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ORIGINAL ARTICLE

Estimation of Groundwater Flow Budget in the Upper Central Plain, Thailand from Regional Groundwater Model

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Abstract**:** Groundwater is playing an important role in water abstractions and consumptions especially in the Upper Central Plain, Thailand. The farmers tend to grow rice more by achieving irrigation using surface water but the amount needed for rice cultivation was not proper in dry years and farmers tended to use groundwater as a supplement. The excessive extraction of groundwater will be increased especially in the dry years due to the climate change. This study aims to investigate the groundwater flow budget change pattern mainly focused on analyzing the groundwater and river interaction pattern and volume by using groundwater model (GMS) by seasonal and water year in term of groundwater recharge, river recharge, groundwater storage and groundwater pumping.

Keywords: regional groundwater, flow budget pattern, river interactions, Upper Central Plain, Thailand

1. Introduction

Upper Central Plain is the most important area for Thailand's economy. It is also the most agriculturally productive area without its own large water sources. Demand for water in this area far exceeds locally available supply. The amount needed for rice cultivation was not proper in dry years and used groundwater as supplement. The area therefore depends heavily on water from river basins upstream. Groundwater in this area is mainly recharged by rainfall and stream seepages. There is limited information on groundwater extraction rates at the national level. A number of canals had been constructed in the Central Plain but the canals did not form a controlled irrigation system, however, but simply a distribution net, and whether additional water could be made available depended on the level of the rivers. The local farmers depended on both surface water and groundwater sources especially in the dry season. Farmers cultivate paddy all year round and need irrigation water supply to match with crop requirement all time. They face the water shortage from surface water allocation in these areas. Most farmers turned to use groundwater to

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supplement irrigation water. Hence, there is a need to assess the groundwater potential in order to manage both surface water and groundwater properly. However, the groundwater modeling needs good parameters for simulation. With the limited well data, proper parameter estimation is needed for the groundwater modeling (Sucharit K., Panot P., 2002, 2003). In this area there are some studies on the conjunctive use (Sucharit K , Werapol B. 2006), thought the parameters used are from the trial-error method.

2. Study objectives

The main purpose of this study is to investigate the flow budget change of groundwater and to analysis the patterns of river interactions in seasonal (rainy, dry) and water year (drought, dry, normal, wet: classified by the dam storage in November 1 of each year) by using groundwater modeling system (GMS) software.

3. Study area

The Upper Central Plain is located in the Northern part of Chao Phraya Plain covering the areas of Sukhothai, Phitsanulok, Kampangphet, Pichit, and Nakornsawan Provinces. Total area is 47,986 square kilometers. Average height is approximately 40-60 meters above mean sea level. It is composed of five basins that are Lower Ping basin, Lower Yom basin, Lower Nan basin, Upper Sa-Gae-Grang basin, and Upper Chao Phraya basin. The main rivers in the study area are the Yom River (West) and the Nan River (East) which are parallel flow from North to South, as shown in Fig. 1. The average annual rainfall is between 900 to 1336 mm/year with more than 81% of the annual rain falling during the rainy season from April to September, and less than 19% of the annual rain falling during the dry season from October to March. Pan evaporation ranges from 1400 to 2000 mm/year with the lowest evaporation in August and the highest in February. The humidity is generally varying from 70% to more than 80% in the wet season. The temperature varies between 27°C in the coolest month (January) and 32°C in the hottest month (May).

