Seminar on Irrigation Technologies for Sustainable Agricultural Development
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“Water Cycle in Rice Growing Floodplain in the Groundwater Recharge Area, Thailand”

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1 Introduction

The central plain of Thailand is the major rice producing area of the country. It is divided into upper and lower central plains. The upper central plain comprises of floodplains of the Ping, Wang, Yom and Nan Rivers flowing from the North and combined to form the Chao Phraya River in Nakhon Sawan province (see river system and land shape in **Fig.1**). Sediments in the upper central plain are mainly alluvium and fluvial deposits resting on the bed rock. Usually, these sediments are intercalated in layers, and some are in lenses. They are found as exposure and underlay younger sediments that slope to deeper groundwater basins in the lower central plain. The large reservoirs have been constructed in the Ping, Wang and Nan Rivers, with an exception of the Yom River. These large reservoirs supply water for agricultural and domestic uses in downstream areas in the dry season and protect people from floods by keeping surplus water in the wet season. Because large reservoirs are not available, the Yom River area frequently suffers from floods, particularly in floodplains without an irrigation system (no flood protection structures). On the other hand, this non-irrigated area often has water shortage problems, particularly in the dry season because the Yom River has a low flow or even no flow in some period. Owing to the unbalance of demand and supply, most farmers in floodplain paddy fields of this non-irrigation area extract groundwater from their own groundwater wells for cultivation all year long. The number of wells has been on the increase during this past decade. Farmers have pumped out such a great amount of water from these wells, resulting in a severe decrease of the groundwater level with no sign of recovery.

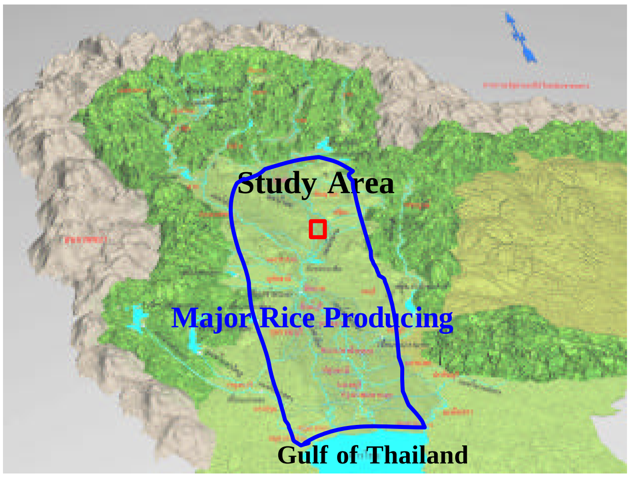


Fig. 1 Location of Study Area and Land shape

In order to utilize water resources in a wise and sustainable manner, the idea to recharge surplus water in the wet season to underground levels is introduced as it helps decrease flood hazards as well as recovering the ground water level. First, it is necessary to study the groundwater balance that requires many continuously collected data. Unfortunately, detail data and study on groundwater cycle of a floodplain in Southeast Asia is not available because lack of observation system and detailed information. In this study, the observation systems and field data were systematically recorded to analyze the groundwater cycle in an area where floods are frequent. The information on water cycles and techniques employed in the study is hoped to be of contribution to groundwater elucidation and planning in general, as it should be applicable to other areas as well as Southeast Asia. It should equip water resource planners with essential knowledge when they are to propose a project for an area with similar characteristics to the study area.

2 Objective and Contents of the Study

The purpose of this study is to conduct a precise study on the underground features to reduce flood hazards and recover a suitable groundwater level by recharging floodwater. Thus, this study will cover the groundwater cycle of unconfined aquifer and the possibility of artificial recharges in the study area with these following outlines:

1) To make a geo-hydrological map of the study area.
2) To study the seasonal change of the shallow groundwater level and the interaction to the environment.
3) To estimate the amount of groundwater extracted for cultivation.
4) To do groundwater flow (GWF) simulation in order to understand the groundwater balance.
5) To estimate the recovery of the groundwater level when the recharge method is introduced.

The data collection, analysis of the groundwater level and influencing factors, groundwater balance simulation, experiment of artificial recharge, recovery of the groundwater level via artificial recharge and discontinuation of water pumping are presented with the following contents:

3 The Study Area and Characteristics

Part of the low land paddy fields in Phichit floodplains, a major recharge area of the upper central plain, was selected as the study area.

The study area is located 350 km north of Bangkok on the west side of the Yom River (**Fig.2**). This area is influenced by floods from the Yom River, with nourishing soil of sedimentation from the river for over a long period, and is thus suitable for agriculture. The study area is approximately 120 km^2 in Pho Prathap Chang District of the Phichit province. The significant characteristics of the study domain, including land use situations, weather conditions, groundwater, water supply situations, floods and runoff flow of the Yom River can be summarized as follows:

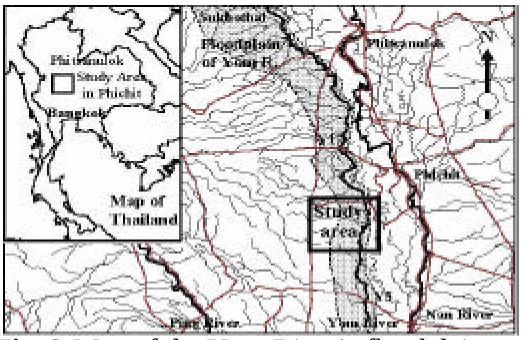


Fig. 2 Map of the Yom River's floodplain and study area

1. The study area is in a groundwater recharge area. The topography consists of floodplains (ground surface slope at less than 1%) and low river terrace (ground surface slope at less than 3%).
2. The climate is tropical and monsoonal, with two seasons: the dry season (from November to April) and the wet season (from May to October). The yearly average precipitation in the study area is 1,389 mm with 80 rain days. The pan evaporation is approximately 1,572 mm/year.

3. The land use in the study area is farmland, most of which are rice fields (see **Fig. 3**). Most rice fields are cultivated twice a year. The cropping intensity (**Fig.4**) is of low value in highlands because of lack of water, but is of high value in lowlands. The values range from 121% to 198%. There are about 900 wells for farm use in this field. 46% of these wells are less than 30m depth, while 54% have well depths between 30 to 80m.
4. The study area does not have an irrigation system; farmers mainly utilize water from the river, irrigation ponds, and groundwater. During the dry season, the Yom River has little or no flow for 2 – 3 months; therefore, during this period farmers cannot use river water for crops at all. Instead, farmers have to turn to groundwater for water supply for their rice fields. As a result, the groundwater level is gradually decreasing.
5. About 56% of the study area is the Yom River floodplain. This is caused by the high drainage capacity in the upper part of the Yom River, and the low drainage capacity of the downstream area. Floods also have great impact on groundwater in the study area.
6. This area is a major recharge area of the upper central plain and the top sand layer is quite close to the ground surface, which makes it suitable for the gravity recharge.

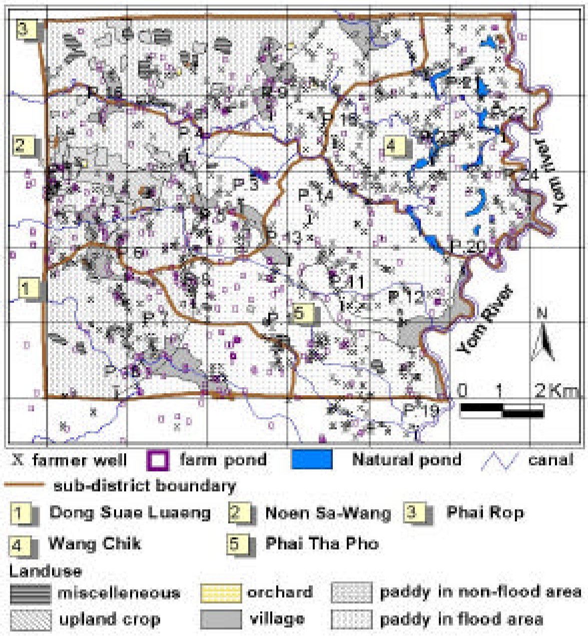


Fig.3 Land use, observation well and farmer well in the study area

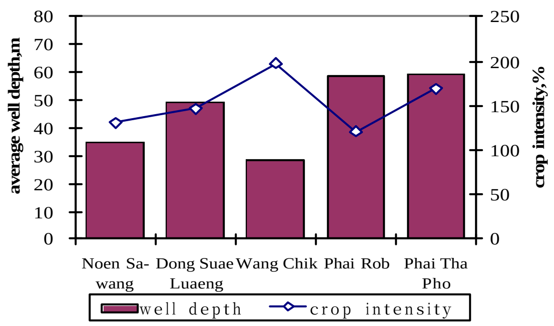


Fig.4 Average well depth and crop intensity in each sub-district

4 Field Observation, Experiments and Results

Many activities were done for this precise study i.e. the installation of the observation system, the hydraulic properties of soil testing, the construction of the recharge system in the field, the interview to farmers and surveys of the flood boundary and the noting of field conditions that influence the groundwater level.

RID and KTU cooperated to install an observation system and conduct pumping tests with details as follows:

- 22 observation wells (running no. from P3 to no.P24) to monitor the groundwater levels of shallow aquifers and 4 observation wells to monitor the groundwater level in deeper aquifers. The sensor and data logger were installed to record automatically the groundwater level with 10-minute intervals, except observation well No.P3 with 5-minute record intervals. In all of observation points, the water levels are manually observed once a week.

