Groundwater and surface water interaction patterns via groundwater model

-case study in Plaicumphol Irrigation Project-

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Abstract**—** In the last decades, water demand has increased due to the rapid development in economy in Thailand. Because of the spatial and temporal distribution of rainfall and insufficient water storage, groundwater has played an important role for agricultural productivity in Plaichumphol Irrigation Project area. In order to better groundwater management in this area, the study aimed to understand the groundwater and surface water interaction patterns via local groundwater model with the grid size of 400 x 400 square meters. Boundary conditions were determined based on the geology, hydrogeology and piezometry of the aquifer of the calibrated regional groundwater model. River water level, pumping wells and recharge rates are also used from regional groundwater model with grid size of 2 x 2 sq.km. Recharge parameter were carried out to estimate land recharge rate and river hydraulic conductance to analysis interaction mechanism and to compare with the developed local groundwater model (flux) results. It is found that in this area, the main factors for groundwater flow budget are land recharge in rainy season and river recharge in dry season. The interaction volume and patterns between surface water and groundwater were analyzed from water balance via developed local groundwater model. Based on the change in water year, the aquifer gains water as land recharge is 2.72MCM/day in wet year and 2.18MCM/day in drought year of the total inflow. River recharge (river loss) to the aquifer is 2.25MCM/day in wet year and 1.82MCM/day in drought year.

Keywords—sw-gw interaction; field measurement; seepage; flow budget; Plaiumphol Irrigation Project

I. INTRODUCTION

There were several studies in this area such as groundwater modelling for conjunctive use patterns [1], groundwater and surface water dynamic interaction model [2], groundwater model to mitigate the climate change [3], and conjunctive used management [4]. Because of the spatial and temporal distribution of rainfall and insufficient mount of water storage, groundwater is an important role of agricultural productivity in Plaichumphol Irrigation Project area. The farmer used groundwater 1.43MCM/year [4]. However, these amounts are not enough for their cultivation. In this area, groundwater discharge occurs where groundwater level is hydrographically higher than the surface water level. Depending on the structure of the hydrogeological cross-section and the profile of groundwater table, the groundwater discharge varies by hydraulic connection between aquifer and river. Therefore, an understanding of the interaction between groundwater and surface water is need for effective management of water management.

A. Purpose of study

The main purpose of this study is to understand the groundwater and surface water interaction mechanism (volume and patterns) via development of local groundwater model. For this purpose, soil moisture sensor system and seepage meter measurements were carried out in Plaichumphol Irrigation Project area (PIP). The field soil moisture sensor system was developed to monitor soil moisture to understand land recharge for developing groundwater model. The seepage measurement was conduct to estimate discharge and recharge from river seepage to analyse interaction and to compare and check the calibrated values from local groundwater model (flux).

B. Study area conditions

The study adopted the Plaichumphol Irrigation Project (PIP), as a case study for the groundwater and surface water interaction. This area located in Phitsanulok Province, the lower northern region of Thailand. The irrigated area is 338sq.km of total project area (436sq.km) is shown in Fig.1 [4]. Main Surface water basin is dissected by Yom river in the west and Nan river in the east which drain from north to sourth. The elevation of topography is 40-60m.MSL.

II. MATERIALS AND METHODS

A. Aquifer characteristics

There are mainly three types of hydrogeological characteristics in this study area, namely high terrace deposits, low terrace deposits and recent flood plain deposits. The aquifer system in this study was defined as semi-confined layer and confined layer with three deposit types whereby the thickness is 40-100m and 100-200m. The groundwater aquifer has formed the geological basis as a depositional flood plain, flow from north to south-east.

