Surface and groundwater dynamic interactions in the Upper Great Chao Phraya Plain of Thailand: semi-coupling of SWAT and MODFLOW

[1]Werapol BEJRANONDA, [1]Aksara PUTTHIVIDHYA [1], Sucharit KOONTANAKULVONG, [2]Manfred KOCH

[1]Department of Water Resources Engineering, Faculty of Engineering, Chulalongkorn University, Thailand, sun2child@yahoo.com
[2]Department of Geohydraulics and Engineering Hydrology, University of Kassel, Germany

Abstract Surface and groundwater dynamic interactions in the Upper Great Chaophraya Plain of Thailand is being explored. SWAT and MODFLOW, surface-soil water and groundwater models, are semi-coupled to determine flow behaviour and hydrological components. The coupled models are executed by running simulation individually while monthly river-groundwater interaction and groundwater recharge are employed to generate surface and groundwater dynamic interactions. The calibrated results from coupled simulations show that the coupling method improves the streamflow and groundwater simulations. Moreover, the water balance analysis can describe the local surface and subsurface water interaction. Furthermore, streamflow and groundwater level calculations, especially in the dry season, are improved by 12% and 2.3%, respectively. The dynamic simulation results reveal that interaction is seasonal dependent The improvement of water balance analysis suggest that coupled modelling is a key to clarify the relationship between surface and subsurface water as well as its interaction.

Keywords: Coupling, Interaction, SWAT, MODFLOW, Water balance

1. Introduction

In spite of the tremendous steps made in recent years towards becoming an industrialised country, Thailand still economically defines itself as an agricultural country, as the export of agricultural products is still bringing in a large portion of the national revenue. Boosting up rice production and the often precarious living conditions of the rice farmer has, thus, been an active policy of the Thai government in recent years and has leaded it to develop agricultural price-subsidized schemes and many irrigation projects in the Great Chao Phraya Plain to support local farmers. At the same time, both surface water and groundwater resources have been developed to respond to an increased water consumption. Since it is not possible to provide sufficient surface water for irrigation, a conjunctive use scheme should be developed. Hence, there is a lack of a comprehensive water balance analysis, which is necessary to understand the surface water behaviour, and, because of the intertwined interaction, also the subsurface water resources, both of which are prerequisites for the conjunctive use study.

The mathematical model is an important tool in water resources planning and management. Surface water and groundwater models have been used to estimate water balance managing and allocating. According to the convenience of the model development, classical surface and groundwater models were mostly simulated separately and supposed to use simple interaction of surface-subsurface water in their model boundary. When groundwater use was hugely rising and hydrological elements of whole water system are needed to fully manage, the coupling simulation of both surface and subsurface simulation was then developed.

Coupling of surface and subsurface models started with creating relationship between rivers and groundwater storage (Pinder and Sauer, 1971). Consequently the mathematical models assisted solving the complex flow between surface and subsurface, then deliver the stream-aquifer interaction program MODBRANCH (Swain, 1996), the coupling flow of MODFLOW and BRANCH. The complicated of river networks was developed into the coupling model (Orhan and Mustafa, 2004) to meet practical case study. Moreover 1-D coupling was developed into 3-D, Duflow-MicroFEM linkage (Smits, 2004). Coupling approach has been applied in specific case studies (Charles and Peter, 2004) surface and subsurface models have been joined, including fully-coupling of SWAT and MODFLOW (Il-Moon Chung, 2006). However the fully-coupling of surface and subsurface models are still complicated for practical application and data preparation. The semi-coupling is another approach for practical simulation. For this study SWAT and MODFLOW, surface and groundwater model, were semi-coupled to determine flow behaviour and hydrological components. The model simulation executed by running simulation individually while river-groundwater interactions and aquifer recharge were connected to construct surface-groundwater dynamic interactions. Furthermore, the coupled models were applied to the Upper Great Chao Phraya Basin to study the coupling method.

2. Study area

Upper Great Chao Phraya Plain of Thailand (Fig.1), covers about 38,000 km^2 (180 km x 300 km) of 8 provinces with a population of 4 million people. The main land-use is 63% agricultural, out of which 21% is irrigated, and 24% forest. More than 90,000 groundwater wells exist in the region. The main groundwater basin is dissected by five major rivers that flow from north to south and which have formed the geological basis as a depositional flood plain. The basin is surrounded in the east and west by mountains of volcanic rocks. The average elevation of the basin is 40-60 m.MSL. The basin drains into the lower basin in the south, though the free discharge is partially obstructed by crystalline rocks there. The 900 - 1,450 mm annual rainfall within the study region is apportioned to 81 % in the wet (Apr.-Sep.) and 19 % in the dry season (Oct.-Mar.).

3. Coupling of surface and groundwater model

Model-coupling was developed to improve flow behaviours of surface water and groundwater to correspond to theoretical hydrological system especially in soil and groundwater interface. Coupling process were divided into 3 steps; 1) Study and design, 2) Coupling and testing, 3) Application & Evaluation, as shown in Fig. 2.