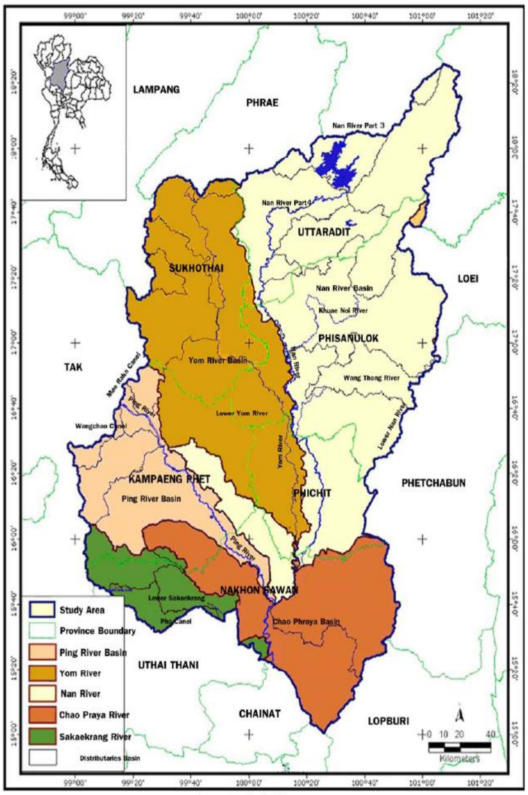

Figure 1 Upper Central Plain Basin, Thailand

4. Methodology

To understand the groundwater flow budget change and river interactions, the groundwater model was developed by estimating the values of aquifer parameters such as specific capacity (S_c) and transmissivity (T) from pumping test (Pwint P. A., Sucharit K., 2017, THA). The outputs of water budget presented the pumping rate, river recharge, river leakage, land recharge by seasonal from 1993 to 2003. The groundwater flow budget and river interaction patterns are then analysed in seasonal (rainy and dry) and water year (drought, dry, normal, wet) patterns from well calibrated/verified groundwater model simulation results.

4.1 Aquifer Characteristics

The high terrace deposits, the low terrace deposits and flood plain deposits are the main hydrogeological characteristic of this area, while the western and eastern areas were consolidated aquifers, composed of granite and volcanic rocks. The western, eastern and northern borders are an impermeable consolidated rock. The southern part is partially blocked by impermeable rocks and forms a narrow through the mountains in the east (See Fig. 2). The aquifer system in this study was defined as a two-layer aquifer, whereby the thickness of the high terrace deposits, low terrace deposits, and recent flood plain deposits represented (Werapol B., Sucharit K., 2006) (See Fig. 3).

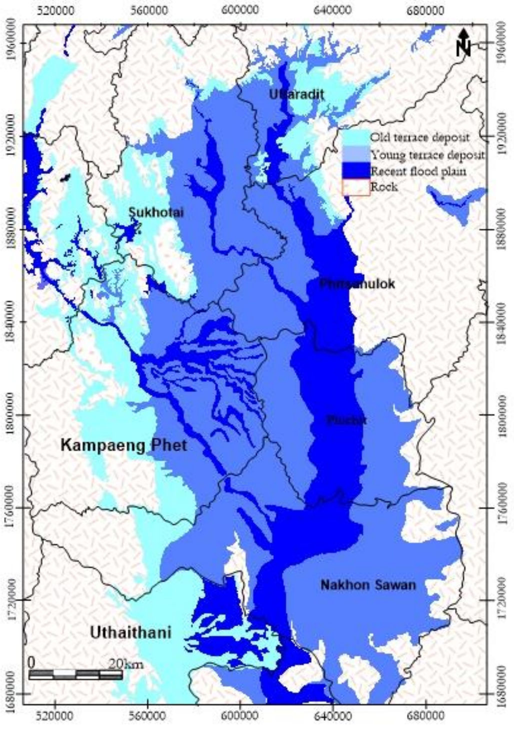

Figure. 2 Aquifer characteristics of the study area

4.2 Groundwater use

The upper part of the Central plain of Thailand is located in a large plain that is very suitable for agriculture, as water resources are normally plentiful. However, with the active price polices mentioned, farmers nowadays tend to grow rice more often, which can be only be achieved through increased irrigation using both surface and also more groundwater, putting more pressure on the available water resources in the region. The major groundwater use in this area is by agriculture, namely, for rice and some sugar cane in the western section of the study area. The average capacity per well is 41m^3/hour, whereas the average pumping rate per well is 79 m^3/day (Werapol B., Sucharit K. and Chokchai S., 2006). Table 1 described the water demand and water situation from 1993-2003. In average the ratio of groundwater use and surface water use were 0.12 and 0.63 respectively. In drought year, the ratio of groundwater use was highest (0.13-0.17) and the lowest was in wet year (0.06-0.09) (Chokchai S., Sucharit K., 2017, THA).