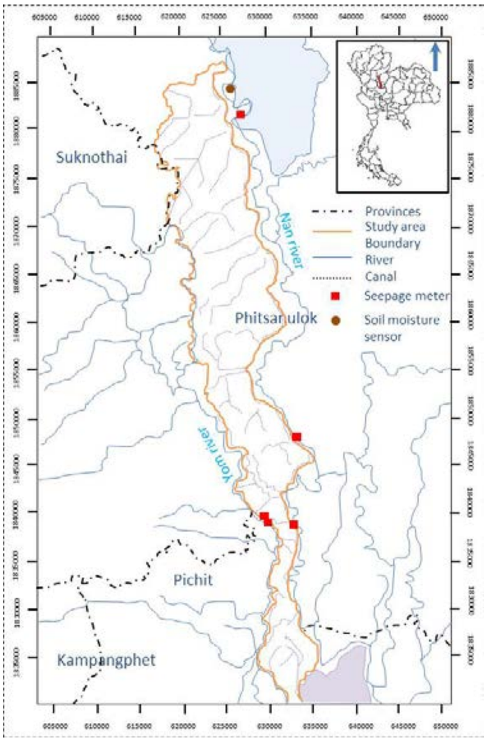

Fig. 1. Boundary of the study area

B. *Method of study*

To develop the local groundwater model, the required ground surface elevations, well locations, groundwater level, surface water elevation and boundary condition were used from the previous study [5]. It was developed with smaller grid size 400x 400 sq.meter. The proper recharge parameters; land and river recharge were measured in the site as shown in Fig. 1. The field measurements of soil moisture via sensor system and seepage meter were done to investigate land recharge and river conductance [6]. The values of these interaction parameters were used to compare with calibrated interaction parameters between groundwater and surface water from the developed local groundwater model.

C. *Equations used*

1) *Groundwater flow model*

Groundwater flow model was accomplished using MODFLOW within the Groundwater Modeling System (GMS) version 10.1. MODFLOW is the U.S. Geological Survey modular finite-difference flow model, which is a computer code that solves the groundwater flow equation. The program is used to simulate the flow of groundwater through aquifers and to predict aquifer fluxes into and out of an aquifer. The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial differential equation.

$$\frac{\partial}{\partial x}\left[Kxx\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[Kyy\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[Kzz\frac{\partial h}{\partial z}\right]+W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where, K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity in the x, y and z directions along coordinate axes, h is hydraulic head, W is a volumetric flux per unit volume and represents sinks and/or sources S_s is the specific storage of the porous material and t is time.

2) *Land recharge*

Recharge rate is estimated using daily soil moisture balance on a single soil water store in Phitsanulok Province [6]. HYDRUS-1D software package [7] was used to simulate one dimensional vertical flow with the standard Richards equation for unsaturated flow as follow:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)-S(h)\right] \qquad (2)$$

Where θ is the volumetric water content by time (t), vertical ordinate (z) assumed to be zero at the soil surface directed upward. K represents the unsaturated hydraulic conductivity, h is the pressure head and S is a sink term to account for root water uptake.

To solve this equation (2), Genuchetn-Mualem model [8] was used to describe the soil water retention θ(h), hydraulic conductivity K(h) and effective saturation as follow:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta-\theta_s}{[1+|\alpha h|^n]^m} & h<0\ (m=1-\dfrac{1}{n})\\ \theta_s & h\geq 0\end{cases} \qquad (3)$$

3) *River hydraulic conductance*

Calculating the flow between river and aquifer is done using a coefficient that represents the streambed conductance. This coefficient, termed C estimated from streambed deposits properties.

$$C=(KWL)/M \qquad (4)$$

Where, K is the hydraulic conductivity of the bed material, L defines the length and the river cell for the calculation node, W is the total width of interaction layer and M is the thickness of aquifer. This equation is used to find the conductance C from seepage and the flow rate of river loss and gain.

4) *River recharge*

In groundwater modelling, the flow across river bed is represented as follow [9]

$$Q=C\,(h_i-h) \qquad (5)$$

Where, Q is the flow between the river and aquifer, taken as positive if it is directed into the aquifer; C is the hydraulic conductance of the river-aquifer interconnection: h_i is the water level (stage) in the river; and h is the head of groundwater.

5) *River loss and gain*

Interaction between surface and groundwater is determined by the relation between surface water and groundwater levels

$$\Sigma^n{}_{i=1}Q=\Sigma^n{}_{i=1}\,(Q_{up}-Q_{down}) \qquad (6)$$

Where, Q is the river loss or gain; Q_{up} is river discharge in upstream and Q_{down} is river discharge in downstream.

III. FIELD METHODS AND MODEL DEVELOPMENT

A. *Land recharge*

Soil moisture sensor system designed with Arduino was developed and installed (1-4m) depth in the soil at an agricultural field (spacing 1m), for land recharge analysis (Fig. 3). There are two probes in the soil moisture sensor and there is circuitry inside the sensor for measuring the resistance and converting it into voltage as output. HYDRUS-1D was applied to simulated water movement with soil hydraulic parameter estimates using field data. The daily rainfall, evaporation and transpiration data were also measured. The soil sample in the field was taken and is classified as well-drained sandy clay loam. The shallow groundwater table was constant at 5 meter from the ground surface during the study period (rainy season). The effects of rainfall and evaporation can be seen from the soil moisture fluctuations with time lag at each depth except at the depth of 4 meter which was wetted all the time and affected from the shallow groundwater level. The daily maximum recharge rate in this area is 4.43cm/day at 2m depth when the soil moisture is saturated [6].