3.1. Coupling-process development

Study and design: Watershed model SWAT-2005 and groundwater flow model MODFLOW-2003 were selected to simulate surface water and groundwater balance. The original edition of SWAT and MODFLOW were set up as a simple case and compared with its analytical method to explore the relationship between surface water and subsurface water. The study of coupling process was design for 3 major subject; coupling components, coupling time-dimension and coupling area-dimension.

Coupling and Testing: Designed coupling processes were applied into the simplified case for testing the coupling techniques, and further analyzed with hydrological equation. Therefore were compared to the simulation output, to check for any coupling mistakes. When the coupled simulation matched with analytical result and theoretical hydrological process, the coupling-process will be applied to the real field data.

Application and evaluation: The original SWAT and MODFLOW were applied to the Upper Great Chao Phraya Plain, also were calibrated and verified. The theoretical coupling-process was also attached in the modeling procedure. Comparing with observed data, the uncoupled and coupled simulations were assessed for coupling-process development. The coupling-process was evaluated with the improvement of model accuracy, defined as difference of error between uncoupled and coupled model.

3.2. Coupling methodology

According to the surface-groundwater balance analysis, the interactions between surface-water and groundwater modeled surface recharge and river-aquifer interactions which were used to couple the model in this study. The percolation (ie., the infiltration from soil water to aquifers included in SWAT modules), and river-groundwater interaction (i.e., the exchange of water between river body and groundwater included in MODFLOW modules) were selected to use in coupling process and interaction components. While the model was operating under coupling process, SWAT and MODFLOW were connected through some selected components that exhibited substituted duplicated functions. For example, in coupled model groundwater recharge was replaced with percolation, and baseflow was replaced with river-gw interaction (Fig. 3). The coupled models were executed by an interface program which was written to operate and transmit the model's information to the coupling process.

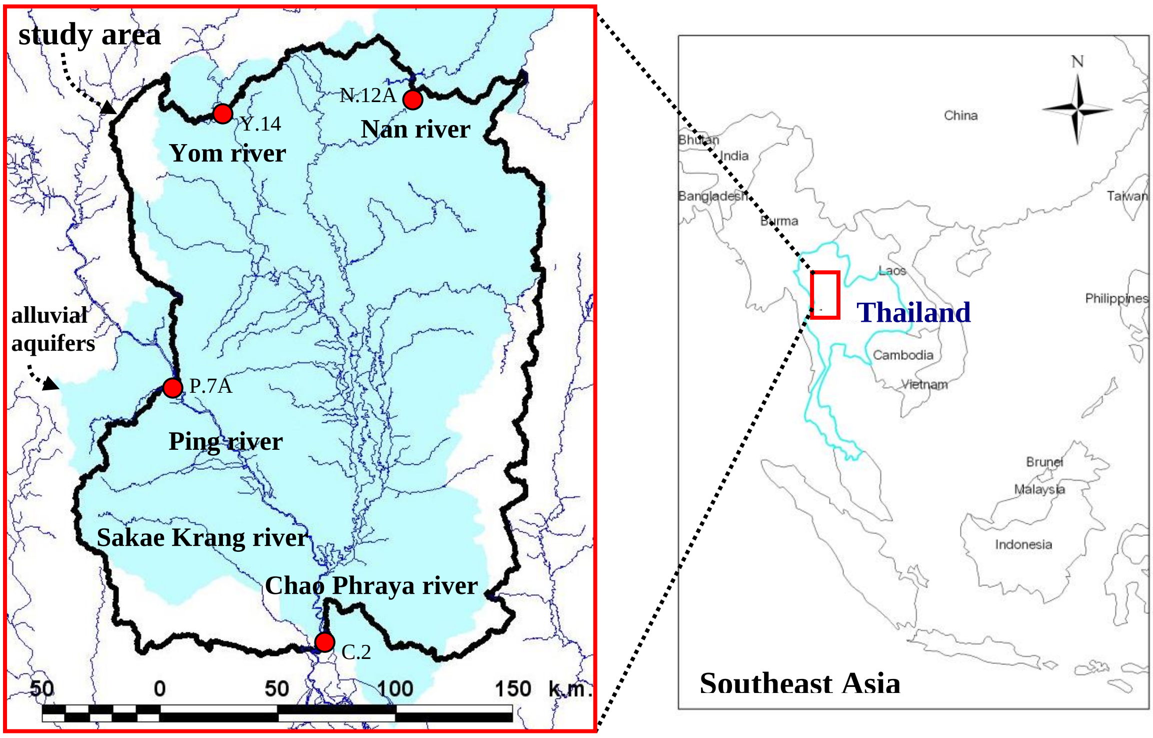

Fig. 1. Study area showing river networks and alluvial aquifers.