- Insight soil properties testing during drilling at observation wells,
- 1 automatic river water level meter with 10-minute record intervals,
- 1 automatic rain gauge with 5-minute record intervals,
- pumping tests at 2 locations.

From the field observations, we found that there are many farm ponds and sandpits scattering in the area. They are deep enough to contact shallow aquifers and may have effect to groundwater level change.**Fig.5** shows the locations of the observation system, farm ponds and sandpits.

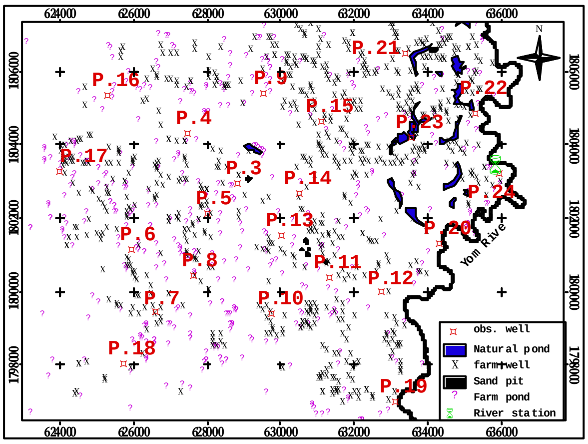


Fig. 5 Location of observation system, farm ponds and sandpits

4.1 Hydrogeology conditions

The hydrogeology condition and soil constructions were summarized based on the boring data of production wells from previous reports, new boring data of observation wells from this study, sediment accumulation analysis, soil properties testing results from both laboratory and field experiments. From the geological cross sectional line in **Fig.6**, the author made the fence diagram soil logs as shown in **Fig.7**. We have learnt that there is a shallow aquifer near the ground surface of the study area which reaches to the depth of 30m, and this aquifer is also near the Yom River and it is divided into two in the western part of the study area.

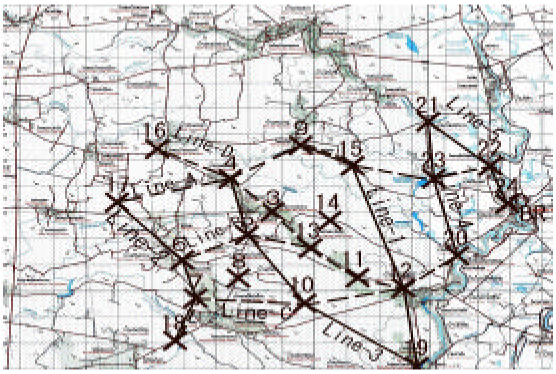


Fig. 6 Geological cross-section line

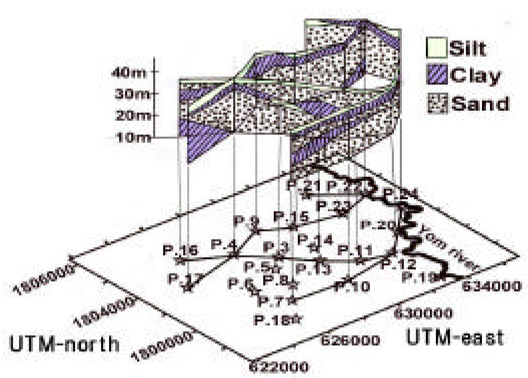


Fig. 7 Soil log constructions in 3-D

The results of the in-situ permeability test at each observation well are shown in **Fig. 8**. The pumping test results from 2 locations in the study area show: transmissibility, T ranging from 12.37 to 19.8 m^2/day; Hydraulic conductivity, K ranging from $1.4x10^{-3}$ to $5.4 x10^{-4}$ cm/s; and storativity, S ranging from 0.001 to 0.20.

4.2 River water level and floods

There is no gauge station of the Yom River water level in the study area, but there is 2 RID staff gauges located nearby. One named Y.17 is located 20 km upstream of the study area and the other named Y.5 is located 20km downstream. The author set a water level meter at the

Phopratabchang Bridge in the study area to observe the Yom River water level (see location in **Fig.5**). The daily river water level data in the study area has been collected continuously since September 2001 to December 2004. **Fig.9** presents the daily rainfall and the river water level at Y.5, Y.17 and at the Bridge. The average bank full elevation in the study area is about 33.4msl.

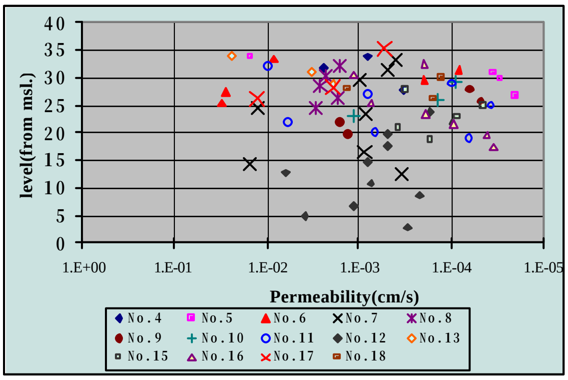


Fig. 8 Results of in-situ permeability testing at observation well points

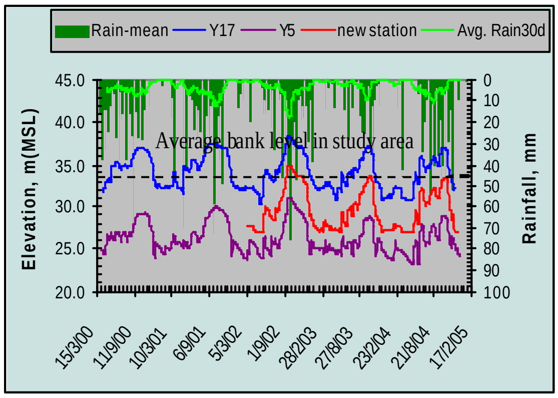
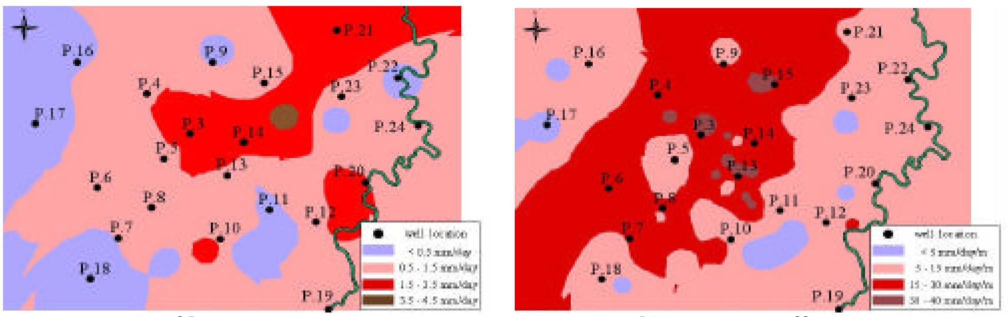


Fig. 9 Daily water levels of the Yom River at Y5, Y17 and the new station in study area

4.3 Infiltrations

The author estimated the recharge from rainfall by using the infiltration capacity value while the recharge from flood water and the water percolation volume in paddy fields rely on the coefficient of the seepage capacity because the high depth of water held on the ground surface. Chuenchookrin et al studied flood conditions in this area and its neighborhood. They conducted an infiltration experiment of the ground surface and calculated the infiltration capacity and seepage coefficient. The author made a distribution map of the infiltration rate and the seepage coefficient, based on their data on this study area as shown in **Fig.10**.



a) Infiltration capacity b) Seepage coefficient

Fig 10 The distribution map of infiltration capacity and seepage coefficient

4.4 Recharge System

The recharge system was constructed at Ban Noen Kwang School (P3), which is in the middle of the study area. The recharge system was 40 cm from the ground surface of the school. It consisted of a square seepage pit of 100 cm in width, 100 cm in length and 110 cm in depth connected to a seepage trench of 200 cm in width, 500 cm in length and 110 cm in depth with four percolation pipes with 4-inch diameter, 240 cm in length penetrating from the bottom of the trench to the coarse sand layer. Gravel with effective porosity 0.29 is installed in this seepage system. In addition, other system components such as a drainage pipe to collect rainfall for the recharge system, an observation well and a rain meter were also provided for the experiment and a real situation investigation. An automatic rain gauge has 5-minute record intervals while a sensor for measuring the groundwater level in the observation wells and the water level in the trench have 2-minute record intervals.

5 Behavior of Groundwater Level and Influencing Factors

From the author's investigation, among factors believed to have some influence on change in groundwater were rains, floods, river water level, ponds for agriculture, natural ponds, sandpits and farm wells. The author analyzed the data obtained from observation system and got the following discussions.

5.1 Groundwater distribution

Based on the GWL observation data of 20 spots (observation well no. P4 and P5 can not be used because of clogging in the well casing), the author made GWL contour maps in selected periods; when GWLs were in the middle rise from the minimum water level, in the minimum water level, in the middle drop from a peak, and in the peak water level. From these GWL contour maps, it is clear that there is an area with high infiltration in the study area; and floods and river water recharged to groundwater through ground surface. During flooding periods, GWL rose quickly, resulting in groundwater ridges, which then flowed to lower-level regions. **Fig.11** shows rainfall, observed GWL, the Yom River WL, and example of GWL contour maps in the peak and lowest period.

