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A CONJUNCTIVE SURFACE WATER AND GROUNDWATER MODEL FOR INUNDATED FLOODPLAIN IN THAILAND

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The interaction of groundwater and surface water induced by flooding in a floodplain with paddy fields was studied. A case study in the lower part of the Yom River in Phichit Province, Thailand was selected during the period 2002 to 2003, and a numerical model for conjunctive surface and groundwater flow was developed for an inundated floodplain. The alternating direction implicit method was applied for model solution. The estimation of hydrological components in the water budget model was based on field records and measurements, including field infiltration and daily water table elevation data. It was found that the average value of the seepage rate in this area was 16.2 mm/d per 1 m of flood depth. The model results showed that groundwater recharge during the flood and no-flood periods were above 70-75 % and 25-30 % of annual recharge, respectively. A comparison of the computed water tables to the observed data showed a high correlation.

INTRODUCTION

In a floodplain hydrological system the link between surface water and groundwater is an important topic for research, particularly for areas with floodwater during the wet season and high groundwater withdrawals during crop cultivation. This is especially true for rain-fed paddy fields in the Yom River Basin in Thailand where land is suitable for growing rice due to the fertile alluvial soils. Uncontrolled water consumption for paddy overdrafts the shallow groundwater and other sources, leading to permanent declines in the water table (Mekpruksawong et al., 2004).

In a previous study of groundwater recovery in this area by the Public Works Department (DPW), a feasibility study of groundwater recovery since 1998 in Phichit province was conducted by Mekpruksawong et al. (2004). Most of the land surface in this area is covered by loamy soil and some mixed sandy-silt or clay. Beneath the topsoil, a very thick coarse sand and gravel is found ranging in thickness from 50 to 100 m, that constitutes a phreatic aquifer. The study established a groundwater balance assuming artificial groundwater recharge based on a 3-dimensional groundwater model. The model assumed a transmissivity coefficient of 120 m^2/h, a recharge rate of 0.12 mm/d (3% of rainfall), conductance of 0.02, and a leakage coefficient of 0.0005. However, there was a lack of field data, boring logs, and groundwater and floodwater records.

The model assumed the number of tube-wells for groundwater withdrawal was increasing by the rate of 2.5% per year which resulted in drawdown of the water table of 12 m in the next 20 years. It was suggested that to restore the water table, artificial recharge by spreading basins and deep well injection from the ground surface to the aquifer should be used. The report also suggested more field work is needed to better determine hydrological parameters, geological conditions, and the hydrologic behavior of the floodplain.

No conjunctive surface and groundwater study has yet been conducted in these floodplains using long-term observational data . This research aimed at data collection to measure groundwater recharge by surface water, particularly by flood and rainwater infiltration, using automatic instruments. This study presents the interaction of groundwater and surface water induced by flood infiltration through field experiments to determine hydrological and geohydrological components and develop a numerical model.

MATERIALS AND METHODS

Study area

The study area was located on floodplain of the Yom River in Phichit Province, Thailand and consisted of 14 ungauged catchments (Figure 1). Typical climate is tropical-monsoon classified by 3 seasons: winter, summer and rainy with average annual rainfall of 1434 mm. The types of landforms are floodplain and low river terrace with the slope less than 1 %. The inner area for studying conjunctive surface water and groundwater in floodplain was around 153 km^2 while the outer area for study of upstream runoff was around 1698 km^2. There were two RID (Royal Irrigation Department) gauging stations (Y17 and Y5) between the upstream and downstream end of the study area with a river reach of 71.8 km. Moreover, a river stage recorder was located at midstream on the Yom River, which was used to study flood depth in the inner zone.