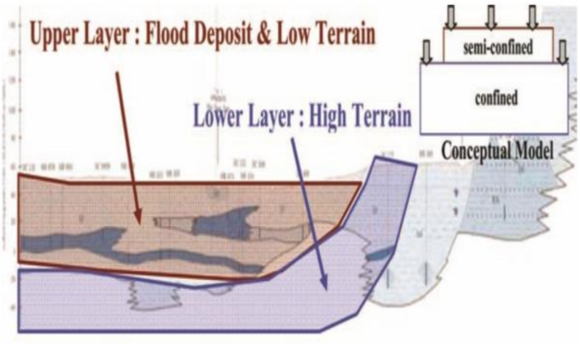

Figure 3 Two-layer aquifer conceptual model

Table 1 the water demand, water use pattern and water situation in 1993-2003

Year	Water Demand (MCM)	GW ratio	SW ratio	Water year
1993	3,885	0.12	0.63	Dry
1994	4,617	0.1	0.53	Drought
1995	3,775	0.09	0.68	Wet
1996	4,757	0.08	0.74	Wet
1997	4,873	0.12	0.66	Normal
1998	4,701	0.13	0.52	Normal
1999	4,535	0.17	0.64	Drought
2000	4,588	0.14	0.67	Normal
2001	4,804	0.08	0.64	Wet

2002	5,445	0.07	0.63	Wet
2003	6,159	0.06	0.63	Wet
Average	4,740	0.12	0.63	

4.3 Groundwater Model

Groundwater model used in this study is MODFLOW (the USGS's three-dimensional 3D finite- difference groundwater model). MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. It is used to predict aquifer response, in terms of head (ground water level) and fluxes into and out of an aquifer, to natural and human induced stresses.

The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial differential equation.

$$\frac{\partial}{\partial x}\left[Kxx\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial x}\left[Kyy\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[Kzz\frac{\partial h}{\partial z}\right]+W=Ss\frac{\partial h}{\partial t} \quad (4)$$

Where,

Kxx, Kyy and Kzz are the values of hydraulic conductivity along the x, y, and z coordinate axes and are function of space

h is the potentiometric head (hydraulic head)

W is a volumetric flux per unit volume representing sources and/or sinks of water.

S_s is the specific storage of the porous material and is function of space and t is time.

The equation, together with specification of flow and head conditions at the boundaries of aquifer system and specification of initial head conditions, constitutes a mathematical representation of groundwater flow system.

4.4 Error estimation

Calibration criterions for both the steady-state and transient simulations were employed to match simulated heads with observed head. The model calibration was accomplished by analyzing the models' performance specified by statistical goodness-of-fit measures- mean error, the mean absolute error (MAE_h), root mean squared error of head ($RMSE_h$), and Nash-Sutcliffe coefficient (NSE_h) as objective functions, and describes as follows:

$$MAE_h = \left|\frac{1}{n}\sum_{i=1}^{n}(h_{o,i}-h_{s,i})\right| \quad (1)$$

$$RMSE_h = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_{o,i}-h_{s,i})^2} \quad (2)$$

$$NSE_h = 1\frac{\sum_{i=1}^{n}(h_{o,i}-h_{s,i})^2}{\sum_{i=1}^{n}(h_{o,i}-h_{o,i})^2} \quad (3)$$

Where,

n is the number of observation wells,

h_o is the observed head (m),

h_s is the simulated head (m)

MSE_h aims at measuring the absolute disparity between simulated and observed heads. Overall, the largest head discrepancies were calculated using $RMSE_h$. The relative degree of the calibration residual measured form the mean observed head water determined by NSE_h is shown in Table 2.

Table 2 the criteria of Nash-Sutcliffe coefficient

Properties	Value
Very good	$0.75<NSE_h\leq1.00$
Good	$0.65<NSE_h\leq0.75$
Satisfactory	$0.50<NSE_h\leq0.65$
Unsatisfactory	$NSE_h\leq0.50$

4.5 Data used

The data used for groundwater model development, i.e., boundary conditions, pumping distribution, are based on the previous study (Chokchai S., Sucharit K., 2017, THA). However, to improve the simulation accuracy, the smaller model grid size (2 x 2 sq. km) was chosen and the parameter estimation and its distribution, the transmissivity distribution was estimated by using empirical formula of specific capacity and transmissivity in linear on a log scale and hydraulic conductivity distribution was estimated by using geostatistical methods which proved to give better simulation results compared with the previous study (Pwint P. A., Sucharit K., 2017, JT).