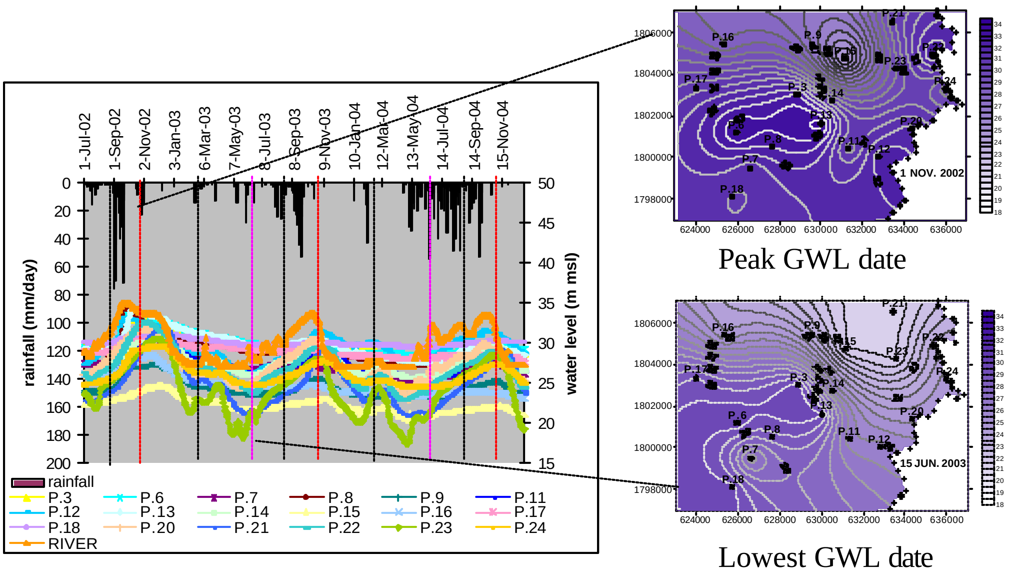
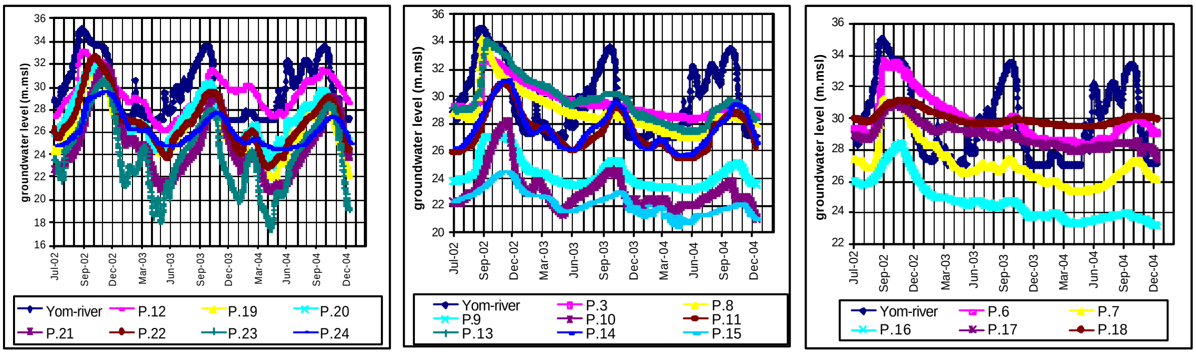


Fig. 11 Rainfall, observed groundwater, Yom river water level and GWL contour map.

5.2 Influence of the YOM River water level

Generally, the Yom River water can recharge groundwater by lateral flows or seepage from the bottom of the river. However, it depends on soil construction and river water head, as well. To understand the influence of the Yom River on GWL change, the author divided areas of observation wells to 3 regions: 1: area close to the Yom River, 2: middle area, and 3: upland area. The GWL and river water level (RWL) were plotted in **Fig.12**.



a) Near Yom River area b) The Middle area c) The upland area

Fig. 12 Daily GWL and Yom River WL

Because GWL data shows delay time to RWL, the author did a statistical analysis of the relationship between GWL and RWL at all observation points by delaying the RWL data day by day. The dispersions (R-squared) of the linear regression between delayed RWL and GWL was calculated for each lag time and were plotted in order to choose a suitable delay time with the highest value of dispersion (R-squared). The result showed that the average dispersion was a high correlation of 0.77 in a river neighborhood area, 0.69 in the middle area, and 0.35 in the highland. This means that GWL in the river neighborhood area and part of the middle area are strongly influenced by the Yom River water level, and GWL in the highland area has little relation to the Yom River water level. In addition, the calculation phases were 14-43 days in the river neighborhood, 23-50 days in the middle area, and 16-57 days in the highland. We can conclude that GWL in the river neighborhood area takes a few days to respond to the change in the river water level. The reason of this phenomenon is that floods will reach the neighborhood area of the Yom River through to the middle area, but won't reach the highland. It can also be predicted that floods by the Yom River is a very big source of recharge water to groundwater in the study area.

5.3 Influence of the flood condition

The author used ground surface elevation data and the Yom River data from a data logger to draw a maximum flood boundary map of 2001-2004 (**Fig.13**) and rechecked for accuracy by field observation information. The maximum flood areas were 60, 85, 35 and 30km^2 in 2001, 2002, 2003 and 2004 respectively. The heavy floods in 2002 covered about 70% of the study area and took over 3 months to subside. While little flood, due to less rainfall, in 2003 and 2004 covered about 30% of the study area and took 1.5 months to subside. The author assumes that probability distribution of momentary peak discharge at Y.17 represents that of to the gauging station in the study area because it has long period record. The Gumbel distribution result presents the return periods of 2002, 2003 and 2004 are approximately 24 years, 3 years and 3 years respectively.

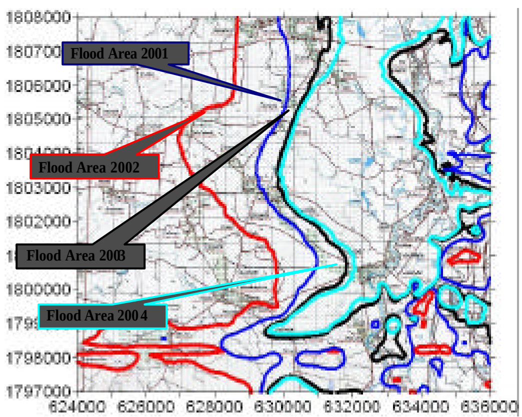


Fig. 13 Maximum flood boundaries in 2001, 2002, 2003 and 2004

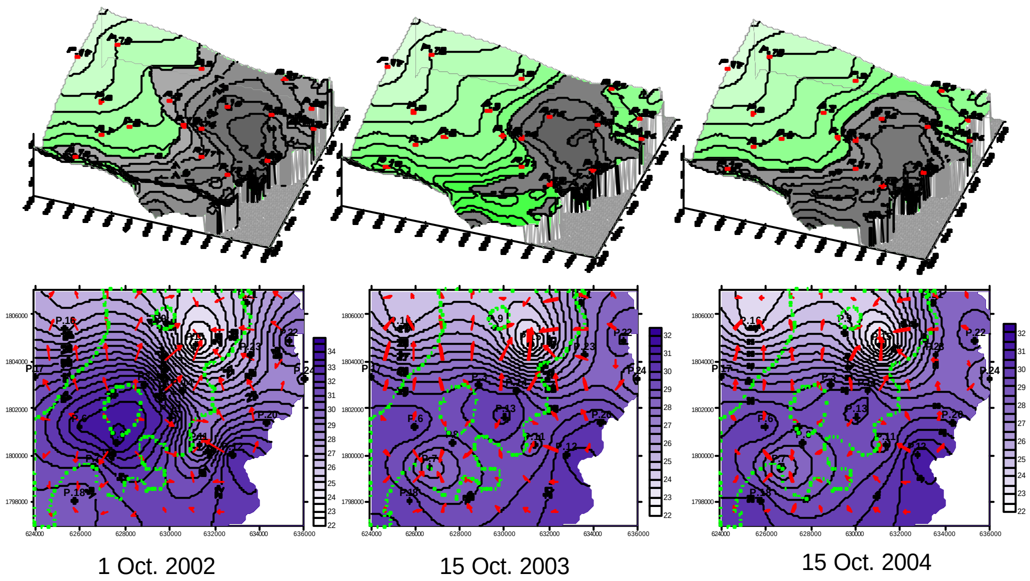


Fig. 14 Flood map and GWL contour in high flood period

The author also examined the recharge mechanism of the groundwater by comparing GWL distribution with this flood range and flood depth (see **Fig.14**). The result clearly showed that the GWL suddenly rose by infiltration in accordance with floods through high infiltration areas (surrounded by a green line), natural ponds, farming ponds and sandpits.