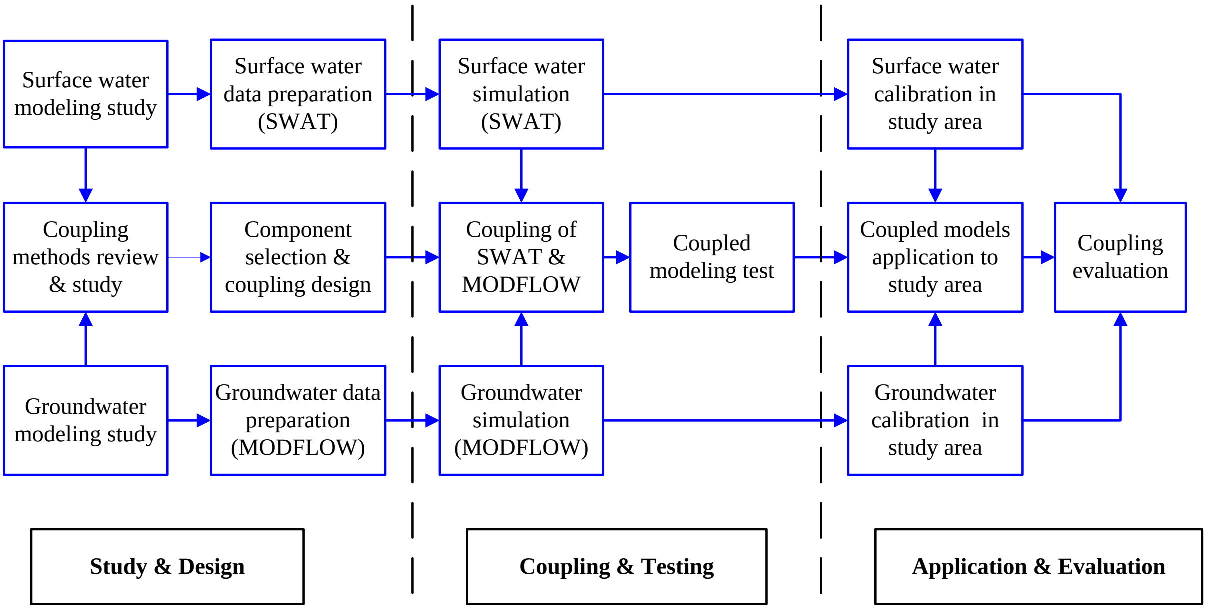

Fig. 2. Study scheme of coupling model.

3.2.1. Aeral coupling

Space dimension of surface and subsurface water model were calculated in difference way. SWAT l, distributed parameter model, was constructed with polygon-basins and river-network. MODFLOW, finite difference model, was constructed with grid-cells and river-nodes. Hence, the difference of spatial distribution of surface and subsurface model brought the coupling process accounted for the interactions into land and river phases. Land Phase was derived recharge from SWAT polygons to MODFLOW grid-cells and River Phase was 2-way interaction of SWAT streamflow poly line to MODFLOW river node (shown in Fig.4). The river recharge/baseflow in subbasins was calculated with river-groudwater interaction function in MODFLOW. In order to construct interaction entire study area, surface boundary was necessary to cover the subsurface boundary. The GIS technique assisted coupling process joining subbasin-polygons to grid-cells in MODFLOW.

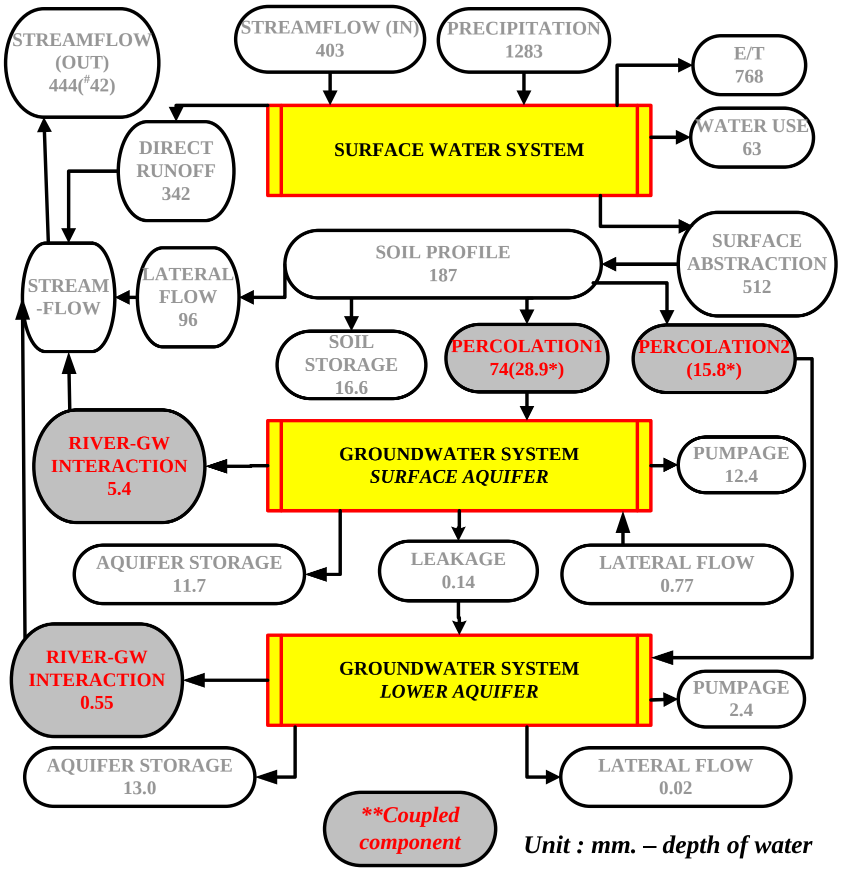

Fig. 3. Surface water and groundwater hydrological components with water balance analysis result.