5. Results and Discussions

5.1 Development of regional groundwater model

The groundwater flow model (MODFLOW) is developed to simulate groundwater flow condition and to simulate the change of groundwater storage. Observed groundwater level and hydraulic parameter derived from this study were used as input data. The model was calibrated with new parameter estimation (as mentioned in 4.5). The aquifer system for the study are is defined as lower and confined layer between 100-200 m. The 3D block-centered grid model representing the groundwater basin has a grid size 2 km × 2 km, resulting in 13166 elements in the layer. The model development design is shown in Fig. 4 and Table 3.

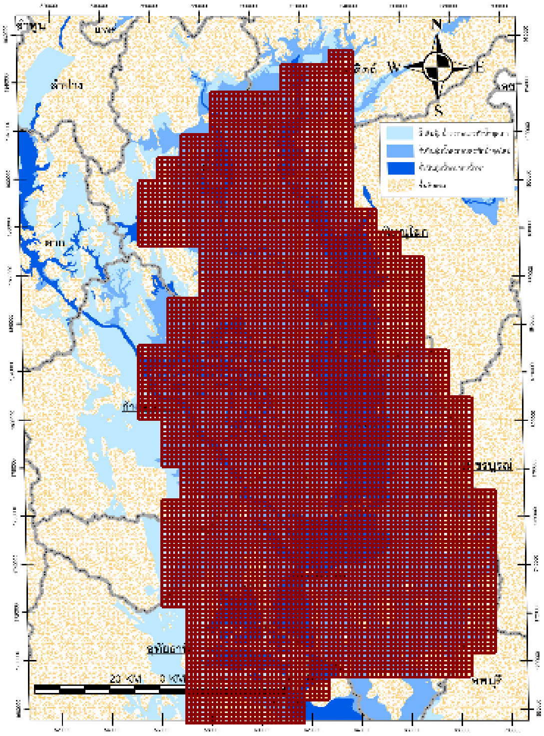

Figure 4 Regional groundwater model grid design

Table 3 the properties of model grid design

Item	Value
Grid type	Cell centered
No. of surface notes	43146
No. of cells	28272
Cells in x direction	152
Cells in y direction	93
Grid spacing (km)	2

5.1.1 Steady state model calibration

The hydraulic parameter estimated was put into the model and used optimization scheme. The computed heads were compared with the observed data. The results showed that the simulation values were closed with the observed values for hydrological parameter estimation in steady state. The good performance, when compared with the observed data, is shown in Fig. 5.

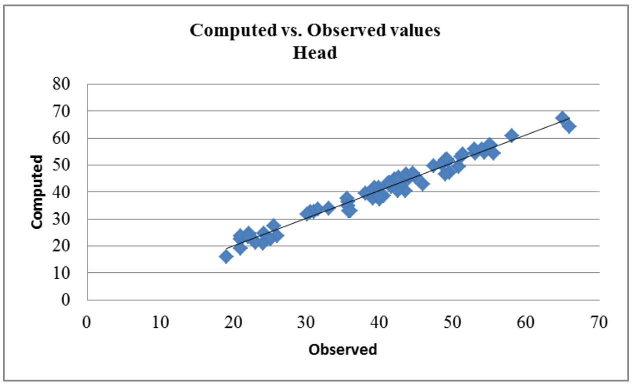

Figure 5 Comparison of computed and observed GWL in steady state

5.1.2 Transient state model calibration

It is similar with the result in the steady state. The computed GWL values are closely relation with the observed data in transient state (see Fig 6). The total error summaries in both states (steady and transient) were shown in Table 4.