5.4 <u>Influence of groundwater extraction</u>

Usually, farmers will first try to use surface water from all sources before they resort to pumping GW as they will have not to pay for fuel or electricity power. The groundwater demand for cultivation can be obtained from the water balance in paddy fields, as shown in **Fig.15**. The groundwater pumping demand at time t, *Qp*(t) is calculated by the following equation:

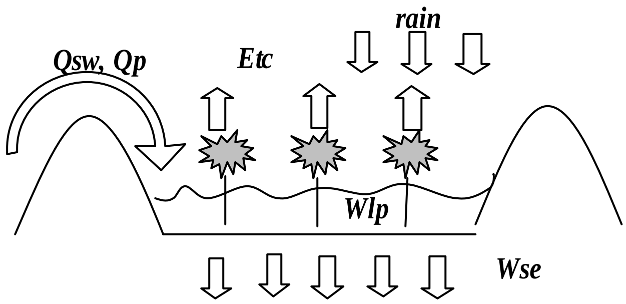


Fig. 15 Water balance model in Paddy field

$$Qp(t) = Qsw(t-1) - \left[Etc(t) + Wlp(t) + Wse(t) - Rain(t)\right] \times A$$

where, $Qp(t)$ = groundwater pumping requirement at time t (m^3/day),

$Qsw(t-1)$ = available surface water in ponds or canals in previous times (m^3/day),

$Etc(t)$ = crop evapotranspiration at time t (m/day),

$Wlp(t)$ = water needed to soak paddy fields before starting the cultivation (m/day), for upland crop, this value equals zero,

$Wse(t)$ = water seepage flux from paddy fields to the subsurface at time t (m/day),

$Rain(t)$ = rainfall depth at time t (m/day),

A = crop area (m^2).

The author collected information of crop pattern, climate data, crop coefficient, storage capacity of ponds and canals from the district's agricultural office, RID, the Meteorological Department, field observation and interview with farmers and calculated the shallow groundwater extraction. Based on the interviews with farmers, the water for land preparation Wlp equals 100 mm per one crop season. Generally, farmers maintain the water depth of about 8 cm in their paddy fields. Therefore, the water seepage flux from paddy fields to the subsurface $Wse(t)$ was calculated based on this depth and seepage coefficient value. The author found that GWL greatly drop in cropping season.

5.5 Influence of ponds and sandpits on GWL

The study area has a top sand layer (shallow aquifer) rather close to the ground surface, and ponds or sandpits probably connected to aquifers. The commercial sandpits are generally over 10m deep, so their bottoms directly contact with the aquifer.

The number of ponds and sandpits is so high that analyses of each site cannot be done. Then, the author set a water level sensor and a data logger at the sandpit between points P11 and P13 and analyzed the influence of this sandpit on GWL change at points P3, P10, P11, P12, P13 and P14, which were close to this sandpit (distance between sand pit and well is less than 2500m). The water level data in sand pit and observed GWL data shown in **Fig.16**.

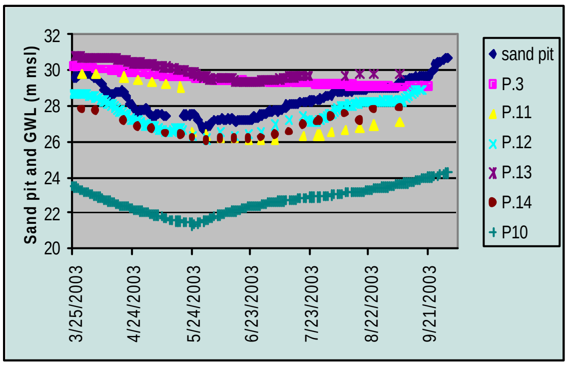


Fig. 16 The GWL and sand pit data during 25 Mar.-2 Oct.2003

The regression analysis result at points P10, P12 and P14 showed a good relationship between GWL and WL at sandpits with the dispersion over 0.80. At points P3, P11 and P13 the relationship between GWL and WL at sandpits during the whole period showed low dispersion. However, when the author conducted an analysis by classifying GWL periods into two: descending and ascending, it yielded a high dispersion value. Hence, it can be concluded that sandpits influenced GWL change and they connect surface water to GW. The flooded water can recharge to aquifers through these sandpits directly. Therefore, many ponds that scatter in the study area should have some influence on GWL change as well since some of them lie on aquifers or are in high infiltration areas.

6 Ground Water Budget Simulation by Thiessen Polygon Type Tank Model

This area has a very complex groundwater recharge system caused by flood water, rain water, farm and natural ponds, water seeping from paddy fields and sandpits. The author has obtained a great amount of observation data such as rainfall, groundwater level change at 20 observation sites, distributions of seepage capacity, the Yom River water level change and flood conditions. The author can calculates the recharge rate through the ground surface in case of rain, floods and cropping using these data and a crop pattern. However, the recharge estimation from sandpits, farm ponds and natural ponds requires details of their geometry, physical characteristic and its associated replenishment. Unfortunately, the costs and time needed to obtain this detailed information is inconsiderable due to the large number of sandpits, farm and natural ponds with various depths. The author thus surveyed the locations of sandpits and farm ponds, and introduced the Thiessen polygon type Tank model – a simple water balance model to estimate the recharge rate from farm ponds, natural ponds, and sandpits to underground and the results can be presented in form of water balance of modeled area too. The concept of this tank is shown in **Fig.17**.

The model area is divided into small polygonal zone. The dynamic response of the portion of the model included within each zone is represented by a single water level elevation. The equation of continuity of an unconfined aquifer, in which there is no vertical variation of properties, is given by

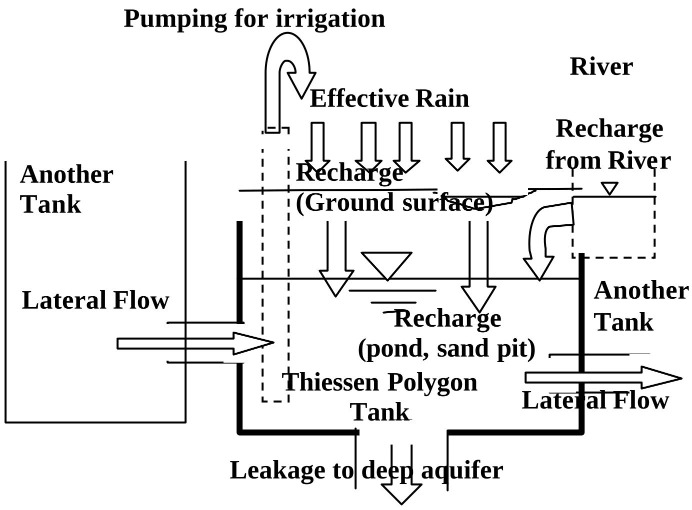


Fig. 17 Water budget in Tank

$$\Sigma_i (h_i - h_B) Y_{i,B} = A_B S_B \frac{dh_B}{dt} + A_B Q_B, \qquad Y_{i,B} = \frac{J_{i,B} k h_{i,B}}{L_{i,B}}. \tag{1}$$

Where, A_B is the area of tank B, $Y_{i,B}$ is the conductivity between tanks i and B, $J_{i,B}$ is the flow area between tanks i and B, $L_{i,B}$ is the distance between tanks i and B, k is the hydraulic conductivity of the aquifer, and i is the number of tanks neighboring tank B.

The left side of Eq. (1) refers to the groundwater flow, the first term on the right refers to the change of the volume of the groundwater in tank B, and the second term refers to the sink and source in tank B. The sink and source in tank B are inflows and outflows in vertical directions. The inflows are recharge and the outflows are pumped water and leakage to a lower aquifer. The lateral flows are groundwater flow between tank B and its neighboring tanks i and the leakage from the river. The water budget of a tank in Eq. (1) can be written as

$$\Delta H \times A \times S = (Q_r - Q_p + Q_{in} - Q_{out} - Q_L) \times \Delta t \,. \tag{2}$$

Where S = effective porosity, ΔH = ground water level change in time interval dt, A = area of Thiessen polygon, Q_r = the total recharge rate, Q_p = the pumping rate from aquifer for crops, Q_{in} = the rate of the lateral inflow from the neighboring tanks, Q_{out} = the rate of the lateral outflow to neighboring tanks, Q_L = the leakage rate from the aquifer to deeper aquifers.

As described in the previous chapter, there is one aquifer in the study area, but in the west of the area the aquifer is alternated with a clay lane. To facilitate the analysis, the author has simplified the said data by identifying the number of the aquifers as one. The author has applied the tank model proposed by Tyson and Weber for groundwater balance simulation. **Fig.18** shows a polygonal element map for the simulation. The center of each polygonal element is an observation well. The uniformity of the bottom of the unconfined aquifer was obtained by an average level of soil construction (8 m msl). The aquifer thickness of each tank varies with the groundwater level change. The hydraulic properties were obtained from an average value of field experiments as k = 0.0032cm/s, effective porosity S = 0.083. The simulation area is the inner space of these polygonal elements since the groundwater level of polygons on the edge is needed for boundary conditions. The simulation area is approximately 41.5 km^2 and there are 2 boundary types, with the river boundary on the east and flow boundaries in other places. The period of simulation was from July 2002 to December 2004, and time step *dt* was one day.