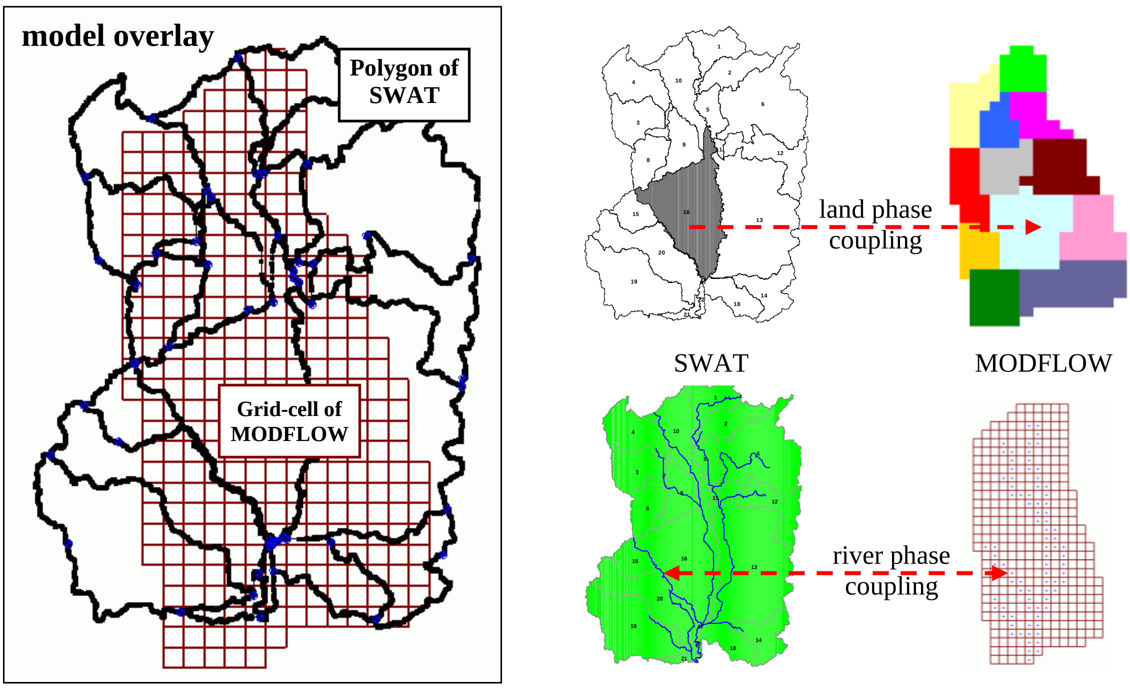

Fig. 4. Linkage between surface and groundwater model.

3.2.1. Time coupling

The groundwater movement is very slow compared to river discharge a big difference in time scale of surface and groundwater simulation. The groundwater model time-interval was 1 month, but surface water flow was calculated daily. Therefore the coupling process exchanged the model input/output data at specific coupling intervals to link the model time-dimension. Interpolation of overlapping time was then used to figure out the different time interval problem. The fineness of time interval depended on the fineness of input parameter which dominated in model sensitivity; pump and recharge rate. In this study, coupling time was defined up to 1 month due to the monthly pumping data.

3.3. Model development

Traditional SWAT and MODFLOW were set up individually, and then coupled together to link surface and subsurface models. The conceptual coupled-model was developed from topography, recharge behavior and aquifers layout. According to uncoupled models SWAT and MODFLOW, the coupled-model boundary was defined following the surface and subsurface boundary. The river network and watershed boundaries were used to describe coupling interaction to specific coupling zone interface. The surface and subsurface of Upper Great Chao Phraya Plain was connected each other, for coupling development, with 5 river course and 22 watersheds.

3.3.1. Surface water model

Surface hydrological processes were mainly represented with rainfall streamflow and soil water. The scattering rain on various land use and soil type caused different water movement behaviors, rainfall turned into runoff flowing out the basin and some seeped to soil-water then aquifers. The conceptual model of surface water drafted the complex surface-water behaviors developing the math model.

The watershed area was used to define model boundary. P.7A, Y.14, N.12A stream gauges were defined as flow-in boundaries and flow-out at the southernmost assigned with stream gauges C.2 constructing surface model boundary. The surface calculation unit was divided into 22 sub-basins covering Ping, Yom, Nan Sakae Krang and Chao Phraya river (Fig.1) flowing north to south. An infiltration (areal recharge) derived from rainfall, landuse characterization and soil-mechanic properties.

