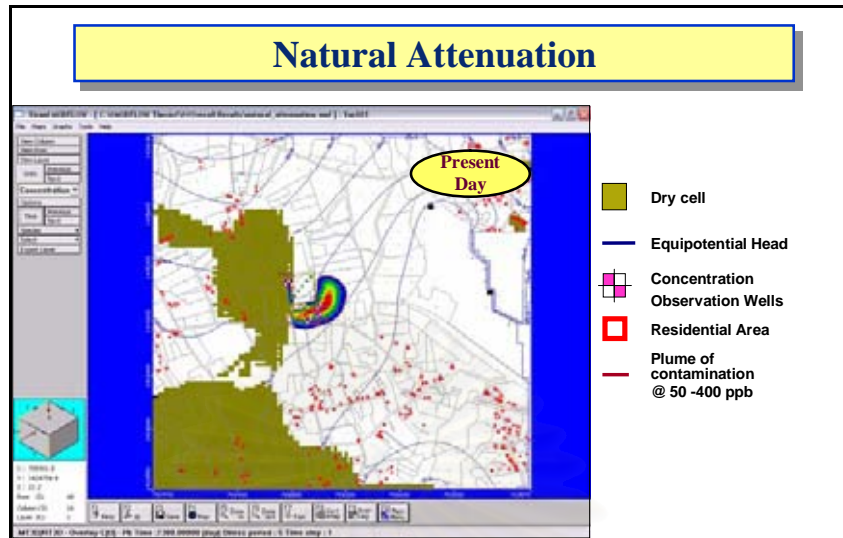
### Section 10: Head Contours



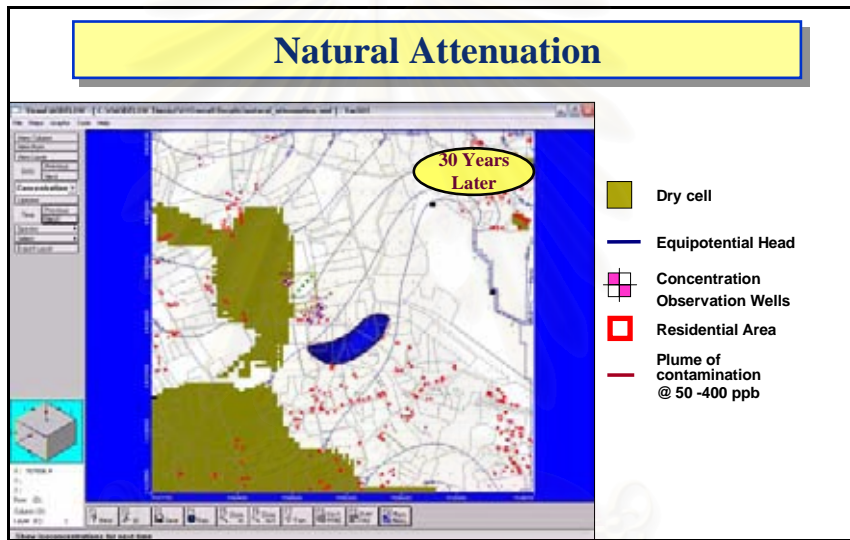
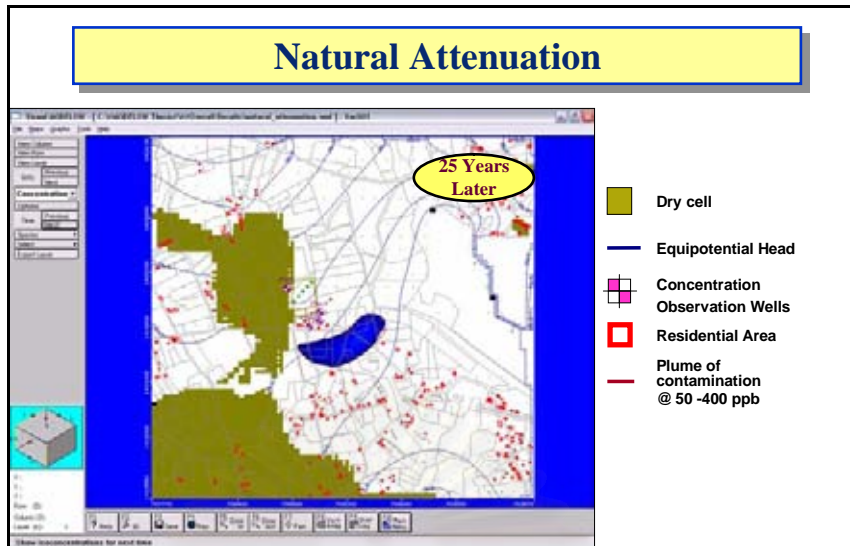
### Section 11: Concentration Contours