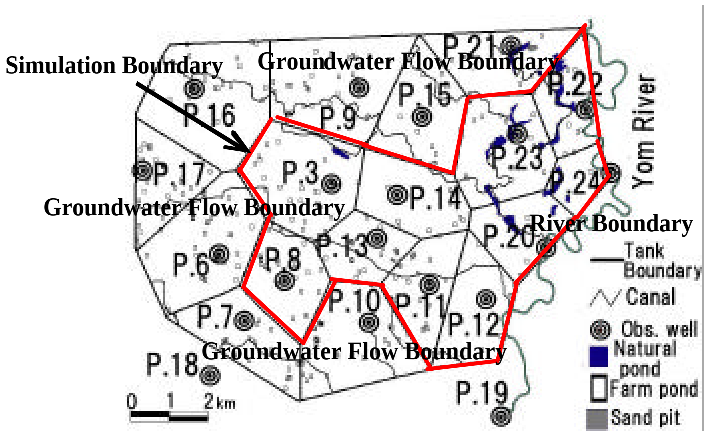


Fig. 18 Thiessen polygon, simulation boundary and boundary condition

Table 1 shows the summarized water budget from Tank model in 5 periods, including wet periods and dry periods. It can be concluded as the following:

Table 1 Summarized water budget in wet and dry periods Unit: x1000 m^3

Items	Wet 2002 July –Dec 2002	Dry 2003 Jan-June 2003	Wet 2003 July-Dec 2003	Dry 2004 Jan-June 2004	Wet 2004 July-Dec 2004
Recharge from rainfall and paddy fields (% of total inflow)	3,736 9.5%	7,006 46.0%	5,839 19.8%	5,424 37.3%	5,321 18.8%
Recharge from floods, ponds and sandpits (% of total inflow)	35,410 90.0%	8,218 54.0%	23,518 79.9%	9,093 62.5%	22,912 80.9%
Recharge from Yom River % of total flow in/out	177 0.5%	-12 0.05%	79 0.3%	33 0.2%	72 0.3%
Pumping volume % of total outflow	-2,240 8.9%	-11,048 41.4%	-5,922 22.4%	-5,280 31.1%	-3,462 14.0%
Lateral flow from outside % of total outflow	-490 1.9%	-434 1.6%	-646 2.4%	-456 2.7%	-698 2.8%
Leakage to lower aquifers % of total outflow	-22,418 89.1%	-15,181 56.9%	-19,873 75.2%	-11,238 66.2%	-20,567 83.2%
Total inflow	39,322	15,224	29,436	14,550	28,304
Total outflow	-25,148	-26,676	-26,442	-16,974	-24,726
Water balance	14,174	-11,452	2,993	-2,424	3,578

1) The recharge volume in 2002 (July-Dec.) was about 39.322MCM while the annual recharge volumes in 2003 and 2004 were 44.581MCM and 42.750MCM respectively. The annual recharge volume from ground surface is over 99 % of the annual inflow volume.
2) The recharge volume in the wet period of the 24-year return period of floods (2002) was about 39.322 MCM, while that in the 3-year return period of floods (2003 and 2004) was 29.436 MCM in 2003 and 28.304 MCM in 2004. Over 79% of the total inflow volume came from floodwater. If there is little or no flood, water supply for recharge through ground surface, ponds and sandpits will diminish.
3) The annual recharge volume from the Yom River is less than 1% of the annual inflow volume and barely affects the groundwater level near the Yom River area.

4) The annual pumping volume from shallow aquifers for irrigation is about 8.7 to 16.9 MCM or 20.9% to 31.9% of the annual inflow.
5) The annual leakage to lower aquifers is about 31 to 35MCM or 66-76% of the annual inflow volume.
6) The groundwater balance in the wet period was that the inflow volume exceeds the outflow volume, but in the dry period, the outflow volume exceeds the inflow volume. The flood water recharge in the wet period greatly contributes to the inflow volume. The water budget in each year depends on flood conditions. The water balances in 2003 and 2004 were -8.4MCM and 1.15MCM respectively.

7 The 3-D Groundwater Flow (GWF) Model

To conduct a precise study of groundwater flow, the 3-D unconfined aquifer groundwater flow (GWF) is modeled using the estimated recharge rate from the Thiessen polygon tank model. The author used the Visual MODFLOW program for the 3-D unconfined aquifer groundwater flow simulation and calibrated the parameter of aquitard to obtain a good match between the observed and simulated GWLs. The partial differential equation of the groundwater flow under non-equilibrium conditions in heterogeneous and anisotropic confined aquifers (McDonald and Harbaugh, 1988).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (9)$$

In this equation, K_{xx}, K_{yy} and K_{zz} are hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L/T]; ***h*** is the piezometric head [L]; ***W*** is the volumetric flux per unit volume representing sources and/or sink of water [T^{-1}]; S_s is the specific storage of the porous material [L^{-1}]; and ***t*** is time [T]. And the groundwater flow governing equation in unconfined aquifer is

$$\frac{\partial}{\partial x}\left(K_{xx}h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}h\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}h\frac{\partial h}{\partial z}\right)+W=S_y\frac{\partial h}{\partial t} \quad (10)$$

Where, ***h*** is the saturated thickness in unconfined aquifer [L] and S_y is the specific yield [1].

The model area was divided into a number of elements: the elements in the horizontal direction were 100 m x 100 m homogeneous rectangles, and the elements in the vertical direction were heterogeneous. The rectangular grids consisted of 100 rows, 140 columns and 3 layers, producing 42,000 individual cells in total. The boundary conditions, as shown in **Fig.19**, were established as known head and river boundary conditions. The data on the groundwater level of observation wells located at the edge of the boundary was used for known head boundaries.

Physical properties of each layer in each grid cell were entered into the Visual MODFLOW simulation model. The following data grids were required; ground-surface elevation, elevation of the bottom of the layer, hydraulic conductivity (*K*), specific yield (S_y), specific storage (S_s). These values were set according to the average value from the field and laboratory testing results. In the first layer, the discontinuous clay lane in the southwestern part of the first layer was disregarded in order to simplify the model. **Fig.20** shows the model of the cross section of the hydrogeological condition.

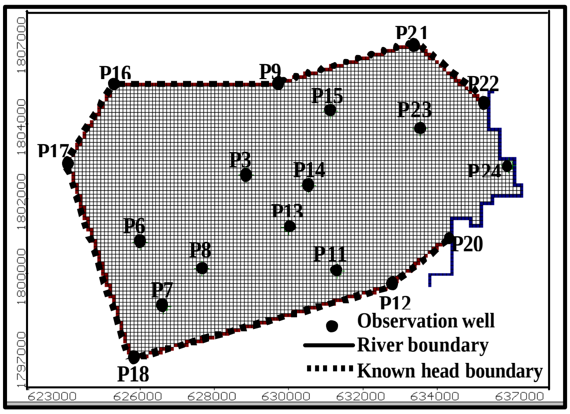


Fig. 19 The model domain and boundary Condition

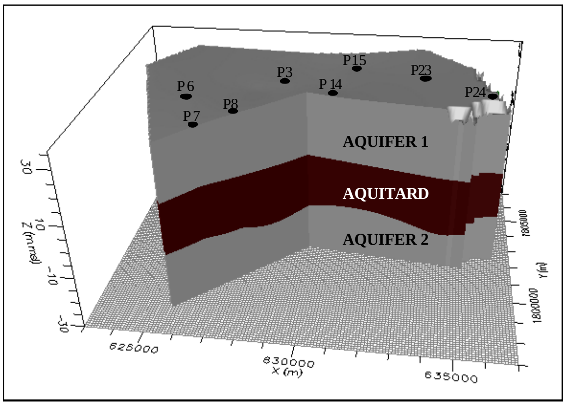


Fig. 20 The cross section of hydrogeological condition in study area

The calculation of the recharge from rainwater, floodwater and water collected in paddy fields was based on the field experiment data, with the exception of the recharge from commercial sandpits, farms and natural ponds, which were calculated by the use of the Tank model as mentioned in the previous chapter. Since Tank model simulation results in the previous chapter shows that the lateral groundwater flow is a minor part of the groundwater budget, the author extended the Tank model simulation area to cover the polygons on the edge; i.e., polygons of observation wells no.P6, P7, P9, P10, P15, P16, P17 and P22. The recharge from commercial sandpits, farms and natural ponds of the edge polygons were calculated by the use of no lateral flow, or known as no-flow boundary. The modeled area was approximately 86 km^2. Farm wells were the only discharge component added. There are approximately 580 farm wells in the modeled area.

Table 2 The model conditions for the main packages

Package	Conditions
Basic Package	- Unsteady state condition, 915 days (1 July 2002- 31 Dec. 2004) - Use 915 stress periods - Use 10 time steps (one time step = 2.4 hours)
Block-Centered flow Package	- Dx = Dy 100 m - Re-wetting method: from below cell
Layer Property flow Package	- Layer types: 1st layer: Unconfined, 2nd layer: Confined/Unconfined, varying S,T 3rd layer: Confined/Unconfined, varying S,T
Well Package	Pumping wells - Number of pumping wells = 518 wells - Observation wells = 10 wells - Screen position of observation well: varies due to drilling data
Recharge Package	- Daily ground surface recharge activated to the most active cell
WHS Package	Solver setting - Maximum outer iterations = 50 - Maximum inner iterations = 25 - Head change criterion = 0.01 - Residual criterion = 1E-5

The transient simulation was done for the period of 915 days, based on the daily data collected from 1 July 2002 to 31 December 2004 (three flood periods and two dry periods). The groundwater level data observed at 10 observation wells were used for model calibration. The hydraulic conductivities in the aquifer 1 and 2 (see **Fig.20**) were used from the value of in situ pumping test results. And the hydraulic conductivity in the aquitard was adjusted to obtain a good match between the simulated and observed groundwater levels. The model conditions for the main package of MODFLOW are summarized in **Table 2**.

The properties of the aquitard varied for a 915-day transient groundwater flow simulation. The simulation results based on the properties of the aquifer and aquitard shown in **Table 3** gave the least root mean square and good accord with the observed groundwater levels of ten observation wells in all of the model domains except in some periods at the observation well P. 23. The water balance simulation results during the wet (Jul.–Dec.) and dry seasons (Jan.–June) calculated with consideration of recharge by ponds and sandpits after flood end are summarized in **Table 4**.