3.3.2. Groundwater model

The groundwater conceptual model, namely the aquifers and their confining boundaries, were defined using the concept of the hydrostratigraphic units which is defined as geologic units of similar hydrogeologic properties. The aquifer system in this study was defined as a two-layer aquifer, whereby the thickness of the upper, semi-confined layer varies between 40 and 100 m and that of the lower, confined layer between 100 and 300 m. The 3-D block-centred grid model representing the groundwater basin has a grid-size 10 km x 10 km (Fig.4), resulting in 320 elements in the upper and 346 elements in the lower layer. The western, eastern and northern borders of the model where assumed as an impermeable body of consolidated rock and were defined as specific inflow boundaries derived from the available head distribution along these boundaries. The southern boundary, which is partially blocked by impermeable rocks and forms a narrow trough between the mountains in the east and west, was set as an outflow boundary. The hydraulic properties of the aquifer, hydraulic conductivity, transmissivity and specific storage, were estimated from pumping tests. The river-aquifer interaction of the five main rivers giving monthly recharge were derived from the hydraulic properties of the river bed materials, the river cross-sections, the river stages and the seasonally varying computed groundwater table. The recharge, river stages as well as surface and groundwater use were adapted in response to the climatic conditions, namely, in terms of the amount of rainfall and the reservoir storage. As for the possibility of return flow of irrigated water into the canals was insignificant in the study area since the drainage canals nearly dried out and the irrigation area covers only 13% of the entire model where the overall recharge takes place (Bejranonda, 2006).

3.3.3. Coupled models

The sensitivity of groundwater model showed that the most significant parameter affecting to groundwater level are areal groundwater recharge and river-aquifer interaction. Therefore, percolation of SWAT (areal recharge) was applied on the top layer and on the outcropping sections of groundwater model, also, the river-aquifer interaction of MODFLOW (channel recharge) was linked to the streamflow network in surface water model.

The conceptual model of coupled model was designed base on original SWAT and MODFLOW modeling in the study area according to the connection of rivers, aquifers and soil-water. During the operation of coupling technique, the major rivers contributed water to aquifers, and vice-versa, calculated by river-aquifer interaction function and 22 sub-basins provided recharge to groundwater regulated by infiltration function (Fig.5). Both surface and groundwater were bonded with groundwater recharge and operated the connection with an interface program (Bejranonda, 2007) to exchange the input and output parameter between the models. The coupled parameters were transferred 2 times, 1) after the original SWAT and MODFLOW were simulated individually the time-series output of percolation was sent into groundwater model input, 2) then the groundwater was simulated with new input parameters and the model given river-gw interaction to streamflow discharge in surface model. The final outputs were kept in the coupled models providing coupled simulation result and hydrological components. Model coupling resultantly made a relationship of original SWAT and MODFLOW and simulated surface water and groundwater conforming to natural hydrological process. In addition, the coupled model gave dynamic interaction to the interface zone of surface and sub-surface model.

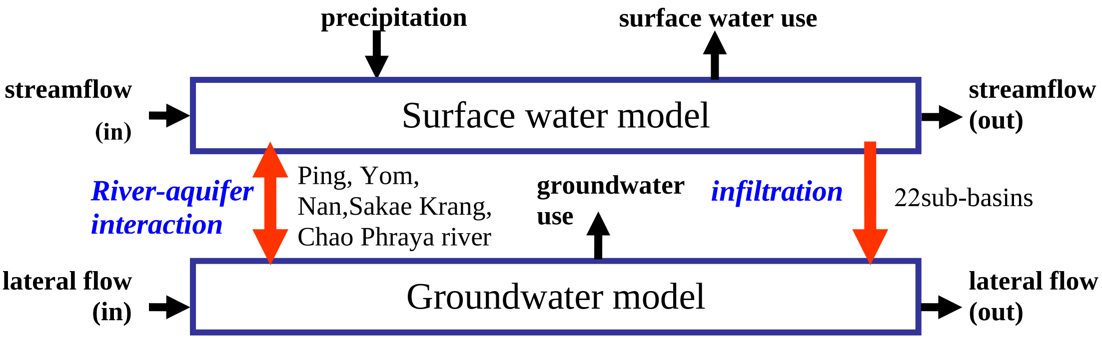

Fig. 5. The schematic of coupled surface-water and groundwater models in study area.

3.4. Calibration and verification

Concerning parameter sensitivity and field data, model parameters were selected for calibration and verification. The original SWAT and MODFLOW were individually calibrated and validated along 1993-2005 covering various water situations.

The calibration and verification of SWAT model were executed with monthly streamflow discharge obtained from stream gauge at basin outlet. CN number of 3 major landuses; forrest, rice and agriculture, and Available Water Capacity of Soil (AWC) of 5 soil-types in SWAT model were calibrated in 1993-1998. Surface water model verification was performed with historical river discharge during 1998-2003 resulting relative seasonally and monthly errors of 53%/36% and 77%/59% respectively in wet/dry season. This model result represented the ability of uncoupled surface water model computation, subsequently compared with the coupled model in evaluation step.