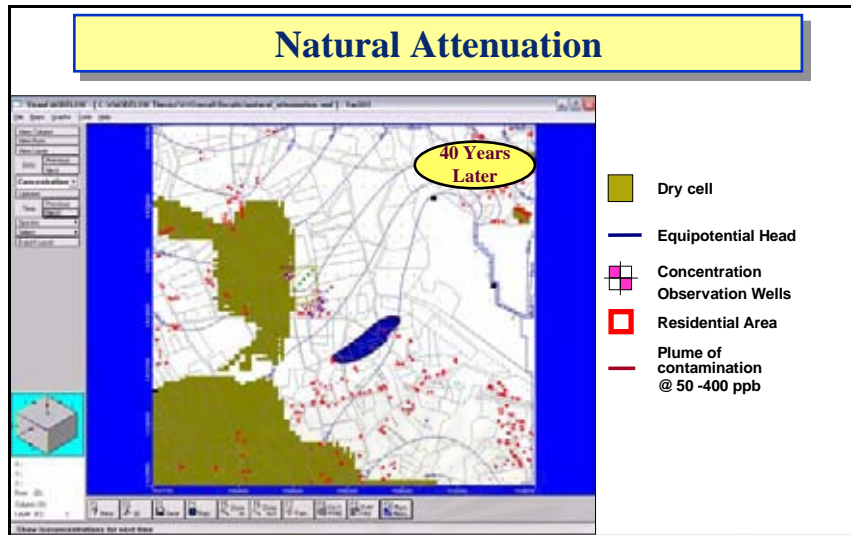


**Result form Natural attenuation remediation**

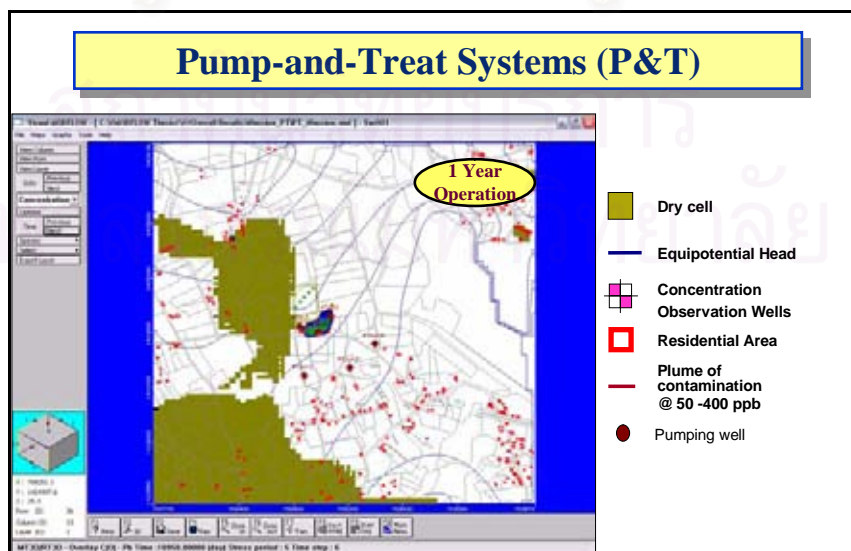
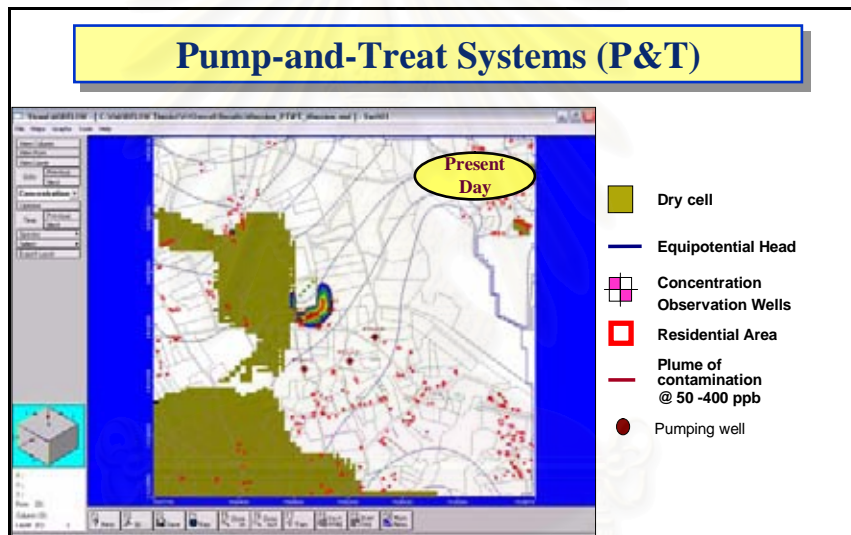