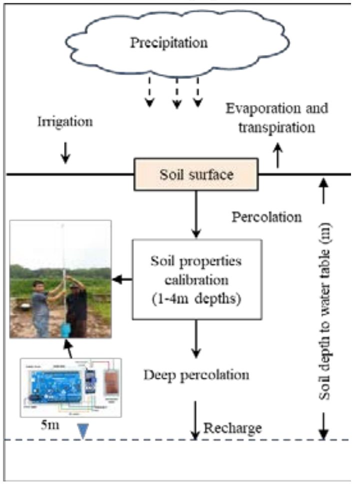

Fig. 2. Schematic of soil moisture sensor installation

B. *River recharge*

Seepage meter was constructed inexpensively in the Plaichumphol Irrigation Project area. The seepage meter used in this study was modified to measure the flow of surface water and groundwater along the river from those described by [10] and consisted of a pan and a collection bag (Fig.4). The seepage meter is made by cutting 15cm long, end sections from a 0.208cm (55gallon) metal drum. Rubber stopper (rubber band) with a single hole drilled in the center to accept tubing and clear flexible tubing that will fit tightly into the hole in the rubber stopper. The plastic collection bag is connected with the vent tube which insert into the rubber stopper compactly. The size of the plastic collection bag depends on the rate of seepage and the period that measurements are made. A large bag is needed for longer measurement periods and location with larger rates of seepage. In water over 20cm depth, a single tube through the top of the seepage meter works both as a vent for any gas released from the sediment and as a connecting for the measuring bag. A known volume of water is filled into the collection bag using the graduated cylinder. Install the collection bag assembly on the seepage meter with the rubber stopper fits in the vent hole that was drilled in the seepage meter.

The results of seepage measurement are in the range of 7.8 to 6.3 m/day for upstream (sand), 5.7 to 5.5m/day for midstream (silt) and 4.8m/day for downstream (clay) and were used to compare with calibrated river recharge parameter from the local groundwater model.

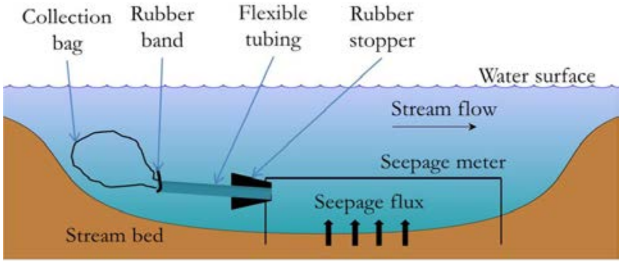

Fig. 3. Cross-section showing a typically installation of a seepage meter

C. *Local groundwater flow model development*

The 3D block-centred grid model represented the groundwater basin which has a finer grid size 400x400 sq.m. The thickness of aquifer system for this study defined unconfined layer between 40-100m. Hydrological features adjacent to and within the model domain represented in the model by mathematical boundary conditions. It was determined based on the geology, hydrogeology and piezometric heads of the previous regional groundwater model [5] were used as boundaries in this local groundwater model. River water level, pumping wells and recharge rates are initially used as input data.

Recharge parameters; land and river recharge values are adjusted and defined to provide the best match between measured and simulated values of hydraulic heads. And pumping rates are also adjusted by seasonal and zoning. The final results of the calibrated model were used for a sensitivity analysis in order to evaluate the model sensitivity to any changes in the model input parameters. The procedure used in this analysis depends on changing only one input parameter and keeping the rest fixed. The purpose was to assess the groundwater response to any change in the hydraulic parameter and which of them have the highest effect on the hydraulic heads.