Groundwater model calibration and verification were performed in steady state as well as in transient state. Following the seasonal crop pattern, the seasonal stress period was used in the calibration of two weeks of recorded historical groundwater levels. Since during 2001-2003, the groundwater use was almost stable, due to a constant situation for the surface water, the average water level during the dry season of 2003 was selected to be the representative steady-state water level for the calibration. 13 groups of the hydraulic conductivity were adjusted during the steady-state calibration process. Transient-state calibration has been carried out, using the 1993-2003 historical water levels, whereby groups of specific storage have been calibrated. The transient simulation is initialised from an average wet-season water level. During the transient-state calibration, the pumping rate weights were fine-tuned, as these are often prone to errors. In summary, the root mean square calibration error is 3.70 m in steady-state mode and average seasonal error 5.67 and 4.79 m. of wet and dry season in transient model. An a *posteriori* transient-state verification/forecast, using two years of groundwater level monitoring data (2004-2005) and water level data from 50 extra observation wells collected during the study period (2005), has been performed, resulting in a root mean square error of 5.95 m. These results

of uncoupled groundwater model expressing ability of groundwater model ability would be compared with the coupled model in evaluation step.
The coupled model composing with calibrated SWAT and MODFLOW were simulated to determine residual error illustrating the coupled model ability. The entire historical data of surface water and groundwater was re-simulated to show the coupled model accuracy. Streamflow discharge of coupled model had seasonally and monthly errors of 42%/27% and 70%/45% respectively in wet/dry season. The root mean square error of coupled groundwater model was 5.62 and 4.69 m in wet and dry season.

3.5. Coupling result

Simulation of surface water and groundwater was operated with both uncoupled and coupled models comparing the effect of coupling sysetm. The calibrated result of coupled simulations in 1993-2003 provided monthly water components in hydrologic cycle included its interaction. The simulation result was analysis relatively to yearly water situation; drought, dry, normal and wet.
Compared with uncoupled surface water model, the coupled surface water simulation showed that calculated streamflow discharge at the study area outlet was especially more accurate in low flow of dry season. Hydrograph pattern was more accordant to the observed streamflow particularly in normal and wet year. Streamflow calculation of uncoupled and coupled models was significantly modified. The shadowed area in Fig.6 showed the different calculated discharge of uncoupled and coupled simulation resulting average 240 million m^3/month of differential calculation. The streamflow hydrograph (Fig.6) composed with low-flow and high-flow period. The coupling increased the lower baseflow into the river in low-flow period, on the other hand, reduced the exceeding baseflow during flood in high-flow period. According to the calculated streamflow hydrograph, the coupling process reduced the discharge error greatly in low-flow and less in high-flow. Regarding to improvement of coupled model, the year 1996 and 2000, wet and normal water-situation, less error years of entire time steps were selected for sample years analyzed the improvement of coupling process.
The coupled models showed that the seasonally groundwater levels were on average, about 4 m below ground surface in the wet season, but drop to 6-9 m. below ground surface in the dry season (Fig.7). Significant head dropped of 2.5-7 m were observed between the wet and the dry season in one year, especially in the dry season of a drought year. The accuracy of groundwater level simulation was improved considerably in dry season, but in the dry season was insignificant. Regarding with coupling process, there was a little bit difference in groundwater level, average 0.03-0.12 m. The coupled models effected the groundwater recharge decrease resulting groundwater level decrease in 0.11 and 0.12 m. of wet and dry season. Because the groundwater recharge was dominated with surface recharge (Fig.8), the river-aquifer interaction less influence to the groundwater level. Nevertheless where the groundwater level close to main rivers, featuring with high hydraulic conductivity, the groundwater level was significant changed as shown in Fig.9.

3.5.1. Coupling evaluation

Both uncoupled and coupled simulation were operated explaining modification of coupling model in order to evaluate an advancement of the coupling methodology. The result of coupled simulations provided monthly stramflow discharge and two-weekly groundwater level. Residual error in the simulations represented the uncoupled and coupled ability in surface-groundwater computation. Comparing streaflow discharge relative error of uncoupled and coupling model (equation 1) presented improvement of couped model in surface wate. Diffference of average absolute groundwater level error of uncoupling and coupling model compared with uncoupled simulation (equation 2) illustarated improvement of coupled model in groundwater. Therefore the model improvement of coupling process was 8-24% and 1-28% as shown the average value in table 1.

(1) $$\text{Evaluation}_{\text{SW}} = \frac{1}{n}\left[\sum_{i=1}^{n}\left|\frac{(Q_{\text{model}} - Q_{obs})_i}{Q_{obs}}\right|_{Uncoupled} - \sum_{i=1}^{n}\left|\frac{(Q_{\text{model}} - Q_{obs})_i}{Q_{obs}}\right|_{Coupled}\right]$$

(2) $$\text{Evaluation}_{\text{GW}} = \frac{1}{n}\left[\sum_{i=1}^{n}\left|(h_{\text{model}} - h_{obs})_i\right|_{Uncoupled} - \sum_{i=1}^{n}\left|(h_{\text{model}} - h_{obs})_i\right|_{Coupled}\right] \div \frac{1}{n}\sum_{i=1}^{n}\left|(h_{\text{model}} - h_{obs})_i\right|_{Uncoupled}$$