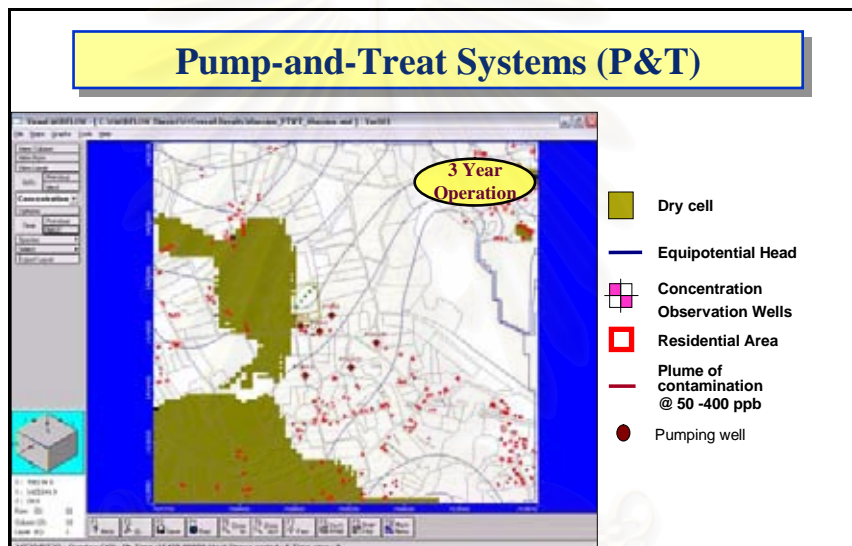
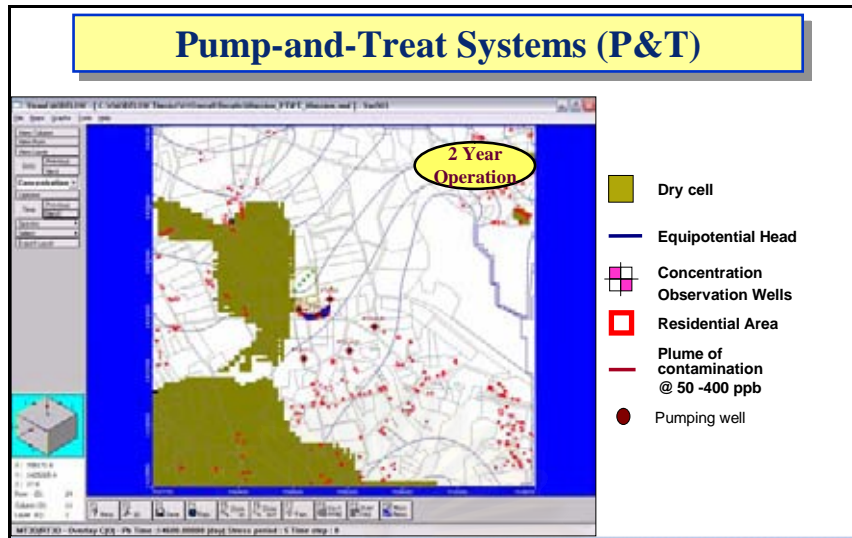