IV. RESULTS OF MODEL APPLICATION

A. *Interaction parameter adjustments*

1) *Land recharge*

Land recharge is defined as the downward flow of water reaching the water table. In this study area, groundwater is mainly recharged by vertically infiltration of precipitation where it falls on the ground surface. Recharge rates were defined by percent of rainfall in each soil group zone. In this study, recharge zones were defined by soil type such as zone 1 is sand; zone 3 is sandy clay; zone 4 is sandy clay loam; and zone 5 is clay (Fig. 4). The initial recharger rate from previous model for sandy clay loam is 6.2cm./day which is higher than the field measurement data (4.43cm/day) [6] for same soil type as shown in Table 1. Therefore groundwater recharge was adjusted and calibrated values. The Mean Error (ME) of calibrated value in the range 0.5 shows the less error (0.12) then other range of initial recharge rate (Fig.5). The calibrated value from the error was noted and used this range to calibrate the initial recharge rate in the local model. As shown in Table 1, the calibrated recharge rate for sandy clay loam is 3.7cm/day and sandy clay is 4.9cm/day which is closed to the field measured data and is also in the range with the past study [11, 12].

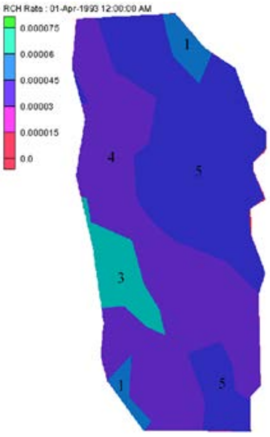

Fig. 4. Recharge rate calibration zoning by each soil zone

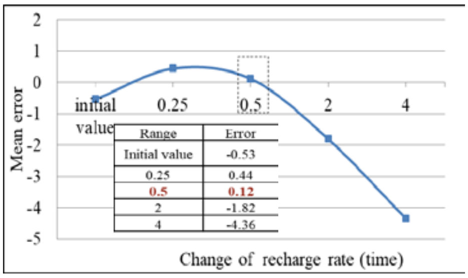

Fig. 5. Recharge rate calibration zoning by each soil zone

TABLE I. RECHARGE RATES BY EACH SOIL TYPES

Soil zone	Soil type	Initial recharge rate (previous study)	Calibrated recharge rate (After adjustment)
3	Sand	12	6.14
1	Sandy clay	9.8	4.9
5	Sandy clay loam	6.2	3.7
4	Clay	7.3	3.1

2) *River conductance*

Seepage flux was measured along the rivers (Nan and Yom rivers) to know discharge and recharge from the river seepage. The seepage values are different from upstream to downstream base on bed materials. The bed materials of upstream, mid-stream and downstream are sand, sandy clay and clay [13]. From the previous model calibration with monitored well records near rivers, the conductivity value range from 2.2 to 2.0m/day in Nan River and 1.2 to 1.9m/day in Yom River. From the field measurement, seepage flux varies from 7.8 to 4.8 m/day. The field measured conductance values shows higher values than those previous model values. Since the upstream is sand, there was a good interaction to the aquifer from upstream to downstream. Therefore, the conductance values along the river were adjusted and calibrated (Fig. 6). The less error of the calibrated conductance values is noted. The calibrated values range from 1.0 to 5.5m/day in Nan River and 1.0 to 1.5m/d in Yom River (Table 2). The calibrated values are also higher than field measurement data. However, these values are close to the other study (0.1 to 4.9m/d) in Saigon River [14] and used in local groundwater model development.

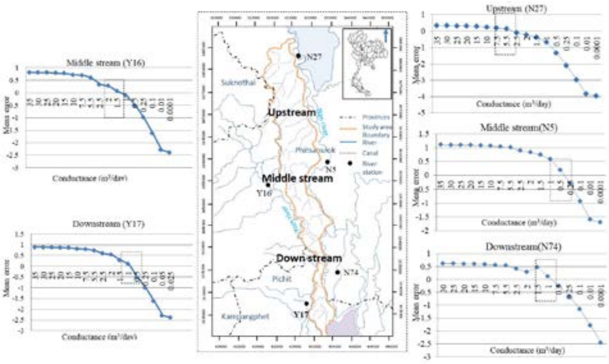

Fig. 6. River conductance rate by river bed materials

TABLE II. RIVER CONDUCTANCE VALUES

Stream	Bed material	Previous study		Calibrated	
		Nan	Yom	Nan	Yom
Upstream	Sand	2.2	-	5.5	-
Midstream	Sandy clay	2.1	1.5	0.5	1.5
Downstream	Clay	2.0	2.0	1.0	1.0

B. *Local model calibration*

First, boundary conditions are defined from peizometric heads of previous region model (Fig.7) and adjusted recharge parameters; land recharge and river conductance values were used and calibrated during the period 1993 to 2003 in both steady and transient states. Recharge parameters were provided the best match with the nearby observed data.