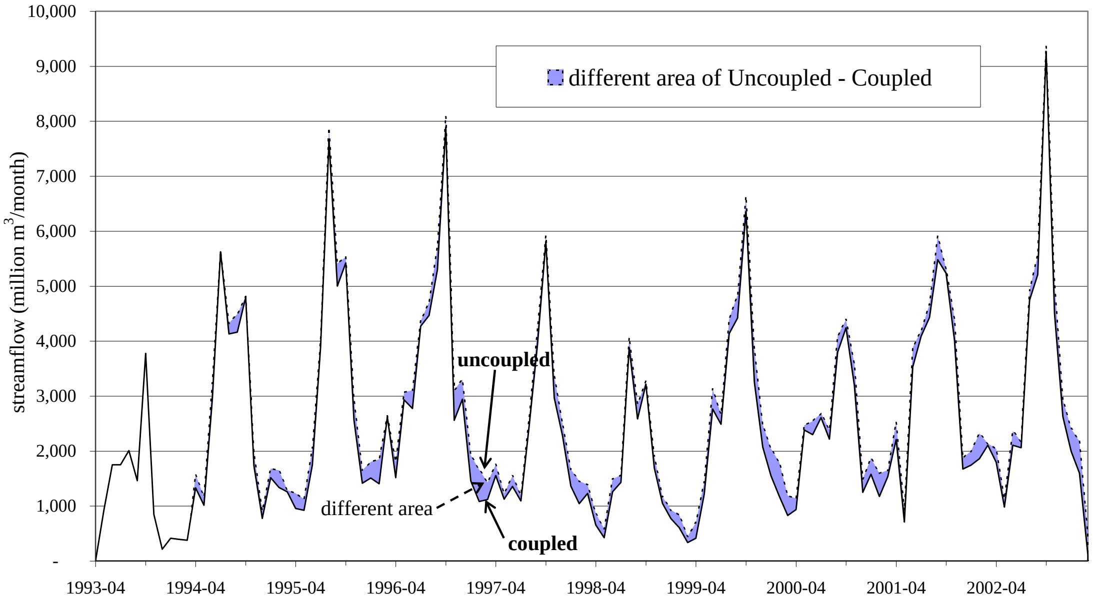

Fig. 6. Comparing streamflow simulation of uncoupling and coupling models.

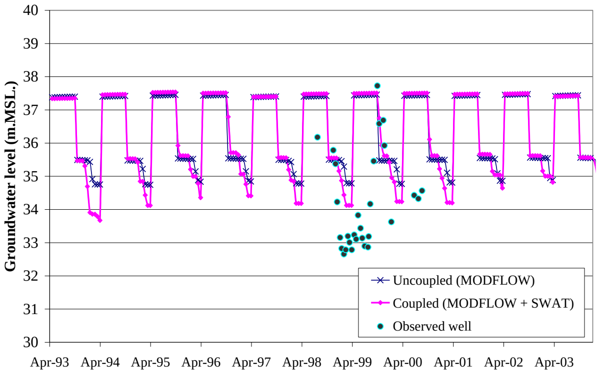

Fig. 7. Groundwater level simulation of uncoupled Coupled and observed data.

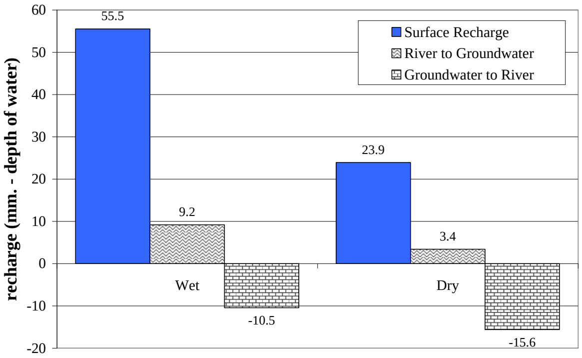

Fig. 8. Interaction of surface and groundwater regarding to the coupled models.

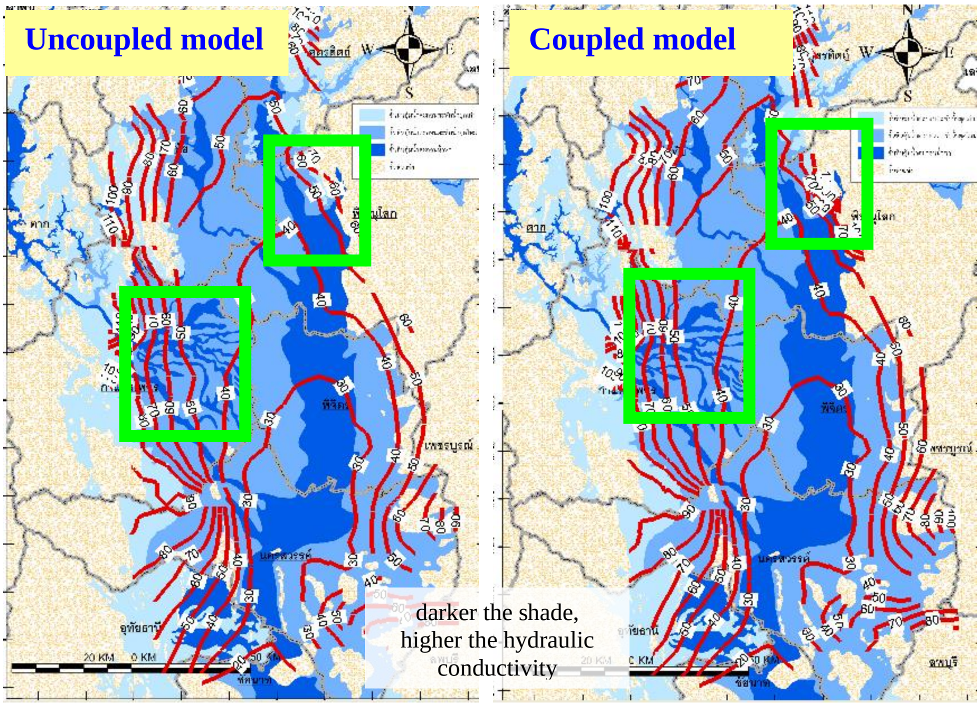

Fig. 9. Obvious different groundwater level at dry season of 2003 due to coupled models.