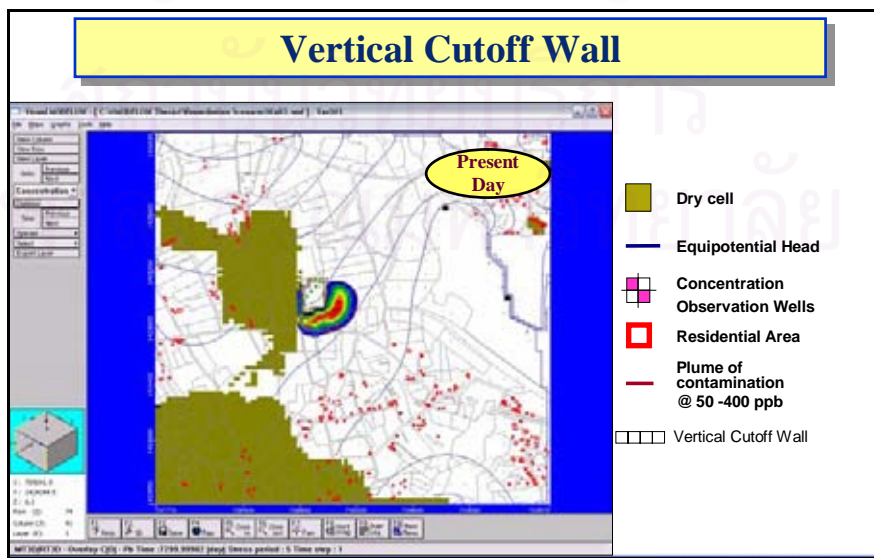


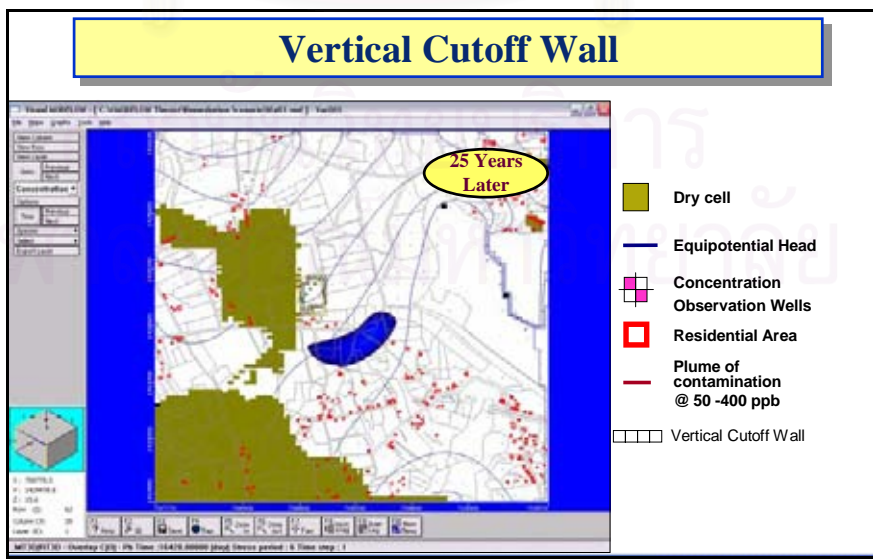
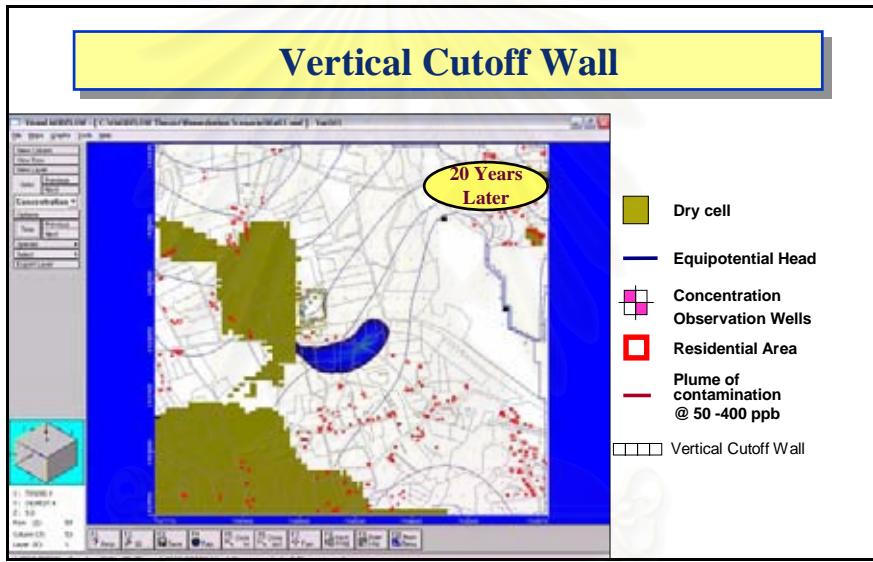