The topography of the inner zone (153 km^2) has an average slope of 0.00014 and natural ground level at +32.89 m above mean sea-level (MSL) as shown in Figure 2. Most of the land-use in this area is paddy field (89.6%) while the remaining is residence, upland crops, orchards, water bodies

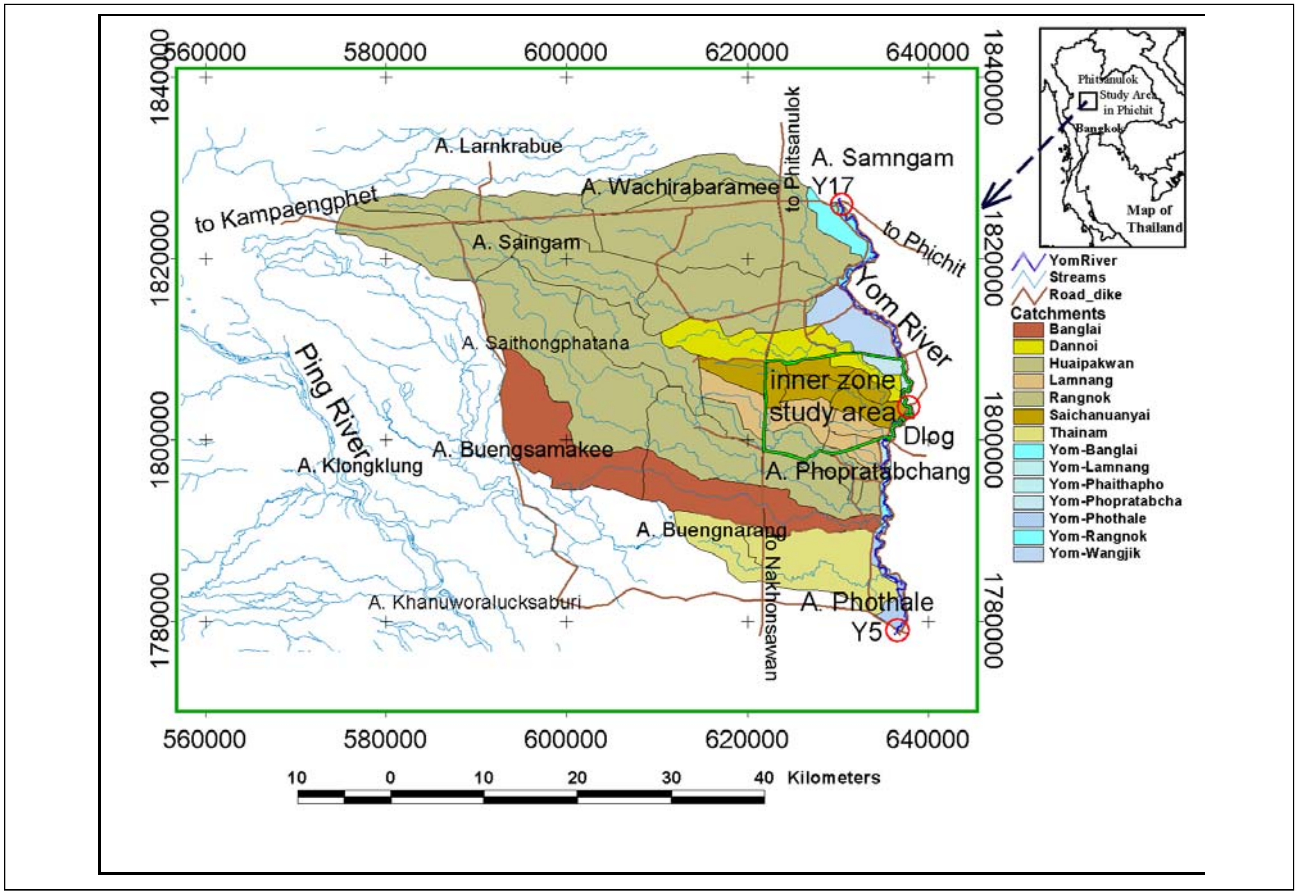

Figure 1. Study area and catchments in Phichit Province, Thailand.

and bare land. Its geomorphology consists of a shallow clay or silt layer topsoil and a shallow thick sand aquifer with average effective porosity of 0.083 (Mekpruksawong et al., 2004).

A common problem is flooding which covers 50 % of this area caused by over-bank flow from the Yom River during the rainy season. In contrast, during the drought period after flooding, there is a general deficiency of surface water for crops and shallow groundwater is withdrawn by farmers using small pumps and tube wells.

Model development

Regression analysis, was used for analyzing and fitting the hydrological components in a water budget model as shown in Figure 3.