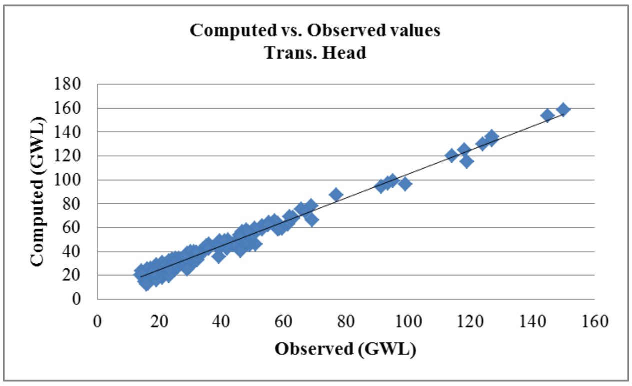

Figure 6 Comparison of computed and observed GWL in transient state

Table 4 the error summary of calibration results

Error (m)	Steady state	Transient state	
		Calibration	Verification
Minimum	-6.94	-4.948	-4.71
Maximum	4.16	4.655	4.14
Mean error	-1.65	-1.38	-1.58
Mean abs. error	2.84	2.54	2.28
RMSE	3.26	3.01	2.62
NSE	0.93	0.95	0.74

5.2 Groundwater budget components

The application of groundwater modeling described as river recharge volume and pattern in the Upper Central Plain area. Groundwater balance was estimated to present exchange flow volume of all components of groundwater budget. The flow budget tools in groundwater model provides the inflow and outflow volume at each cell such as river recharge, land recharge, pumping discharge and storage.

The change of groundwater storage in dry year (1993) of the whole study area was 127 MCM; in drought year (1994, 1999) was 90 MCM, 64 MCM; in wet year (1995-1996, 2001-2003) was 87 MCM, 60 MCM; in normal year (1997-1998, 2000) was 72 MCM, 63 MCM resulting the average rate of groundwater storage was 74 MCM (see Fig. 7).

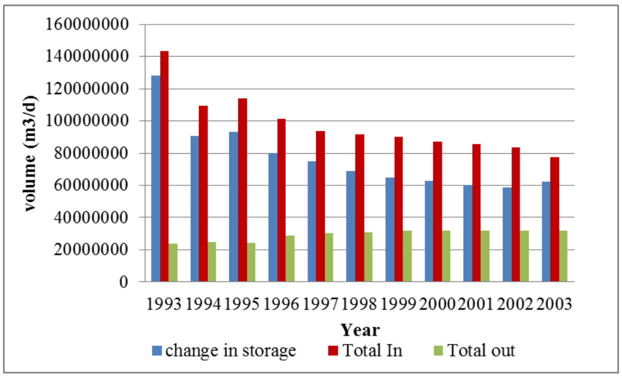

Figure 7 Change of groundwater storage from 1993 to 2003

The seasonal groundwater flow budgets of groundwater system in 2000 (normal year) are shown as diagram (see Fig 8a, 8b). From the analysis, the groundwater flow budget can be described as follows. The groundwater gains the land recharge 8.3% and river leakage to the aquifer is about 88% in dry season. The aquifer loss water to river is about 28% in dry season and 2.8% in wet season of total outflow while the pumping is about 37% in dry season and 15% in wet season of total outflow.

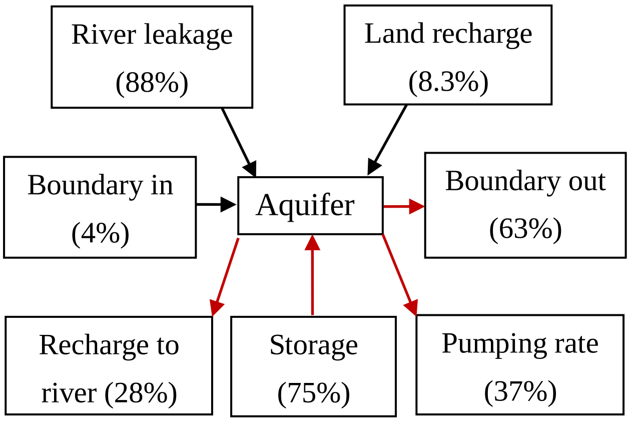

Figure 8a The groundwater flow budget for dry season in 2000 (normal year)