Table 3 Hydraulic conductivity and specific yield

	K_{xx},K_{yy} [m/s]	K_{zz} [m/s]	Sy[1], S_S[m^{-1}]
Aquifer 1	3.2 E-5	3.2 E-6	0.083
Aquitard	2.1 E-6	2.1 E-7	0.050
Aquifer 2	3.2 E-5	3.2 E-6	0.083

Table 4 Calculation results of water budget (3-D GWF simulation) (Unit:MCM)

	2002	2003		2004	
	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season
Well Pumping	-3.1	-7.6	-5.1	-4.9	-4.0
	-6.0%	-18.3%	-11.2%	-16.6%	-9.8%
Ground Surface Recharge	61.0	31.0	40.2	28.0	33.9
	87.2%	100%	91.6%	96.2%	89.7%
River Recharge	8.4	-3.5	3.2	1.0	2.5
	12.1%	-8.3%	7.3%	3.3%	6.6%
Net Lateral Flow from Outside	0.5	-0.4	0.5	0.1	1.4
	0.8%	-0.9%	1.1%	0.5%	3.7%
Recharge to Lower Aquifer	-49.1	-30.2	-40.7	-24.7	-36.8
	-94.0%	-72.5%	-88.8%	-83.4%	-90.2%
Total Inflow	70.0	31.0	44.0	29.1	37.8
Total Outflow	-52.2	-41.6	-45.9	-29.6	-40.8
Total Inflow-Outflow	17.8	-10.6	-1.9	-0.5	-3.0
Rainfall (mm)	635.0	148.0	395.5	406.5	664.5

The results clarified that the major recharge water came from the ground surface recharge (87-100% of the total inflow), particularly from floodwater. The flooding in this area lasted for a long period in 2002 and caused the recharge quantity of the floodwater through the ground surface was as high as 61.0 MCM. The recharge from the Yom River was relatively small in comparison with the floodwater (3%-12% of the total inflow) and had an opposite direction in the dry season of 2003. The leakage to lower aquifers is approximately 72%-94% of the total outflow while the pumping of water was about 6%-18% of the total outflow. In the wet season of 2002, GWL rose up greatly by floods in a wide range of the study area; therefore, with the flood water recharge from ground surface, the quantity of leakage to lower aquifer also increased. Farmers were not able to grow rice due to lack of surface water in the dry season of 2004 because of a shortage of rain water in 2003. As a result, in the dry season of 2004, there was less inflow and outflow to aquifer 1, and the difference between inflow and outflow were only small. In the other periods - the dry and wet seasons of 2003 and 2004, the outflow from the groundwater exceeded the inflow. Pumping the groundwater greatly influenced this, and the rise of the groundwater level is considerable should there be no pumping. Nonetheless, this indicates that this study area may face severe problems of a low groundwater level if the number of wells rises in the future.

The 3-D GWL simulation was done in case pumping was discontinued in order to see whether the GWL may increase. The results of GWL rise at each point shown in **Fig.21**. The GWL has significantly risen up in the period of when the pumping is discontinued particularly at point P15 (about 1.0-2.9 m), which has the highest concentration of farm wells. The average GWL rise during simulation period is approximately 40 cm. The author draws the contour line of the increase of GWL in the high period (15 Feb. 2003, 1 Jul. 2003, 1 Jan. 2004, 1 Jul. 2004) and the low period (1 Oct. 2002, 15 Apr. 2003, 1 Oct. 2003, 15 Apr. 2004, 1 Oct. 2004) in the modeled area in order to clearly understand the distribution of this value as example show in **Fig.22** and **Fig.23** respectively. It was found out that near the Yom river area does not much influence from stopping pumping of GW.

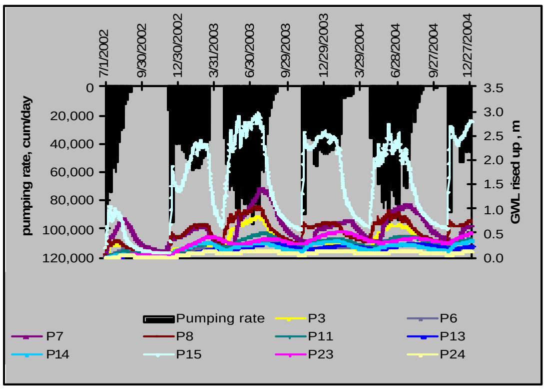


Fig. 21 The GWL rises at each point

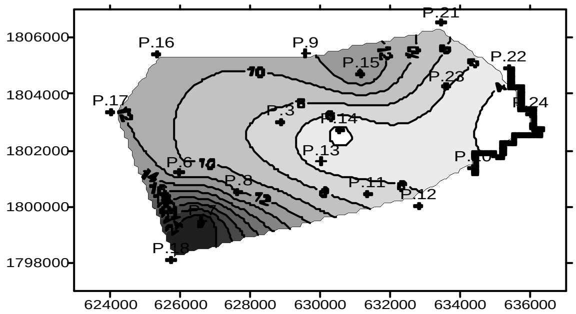


Fig. 23 GWL rise in 1 Jul.2003

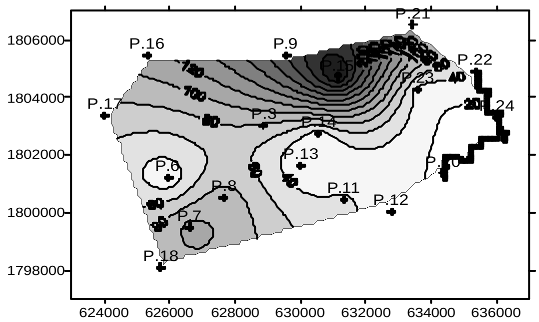


Fig. 22 GWL rise in 1 Oct.2002

8 Recharge System Analysis

The author selected a school building (at P3) with a roofed area of 460m^2 as a recharge system site and built a recharge system at the end of December 2000. The outline of equipment and the construction work of the recharge system in the field had already shown in **Fig.24** and **Pic.1**.

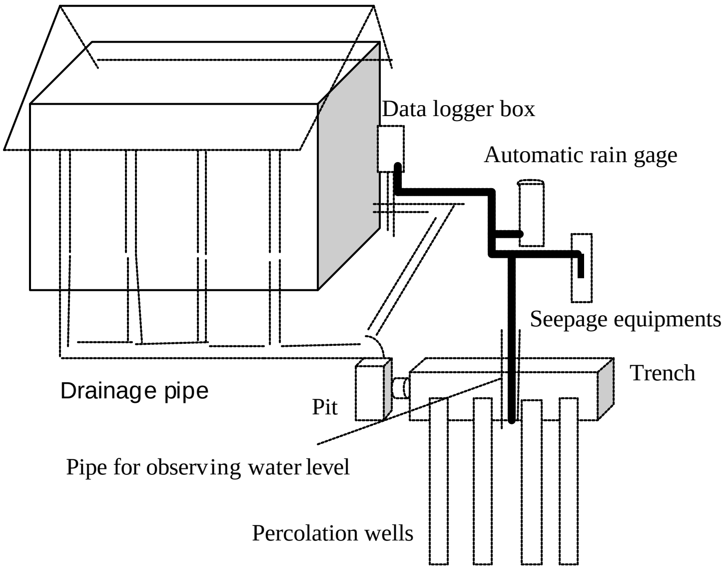


Fig. 24 Outline of equipment in the field **Picture 1** Recharge system (before gravel filling)

From soil log data of P3, the soil layer located at the depth of 0-1.2m from the ground surface was medium-density sandy silt (ML) with plasticity, and the soil layer located at the depth of 1.2-4.0m from the ground surface was loose to medium-density silty sand (SM) with non-plasticity. At 4.0-8.10m from the ground surface was a layer of poorly graded sand (SP) with medium-density non-plastic, which is a shallow groundwater aquifer. At 8.1-10.0m from the ground surface was slight to medium-density sandy silt (ML) with plasticity that lay between the first and second aquifers. The observation well was 8.40 m deep with screen pipe at the depth of 4.0 to 8.10 m.

The purpose of artificial recharge is to investigate the function work of recharge system and calculate the seepage capacity coefficient of percolation wells after complete construction. There were 3 experiments as follow;

- First experiment was done in March 2001. Constant discharge was supplied to the system at the last manhole. At first, water speed from manhole to pit was very fast and then became slowly, our notification found out that there were air bubble flow back from pit to manhole which caused from insufficient air ventilation inside the system.
- The second experiment was done in 10 August 2001 after improving the system by installing air ventilation pipes in pit and trench, and enlarged pit side to 200 cm width and 200 cm length. The constant discharge of 28 liters per minute was supplied to manhole for 70 minutes. Water level in trench and ground water level were recorded every minute by data logger and recheck by manual.
- The third experiment was done in August 2004 to investigate the system efficiency after using over 3 years.

The seepage capacity coefficient (seepage velocity per unit head of water) of pit, trench and percolation wells was determined by field test and used to simulate flow in recharge system. The relation between seepage discharge and seepage capacity coefficient was shown by this equation;

$$Q_s = a_c A H, \tag{3}$$

where, Q_s = seepage discharge (cm^3/s), a_c = seepage capacity coefficient (s^{-1}), A = seepage area (cm^2) and H = head of water (cm).

In case of infiltrate both horizontal through side wall and vertical though bottom of circular hole, integrating Eq. (3), we get seepage discharge as

$$Q_s = a_c\left[\frac{p}{4}D^2h_t + \frac{pD}{2}h_t^2\right], \tag{4}$$

where D = diameter of hole (cm), h_t = water level in hole at time t (cm).