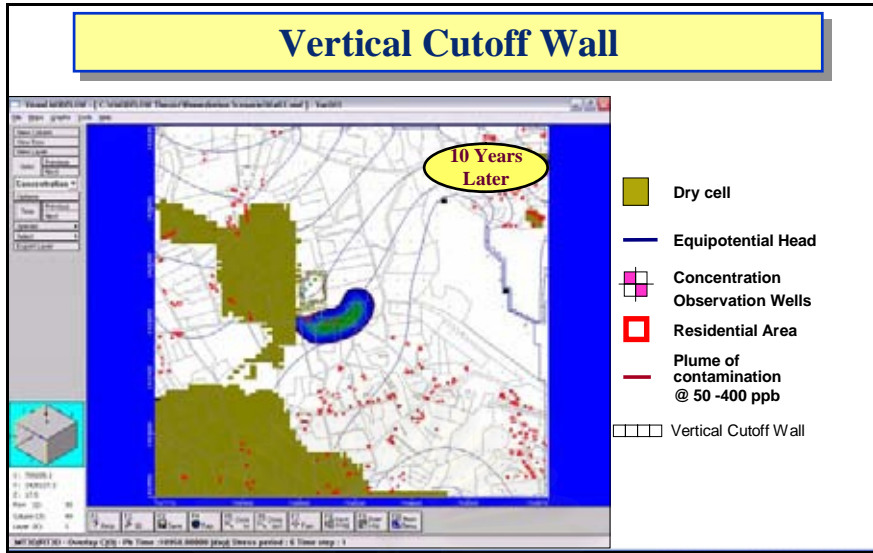
### Result from Pump & Treat System remediation