Table 1. Model-accuracy development due to coupling process.

parameters	Improvement due to coupling process		
	average	wet season	dry season
Streamflow discharge	11.5%	7.5%	16.7%
Groundwater level	2.3%	0.55%	2.9%

Table 2. River-aquifer interaction modification of sample water-years.

water situation	decrease of abs. error in river-gw interaction after coupling				
	monthly streamflow			seasonally streaflow	
	whole year	wet	dry	wet	dry
1997 (wet water-year)	-13%	-7%	-18%	-10%	-15%
2000 (normal water-year)	-11%	-5%	-17%	-8%	-14%

The improvement of coupled model showed that the coupling process worked on the model accuracy greatly in dry season. Concerning the yearly water situation, the coupling process affected wet year greater than less water year following the modified interaction of river-aquifers shown in table 2.

3.5.2. Dynamic Interactions

The coupling process generated synchronous interaction between surface water and groundwater. The interaction was developed to dynamically response the variant of surface water and groundwater element at the interface zone. Moreover the unmatched interactions of surface and subsurface models (Table 3) were easily solved with the coupling methodology. The water balance of coupled models (Fig.3) illustrated that the interaction of surface and sub-surface water was 5% of total flow-in of the study area. The seasonal interaction in Fig. 9 indicated that the aquifer contributes only an average 3% of the annual aquifer-recharge into the rivers in the wet season, but was recharged from the rivers in the dry season with 77% of the total recharge in dry season. Furthermore, Fig. 9 shows that over recent times, while the groundwater use has been increasing and the surface water supply decreasing, the river-aquifer interaction has been declining. The surface recharge was increased both in wet and dry season due to adapted infiltration rate and temporary soil water storage giving dry season recharged much more from soil layer. Although the model coupling made groundwater recharge significantly increased (Table 3), but the exceeding recharge located mostly along the boundary line of the groundwater model, where were forests and mountains, affecting less rising groundwater level.

Table 3. Average annual flow of coupled components.

Parameters	before coupling		after coupling
	SWAT	MODFLOW	coupled model
Surface recharge (mm.)	-	17.2	47.4
River-gw interaction (mm.)	71	90.	13.5

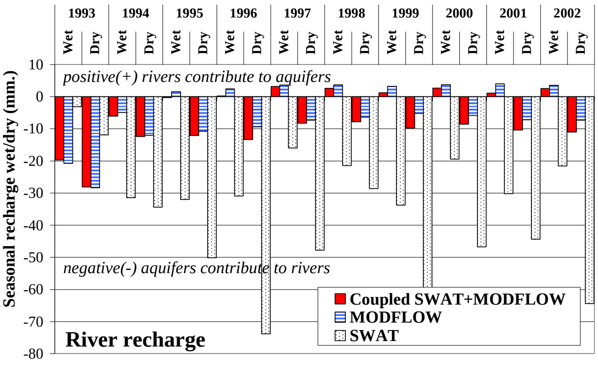

Fig. 9. Seasonally river recharge.

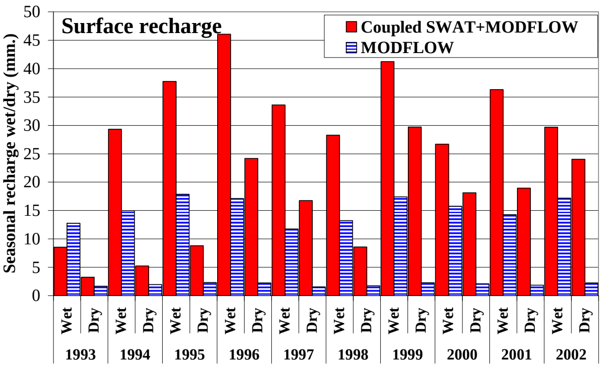

Fig. 10. Seasonally surface recharge.

4. Conclusion

The semi-coupling is another choice of simple and easy methodology to develop the surface and sub-surface hydrological model. The comparison of uncoupled and coupled models illustrated that the semi-coupling method made the simulation of streamflow and groundwater improved, the water balance analysis is able to describe the local interaction of surface and subsurface water. The streamflow and groundwater level calculations were enhanced, with respectively 12% and 2.3% better than those of uncoupled results, especially in dry season, normal water year and wet year. For this study, the groundwater level was insignificant change due to coupling process in wet season. The selected components of surface-water and groundwater model were connected each other generating its dynamic interactions with monthly hydrological components. Accordingly to natural hydrological process, the study result showed that the coupling methodology is a key to better simulate surface-water and groundwater models.

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