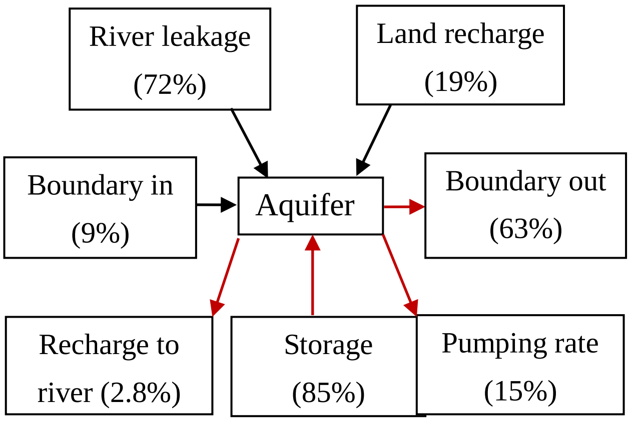

Figure 8b The groundwater flow budget for rainy season in 2000 (normal year)

Based on the change in water year, the aquifer gains water as land recharge are 0.08% MCM in dry year; 0.09% in drought year; 0.78% MCM in normal year; and 0.73% in wet year. The aquifer gains water from river are 0.33 MCM in dry year; 0.34 MCM in drought year; 0.84 MCM in normal year; and 1.01 MCM in wet year. The aquifer loss water to river is 10.1 MCM in drought year; 7.77 MCM in dry year; 5.72 MCM in wet year; and 6.55 MCM in normal year. The amount of water storage is about 62% of total inflow of water. The detailed groundwater flow budgets of water year from 1993 to 2003 are shown as follows (see Table 5).

Table 5 the seasonal flow budget of groundwater system during 1993-2003 in water year (unit: MCM)

Time period	1993		
Water Year	Dry		
Season	rainy	dry	annual
River Leakage	0.62	0.02	0.64
Recharge to river	10.4	11.09	21.49
Storage change	10	11.13	21.13
Land recharge	0.72	0.83	1.55
Pumpage	0.52	0.62	1.14
Flow in (Boundary in)	0.41	0.41	0.82
Flow out (Boundary out)	1.09	1.11	2.2
Time period	1994		
Water Year	Drought		
Season	rainy	dry	annual
River Leakage	0.65	0.01	0.66
Recharge to river	6.55	8.9	15.45
Storage change	6	9.12	15.12
Land recharge	0.84	0.99	1.83
Pumpage	0.49	0.66	1.15
Flow in (Boundary in)	0.41	0.41	0.82
Flow out (Boundary out)	1.13	1.14	2.27
Time period	1995-1996		
Water Year	Wet		
Season	rainy	dry	annual
River Leakage	0.7	0.001	0.701
Recharge to river	4.82	10.5	15.32
Storage change	3.77	10.7	14.47
Land recharge	0.98	0.84	1.82
Pumpage	0.51	0.05	0.56
Flow in (Boundary in)	0.41	0.41	0.82
Flow out (Boundary out)	1.15	1.15	2.30
Time period	1997-1998		
Water Year	Normal		
Season	rainy	dry	annual
River Leakage	1.12	0	1.12
Recharge to river	3.77	9.33	13.1
Storage change	2.39	9.6	11.99
Land recharge	0.71	0.85	1.56
Pumpage	0.52	0.63	1.15
Flow in (Boundary in)	0.42	0.41	0.83
Flow out (Boundary out)	1.14	1.14	2.28
Time period	1999		
Water Year	Drought		
Season	rainy	dry	annual
River Leakage	1.84	0	1.84
Recharge to river	3.43	8.89	12.32
Storage change	1.63	9.19	10.82
Land recharge	0.98	0.9	1.88
Pumpage	0.52	0.69	1.21
Flow in (Boundary in)	0.41	0.41	0.82
Flow out (Boundary out)	1.13	1.13	2.26

Time period	2000		
Water Year	Normal		
Season	rainy	dry	annual
River Leakage	1.91	0	1.91
Recharge to river	3.27	8.69	11.96
Storage change	1.49	9.01	10.5
Land recharge	0.89	0.82	1.71
Pumpage	0.52	0.64	1.16
Flow in (Boundary in)	0.42	0.41	0.83
Flow out (Boundary out)	1.12	1.12	2.24

Time period	2001-2003		
Water Year	Wet		
Season	rainy	dry	annual
River Leakage	2.02	0	2.02
Recharge to river	3.05	8.39	11.44
Storage change	1.22	8.83	10.05
Land recharge	0.83	0.62	1.45
Pumpage	0.52	0.56	1.08
Flow in (Boundary in)	0.41	0.41	0.82
Flow out (Boundary out)	1.1	1.09	2.19

5.3 Groundwater and river interactions

The river interactions (river leakage and recharge to river) play an important role in the groundwater budget in the study area (based on the results from5.2). More investigations on river interactions were performed and the results are summarized as follows.