From Eq.(4), the seepage capacity coefficient, a_c is a slope of graph between seepage discharge and seepage volume as shows sample of testing result of percolation well no. 1 in **Fig.25**. The results of testing during construction (Dec.2000) shown that seepage capacity coefficient of pit and trench is 2.9x10^{-4} hr^{-1} (8.1E-8 s^{-1}) and 7.2x10^{-4} hr^{-1} (2.0E-7 s^{-1}) respectively, while four percolation wells have values of 1.008, 0.144, 0.18 and 0.3492 hr^{-1}.

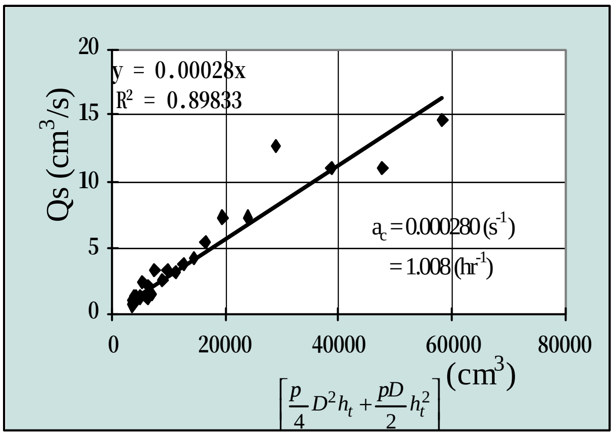


Fig. 25 The seepage capacity coefficient of percolation well no.1

The concepts of tank model for simulation flow in recharge system shown in **Fig.26**. The rainfall discharge from roof or artificial discharge (Q_{in}) flows to pit, whenever water level rises up to H_1, over flow (Q_f) from pit flows to trench and then water start seepage from trench (Q_{s21}) and percolation well (Q_{s22}) to the underground. All of water that infiltrate to underground become groundwater. Water discharge from rainfall is calculated from rational method as following

$$Q_{in} = CIA, \tag{5}$$

where, Q_{in} = water discharge to seepage system (cm^3/s), C = runoff coefficient, I = rainfall intensity (cm/s) and A = roof area (cm^2).

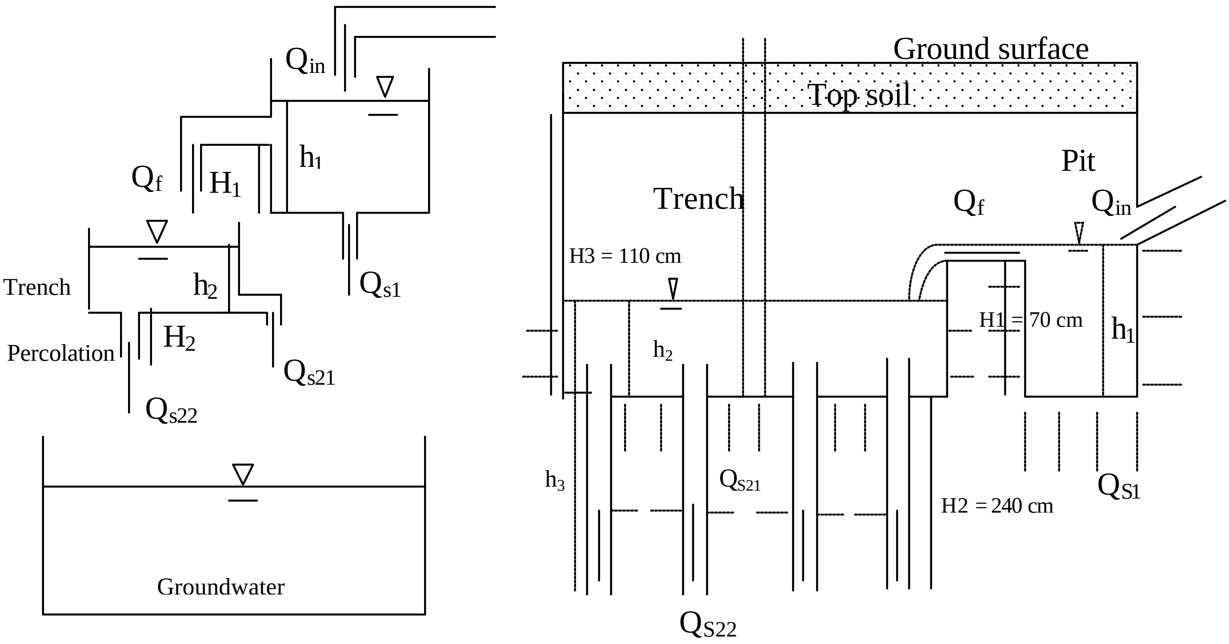


Fig.26 The concept of simulation using tank model concept

In this case, several rainfall storms recorded from rain meter were used to estimate supply discharge from drainage system to recharge system. Water level in trench from simulation using Tank model concept will be compared with observed values from data logger to calibrate rainfall-runoff coefficient (C in Eq.5). **Fig.27** shows the record of rainfall, water level in trench and ground water level in observation well from data logger of storm on 27 August 2001. This illustration storm has total rainfall depth 16.5 mm. and duration 155 minutes. The simulation result of this storm shows in **Fig.28**, C = 0.40 give simulated water level in trench closest to observed value from sensor. Therefore, runoff depth from roof flows to recharge system is equal 40% of total rainfall or 6.4 mm. This 2.94 m^3 runoff volume causes rise up water level in trench to 28 cm and ground water level rise up to about 3.6 cm.

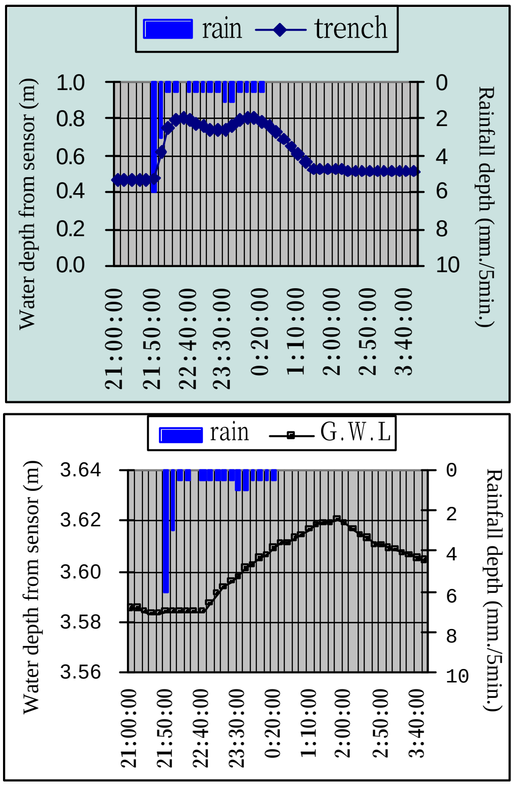


Fig. 27 Recorded value of storm , 27 August 2001

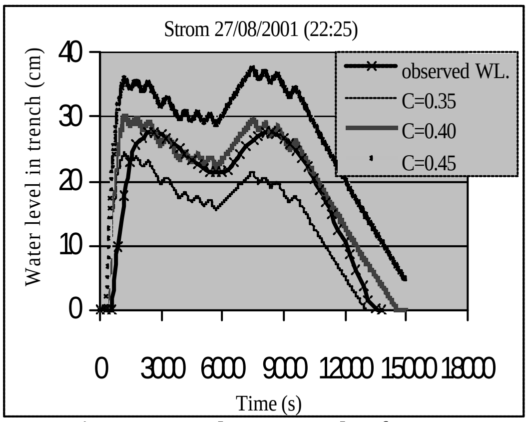


Fig. 28 Simulation result of storm, 27August 2001

Consider the storms during December 2000 – January 2002, there are 68 storms with complete data both rainfall and water level in trench. The simulation result of 23 storms before improving system (Dec.2000–10 Aug.2001) and 45 storms after improving system (10 Aug. 2001-Aug. 2002) shown in **Fig.29**. From this figure, before improving system we can recharge rainfall to underground about 87% of total rainfall. After improving system, the recharge efficiency is significantly increase to 45.8% and 33.0% for rainfall depth less than 15 mm. and more than 15 mm. respectively. From this result, it can be estimated that if the recharge systems are constructed in the whole study area of 67,000 houses, with the average recharged rainfall to top aquifer 45.6% of the total rainfall or 0.65 m^3/year/1m^2 of the roofed area, then, the total recharge volume about 200,000m^3/year can recharge to aquifer.

The ground water level rise up of each storm is estimated from ground water level recorded by sensor. The relation between recharged volume and rise up of ground water level shows in **Fig.30** The ground water rises up near recharge system about 1.10 cm. per 1 m^3 of recharged volume. The recharged rainfall to underground can be increased if more percolation wells were set and enlarge drainage system.