A steady-state model was then calibrated with data from development time and the transient model was constructed using the calculated heads from a steady-state model as initial head conditions. The time period for simulation is divided into two stress period. A steady-state period is 1993 and the transient period is from 1993 to 2003. The computed peizometric head values of a steady-state and transient state gave the good performance when compared with the observed data (Fig. 8) and the total error summary in both states are shown in Table 3.

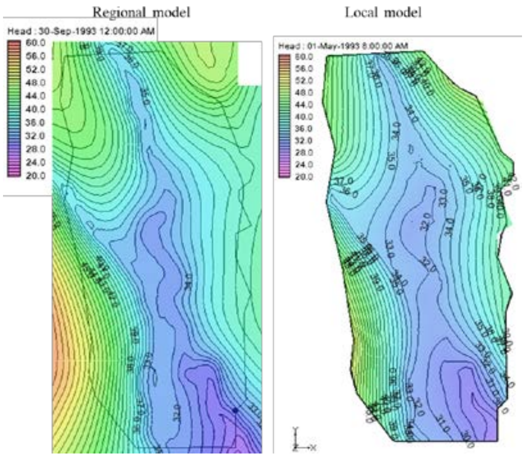

Fig. 7. Groundwater level condition of the model (Right: previous regional model, Left: local model)

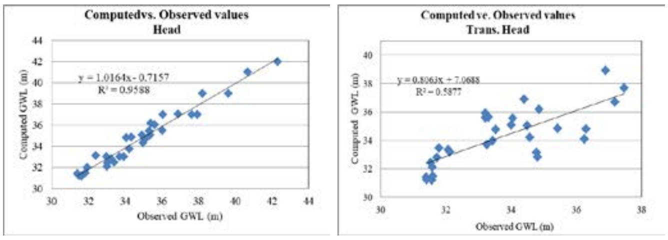

Fig. 8. Comparison of computed and observed peizometeric heads in both states

TABLE III. ERROR SUMMARY OF CALIBRATION RESLUTS IN BOTH STATES

Error (unit: m)	**Steady state**	**Transient**
Minimum	-0.92	-2.18
Maximum	0.96	2.68
Mean error (ME)	-0.14	0.53
Mean absolute error (MAE)	0.50	1.16
Root mean squared error (RMSE)	0.58	1.39
Nash-Sutcliffe coefficient (NSE)	0.92	0.69

C. *Groundwater flow budget*

Flow budget of Groundwater was analysed to present exchange flow volume of all components of groundwater budget including gw-sw interactions. The flow budget tools in groundwater model provide the inflow and outflow volume at each cell such as river recharge, land recharge, pumping discharge, storage and net of inflow and outflow. The groundwater flow budget is analyzed in seasonal: rainy (April to September) and dry (October to March) and water year patterns (very dry, dry, normal, wet based on dam storage volume) [15] from well calibrated groundwater model results. The annual average rainfall is about 1243mm/year [13]. From the analysis, the groundwater flow budget can be described as follows (Fig. 9).

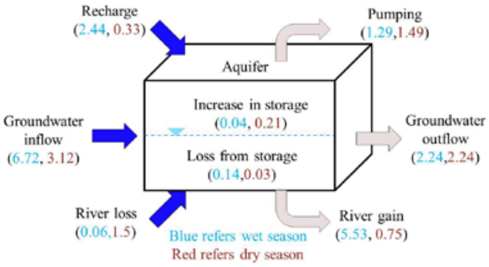

Fig. 9. The conditions of groundwater flow budget

D. *Interaction volume and patterns*

1) *Land recharge*

According to flow budget analysis from local groundwater model (Table 5). Water year is definde the reservoir storage of Bumhipol and Sirikit Dam [15]. In wet year, groundwater flow from the baoundary into the aquifer is 6.34 MCM/day (rainy) and 2.81MCM/day (dry). Land recharge to the aquifer 1.92MCM/day (rainy) and 0.26MCM/day (dry). River loss to the aquifer 0.42MCM/day (rainy) and 1.83MCM/day (dry). Meanwhile, river gains 4.73MCM/day (rainy) and 0.59MCM/day (dry) from the groundwater. In dry year, well pump 1.36MCM/day(rainy) and 1.65MCM/day which is higher that wet year. In this area, the main factor for groundwater flow budget is land rechage in rainy season and river recharge in dry seaon.