The model components included infiltration (I), evapotranspiration (ET), rainfall (P), withdrawal of water from wells, and lateral flow from the local streams and/or river. The model can categorize three cases: no-flood (upland), partial-flood (semi-flood plain), and complete-flood (lowland). The amount of infiltrating water is based on the amount of effective rainfall (P_e), flooded or ponding depth (H), and ponding time (t). During the inundated period, infiltration can be considered as controlled by saturated hydraulic conductivity (K), and rates vary with ponding water or flooded depth. The flux amount to the saturated soil will be seepage rate, A_c=K/H, and for the unsaturated case, A_c=F/H, where F is field infiltration in the unsaturated condition. The continuity equation for computing infiltration flux with the hydrological processes measured over a certain period of time (t) is:

$$I = (P-ET)+(Q_{in}-Q_{out}) - DS \quad (1)$$

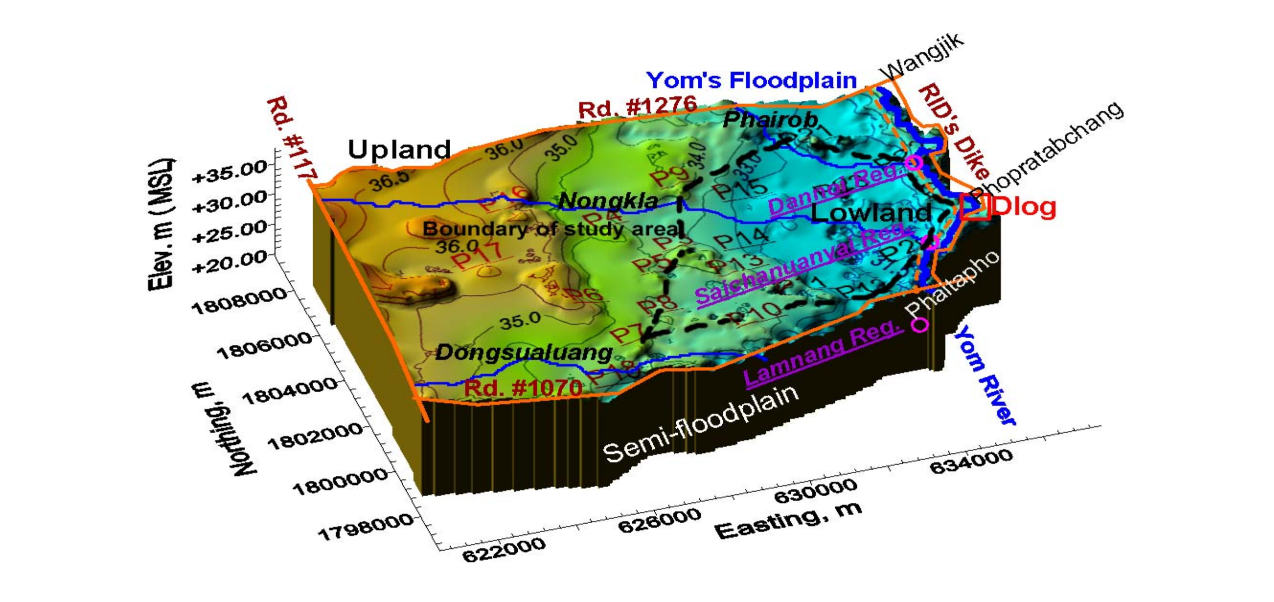

Figure 2. Inner zone with inundated floodplain (dash-line along 11 observation wells).

The term P-ET is the volume of effective rainfall (P_e) during the non-flooded period, and Q_{in}-Q_{out} is the difference of runoff volume between upstream and downstream boundaries of the study area. The overflow through the riverbank, bunds, or stream discharge via regulated structures is considered as Q_{in} and Q_{out} (Chow et al., 1988). The synthetic hydrograph from existing basin characteristics can be applied (Chow et al., 1988) to estimate lateral inflow runoff (Q_{in}) from ungauged catchments.

The change of storage volume (DS) can be determined using the change of daily river stage and the existing topographic map.

The empirical Kostiakov infiltration model was applied to fit the amount of infiltrating water and ponding times using linear regression (Kostiakov, 1932; Ahuja et al., 1976; Chaiyatham et al., 1986; and Hillel, 1998).