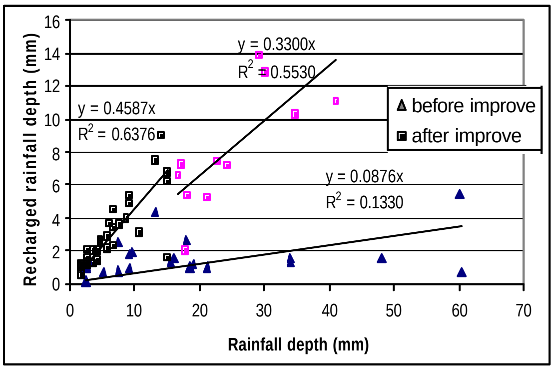


Fig. 29 Relationship between recharged rainfall and rainfall depth

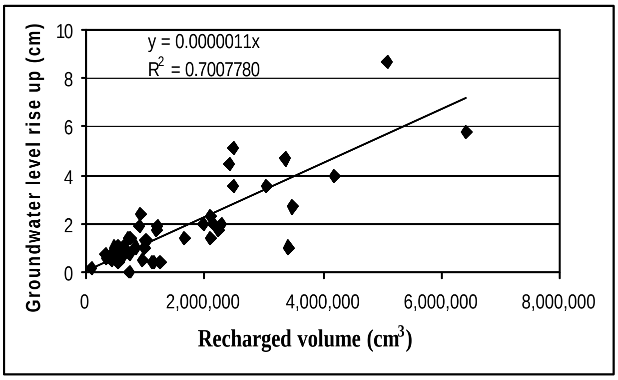


Fig.30 Relationship between recharged volume and groundwater level rise up.

As usual, an efficiency of recharge system decreases after using for some period. The artificial recharge testing on 12 August 2004 was done by continue supply discharge (0.47 l/s) to the last manhole for 80 minute. The simulation by Tank model of this testing found out that seepage capacity coefficient of percolation well decreases from $3.6x10^{-5}s^{-1}$ to $2.0x10^{-5}s^{-1}$or about 50% decreasing. **Fig. 31** shows the observed and simulated results and we can notice that rising limb and recession limb of observed water level in trench have two slopes. This may caused by the different layer of trench. The simulation divides layer of trench into 2 layers, first layer is 28 cm depth from trench bottom with initial property of seepage capacity coefficient ($7.2x10^{-4}$ hr^{-1}, $2.0x10^{-7}$ s^{-1}) and second layer is over 28 cm with coefficient of seepage capacity $5.0x10^{-3}s^{-1}$.

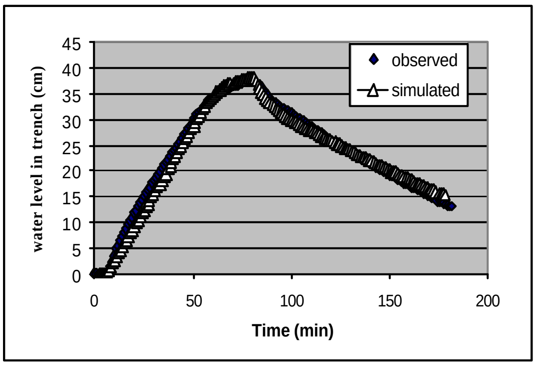


Fig.31 Relationship between observed and simulated

9 Conclusion

Part of the low land paddy fields in Phichit floodplains, a major recharge area of Thailand, was selected as the study area for the precise study on the groundwater cycle of unconfined aquifer and the possibility of artificial recharge by gravity. Observation systems were installed in one precipitation site, one the Yom River water level site and 22 groundwater level sites. The in-situ permeability examination at the time when the 22 observation wells were bored in the study area and pumping tests conducted at two wells showed that the permeability K of soil of the first aquifer ranged from $1.4x10^{-3}$ to $5.4x10^{-4}$cm/s and the storativity S ranged from 0.001 to 0.20. The observations were conducted to achieve the study's aforementioned purpose.

The hydrogeological map of the study area, based on the boring log data at the locations of existing wells and new observation wells dug specially for this study, was to ensure understanding of different layers of the soil. Other field data such as flood boundaries and inundation periods, ground surface infiltration capacity, specifics of farm wells, etc. were systematically collected. The author investigated the behavior of the groundwater and factors influencing groundwater levels in the study area, and found that this tropical floodplain area has quaternary sediments and a rather complex water recharge behavior.

The author attempted to analyze the relationship between the groundwater levels and the influencing factors. Then, the study area was divided into three local areas: river neighborhood area, middle area (4-8 km from the Yom River) and highland (8-10 km from the Yom River) to examine the influence of the Yom River head on GWL change. After that, the author calculated the correlations between GWLs and river water levels at different lag times. The result showed that GWLs in the river neighborhood area and part of the middle area were strongly influenced by the Yom River water level. The ranges of the flood periods in 2002, 2003 and 2004 were estimated and the recharge mechanism of the groundwater was examined by comparing GWL distribution with this flood range. The result clearly showed that the GWL quickly rose by infiltration in accordance with floods through high infiltration areas, natural ponds, farming ponds and sandpits. The author calculated the coefficient of the correlations between GWL and water level at sandpit with more than 10m depth to examine the influence of ponds and sandpit in the study area. The result showed that water levels at sandpit had high correlations with GWL, and we thus can conclude that water levels of sandpits greatly affected GWL.

The recharge through the ground surface from rainfall, floods and water kept in rice fields was estimated by using the ground surface infiltration capacity. On the other hand, the recharge from ponds and sandpits depended on their number and the conditions at their bottoms, which made it difficult to estimate the recharge rate. Thus, the study applied the Tank model concept and used the data collected during the years 2002-2004 for the recharge estimation from ponds and sandpits. The recurrence intervals of the maximum discharge in 2002, 2003 and 2004 are approximately 24 years, 3 years and 3 years respectively. The recharge volume calculation results showed that these values depended on the amount of rainfall and flood conditions in each year. In addition, the result of the Tank model showed that the lateral flow to this area was of a small value.

The three-dimensional unconfined aquifer groundwater flow (GWF) model of the study area was developed by using the MODFLOW program. The program presented two results in terms of attaining water balance: 1. in case of present conditions 2. in case of eliminating groundwater extraction by using surface water instead. The modeled area was approximately 86 km^2. The simulated groundwater level appeared to be in accordance with the observed values with the exception of a few certain locations. According to the water balance calculation results, it can be concluded that the main source of groundwater of this area is ground surface recharge (approximately 87 - 100% of the total inflow), balanced by some leakage to lower aquifers (approximately 72- 94% of the total outflow). The leakage of the Yom River to aquifers does not greatly affect the groundwater level of the whole area, but it influences the groundwater level near the river. The annual water balance of groundwater is strongly influenced by inflow of floods and by outflow caused by pumping. Therefore, if there is little flood and the number of farm wells continually increases, the GWL in this area will decrease. On the other hand, if surface irrigation can support farmers and thus stop farmers from pumping groundwater, the groundwater can rise by 2-290 cm with the average value of 40 cm.

The recharge system was constructed in the study area to recharge top aquifers with rainfall from the large-roofed area. The rainfall depth and the water levels in the system and the observation wells were continuously recorded by the data logger. The basic program for the flow simulation in this recharge system was developed, based on the Tank model both for artificial recharge and natural rainfall recharge testing. The artificial recharge experiments were conducted three times. The first experiment result yielded that there was insufficient air ventilation inside the system. The second and third artificial recharge experiments were done to evaluate the system efficiency after the air ventilation system was improved and again after this recharge system had been installed for 3 years. The simulation result of the natural recharge of 23 storms data (during December 2000 - August 2001) before the system was improved showed that the system could recharge subsurface with rainfall by about 8.7 % of the total rainfall. After the system was improved, the simulation result of 45 storms data (10 Aug. 2001- Aug. 2002) presented a significant increase in recharge efficiency to 45.8 % and 33.0% for the total rainfall depth of less than 15 mm. and more than 15 mm. respectively. If this system is constructed in the whole study area of 6,700 houses, the total recharge volume of about 200,000m^3/year can recharge the subsurface. The analysis of the relations between the recharged volume and the rise of the ground water level showed the ground water near recharge system would rise by about 1.10 cm. per 1 m^3 of the recharge volume. As a result of the calibration of the model's parameter in the third artificial recharge test, the seepage capacity coefficient of the percolation wells decreased from $3.6x10^{-5}s^{-1}$ to $2.0x10^{-5}s^{-1}$ or 50% after 3 years of installation.

The investigation of the detailed hydrogeological situation in such a floodplain was carried out in this study as a first in Southeast Asia. The pin points from results of this study can be concluded that

- groundwater income of floodplain in tropical monsoon area such as Phichit floodplain has greatly income from the flood water. This essential knowledge is benefit for the further studies particularly in water resources planning to understand the groundwater cycle and beware the effect to this cycle when develops water resources project,
- this study should also raise awareness in groundwater modelers so that when they are to build a model, they will have collected information on local activities that could affect groundwater, including sand pits and farm ponds in the area and suchlike,
- according to the information obtained and the fact that there are a few number of houses, recharge by collecting rainwater from roofs had relatively less impact than that by artificial ponds with bottoms reaching the first aquifer. Thus, the most suitable procedure to preserve groundwater by the gravity method is to build a pond which will readily allow floodwater to seep underground during flood time. This study is, in conclusion, to show an alternative effective method of groundwater maintenance in frequently flooded areas in Southeast Asia,
- information on water cycle and techniques employed in the study can be contributed to groundwater elucidation and planning in general, as it should be applicable to other areas as well as Southeast Asia.

10 Recommendation for further study

A study of flood reduction by artificial recharge using ponds and sandpits as a spreading recharge basin should be carried out since there are many ponds and sandpits in flood regions. The suitable location of ponds or sandpits should be considered based on their infiltration capacity, flood occurrence possibility, lithology and depth of groundwater.