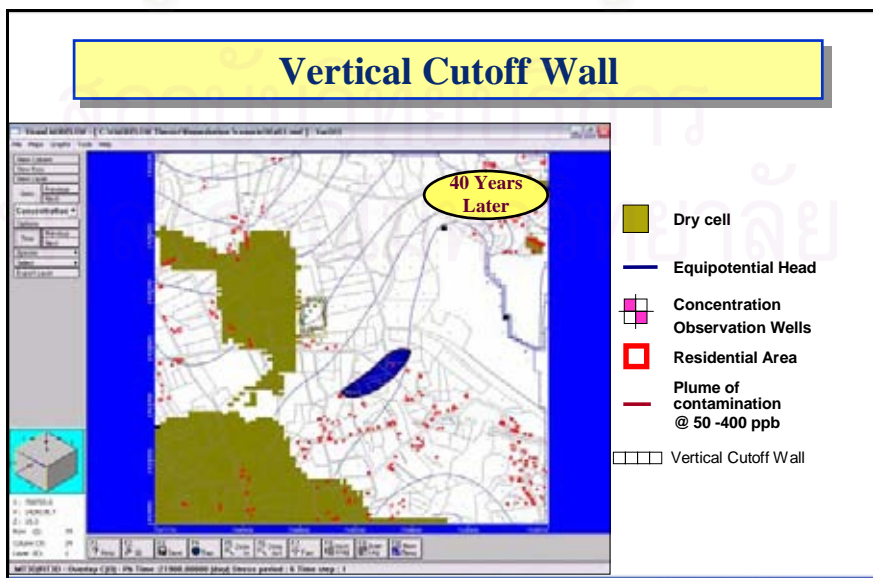
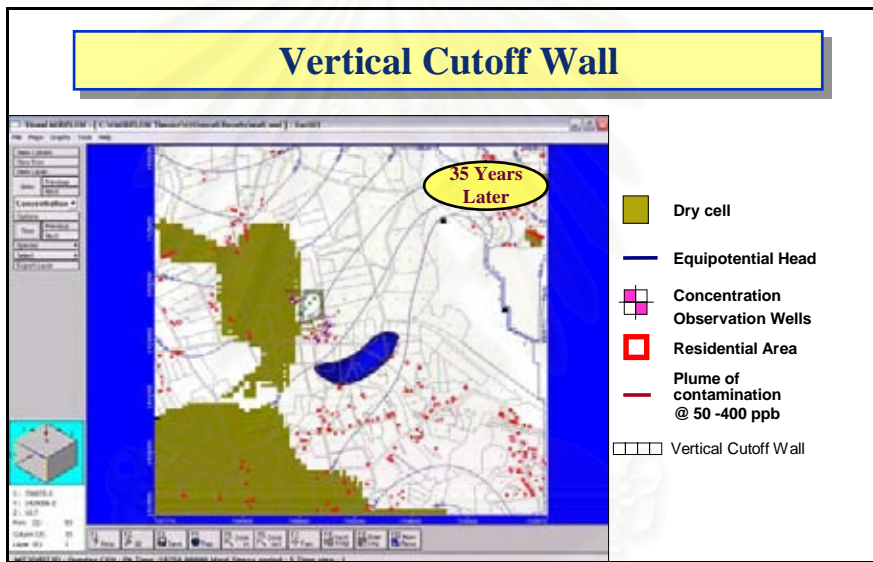
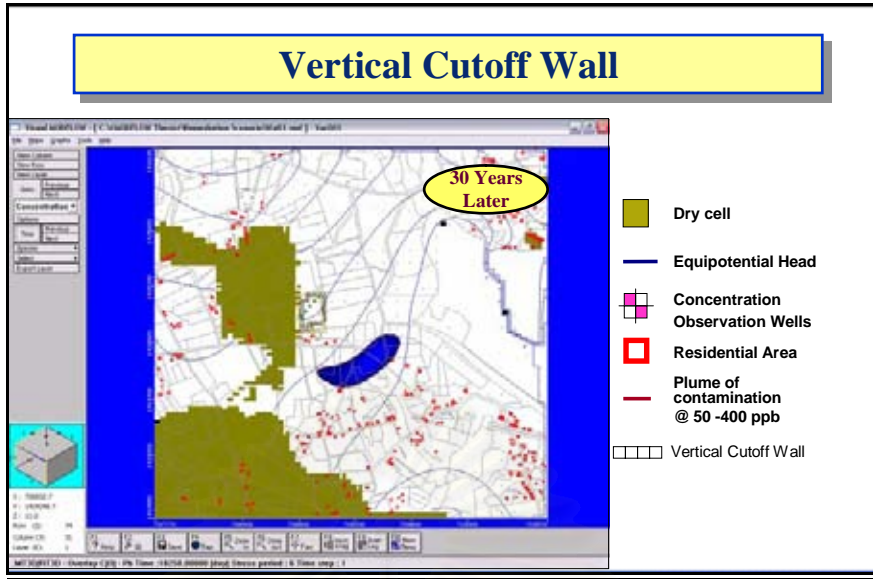




Result from Vertical cutoff wall remediation







## BIOGRAPHY

Mr. Virat Wattanamekhinkul was born on May 10, 1982 in Bangkok, Thailand. He has received her Bachelor Degree of Engineering in Environmental Faculty of Engineering, Chulalongkorn University. He has started her master's degree at the International Postgraduate Programs in Environmental Management, Chulalongkorn University, in May 2004. He has finished her Master's of Science Degree in Environmental Management in Nov 2006.



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