TABLE IV. WATER BUDGET BY SEASON AND WATER YEAR; UNIT: MCM/DAY

Water Year	***Groundwater inflow***		***River loss***		***Land recharge***		***Storage in***	
	Wet	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***
Very Dry	6.77	3.84	0.00	1.82	1.92	0.26	0.01	0.2
Dry	6.95	3.28	0.04	1.83	2.09	0.32	0.00	0.18
Normal	6.22	2.74	0.15	1.91	2.32	0.27	0.07	0.14
Wet	6.34	2.81	0.42	1.83	2.45	0.27	0.01	0.22
Water Year	***Groundwater outflow***		***River gain***		***Well pumping***		***Storage out***	
	Wet	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***
Very Dry	2.39	2.34	5.9	1.21	0.76	1.70	0.17	0.00
Dry	2.38	2.43	5.3	0.62	1.36	1.65	0.00	0.06
Normal	2.21	2.30	4.58	0.52	1.40	1.43	0.02	0.01
Wet	2.07	2.18	4.73	0.59	1.35	1.49	0.03	0.04

2) *River loss and gain*

There are two main aspects of interaction between surface water and groundwater. Firstly, the flow of groundwater support rivers flow and secondly the flow from rivers to groundwater. The rate of flow between river and aquifer is calculated from the different in hydraulic heads in the river and the adjacent aquifer using equation (5). There are mainly three river stations along Nan River and two stations at Yom River.

The condition of river loss and gain during the study period (1993-2003) is shown in (Fig.10). Groundwater loss water 1.2 MCM/day (rainy) and 1.19MCM/day (dry). River gave to the aquifer 0.93MCM/day (rainy) and 0.95MCM/day (dry) in upstream (N27). Water stored in middle stream (N5A) and goes down into downstream (N74) on Nan River. In Yom river, aquifer gave to the river 0.7MCM/day (rainy) and 2.62MCM/day (dry). It means that the river store the water in the upstream and flow to the downstream.

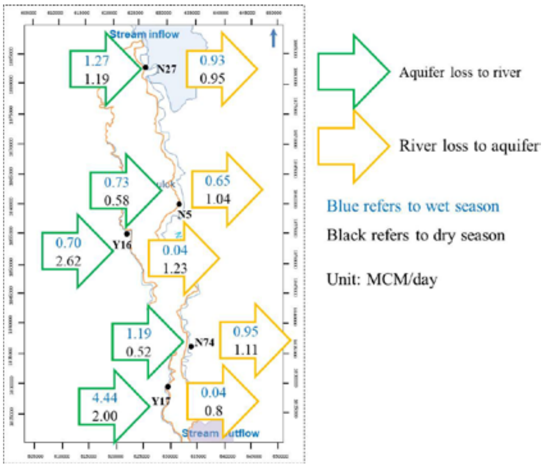

Fig. 10. The conditions of river gain and loss along river reach

V. CONCLUSTIONS

In summary, the local groundwater model was developed by boundary condition from the previous regional groundwater model. Recharge parameters; land and river were adjusted and compared with field measurement data. Land recharge and river recharge were measured in the field measurement. The calibrated land recharge rates are 4.9, 6.1, 3.1 and 3.6cm/day for each soil zone and the average recharge rate of the field measured value is 4.43cm/day. It can be used in the local groundwater model development. The adjusted river conductance values are 5.5m/day for upstream, 0.5m/day for midstream and 1.0m/day for downstream which showed small value than field data.

The interaction volume and patterns between surface water and groundwater was analysed from water balance via developed local groundwater model. Based on the change in water year, the aquifer gains water as land recharge are 2.72MCM/day in wet year and 2.18MCM/day in drought year of the total inflow. River recharge (river loss) to the aquifer is 2.25MCM/day in wet year and 1.82MCM/day in drought year. River recharge to aquifer is higher than land recharge in wet yea. However, river recharge is higher in drought year than land recharge. The river loss and gain is also main affect to the groundwater balance of the study area. River loss water from upstream and water store in middle stream and goes down into downstream. The value of river loss and gain in the rivers were estimated from river conductance and the values are smaller than the field measurement which needs more detail field survey. These findings can be used for future groundwater planning and management in the area.

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