River interactions were calculated directly by exporting groundwater budget at correlative cell in GMS software. River interaction calculations based on the stage in the river, hydraulic head in the part of the groundwater system underlying the river, river bed bottom elevation and hydraulic conductance of the river bed.

River interaction is separated into two components: river leakage to the aquifer and aquifer recharge to river. River recharge-in (river recharge) represents the volume of flow from river to aquifer with minus value and river recharge-out (river leakage) presents the volume of flow from aquifer to river with plus value.

River recharge in dry season (October to March) is higher than in rainy season (April to September) with the average volume of inflow and outflow were 4,176,50m^3/d in rainy and 9,048,200 m3/d in dry season respectively. River leakage to aquifer was 1,636,400m/d in rainy and 2,900 m3/d in dry season respectively (see Fig. 10).

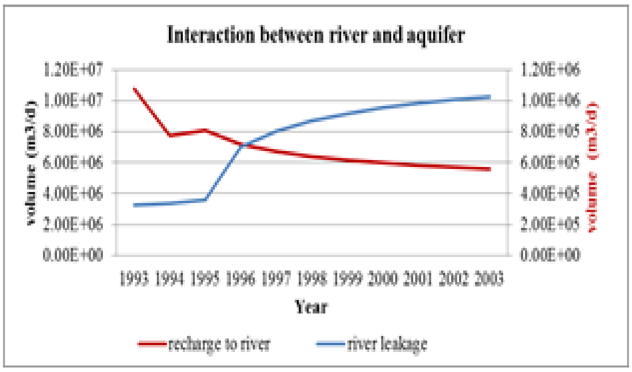

Figure 10 Interactions between river and aquifer

The river leakage is higher than land recharge in the whole year from 1993 to 2003 due to river stage. The pumping rate is 562,400 m^3/d in average year from 1993 to 2003) with increasing trend in the drought year. Land recharge components showed good correlation with annual rainfall in this area (see Fig 11). Recharge to river is reducing due to decreasing land recharge and more groundwater pumping.

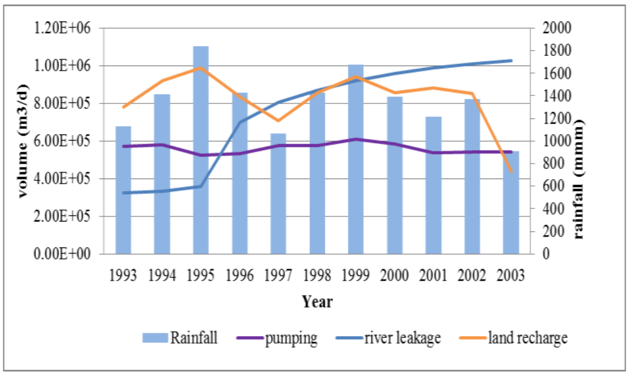

Figure 11 Correlation recharge components and pumping rate

6. Conclusions

In summary, the developed regional groundwater model can properly represent the groundwater flow in the study area where the root mean square calibration error is 3.26m in steady-state mode and 3.01 m in transient mode while the root mean square error of verification model is 2.62m.

The change of groundwater storage in dry year (1993) of the whole study area was 21.13 MCM; in drought year (1994, 1999) was 15.12 MCM, 10.82 MCM; in wet year (1995-1996, 2001-2003) was 14.47 MCM, 10.05 MCM; in normal year (1997-1998, 2000) was 11.99 MCM, 10.5 MCM resulting the average rate of groundwater storage was 60 MCM.

River leakage to aquifer was 25 MCM in rainy season (October to March) and 54 MCM in dry season (April to September) respectively. River leakage in dry season is higher than in rainy season about 60 MCM with the average volume of inflow and outflow respectively. River leakage is increasing due to the river stage while recharge to river is reducing due to decreasing land recharge and more groundwater pumping.

From the groundwater flow budget analysis, it is found that the river interactions especially recharge to river plays major role to balance the groundwater reserve in this area.

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