The Penman-Monteith (P-M) equation was used to estimate reference evapotranspiration

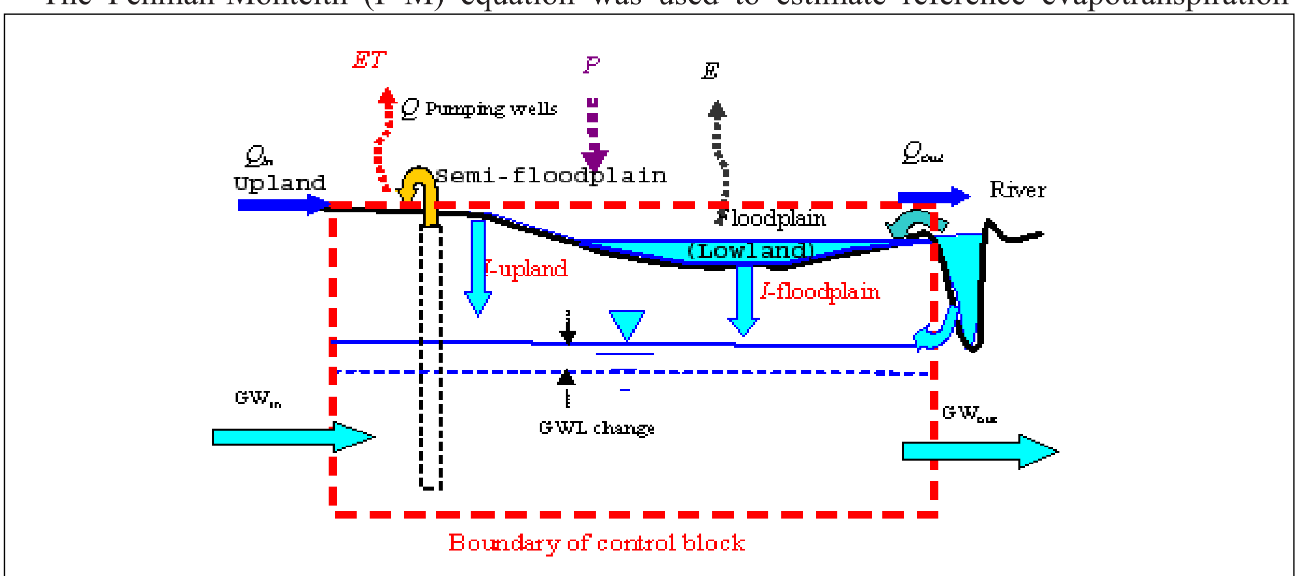

Figure 3. The water budget model.

(ET_o), and crop evapotranspiration ($ET_c=K_c* ET_o$) with crop coefficients (K_c) in no-flood and partial flood seasons (Doorenbos et al., 1977; RID, 1994). Since most of the floodplain is suitable for rice cultivation, the actual amount of water requirement for paddy (V_c) should include water for the land preparation period (W_{Lp}) with land preparation area (A_{Lp}) and activities period (T_{Lp}), growth period (T), and growth area (A_g) as shown in Figure 4. During the inundated period, ET can be considered only evaporation (E). The amount of water for land preparation of 150-250 mm per 3-8 weeks and percolation of 1-3 mm/d per 90-100 days of paddy growing stage were used (Kirdpitugsa et al., 1995).

The model for the solution of the implicit finite difference of groundwater flow below the ground surface during flood (Figure 5) applied the alternating direction implicit (ADI) method developed by Peaceman 1955 (Kinzelbach et al., 1986).

The systematized model includes square-grids, boundaries, and rows and columns. The lateral groundwater discharges and leakage parameters can be computed using Darcy's equation, with known water table elevations as the head boundaries from observation wells along the boundaries (Mekpruksawong et al., 2004). The boundary conditions are 0 at the outside boundary, 1 as no flow, 2 as constant head, and 4 as computed groundwater level (GWL) inside the boundary, respectively. The others are time step (DT), and time of calculation at ending phase (NSH).

The process of calculation in Figure 5 starts with an initial condition: GWL and computed recharge flux at every grid point at the start time of the flood. Then the ADI calculates surface flux from given A_c and further computes water storage in the ground and aquifer, leakage flux to the lower aquifer, and the change of GWL, respectively. The solution of groundwater flow for the next time step using ADI is done in the directions of rows and columns as the iteration numbers with given boundaries and initial conditions. The output of groundwater change will be compared to the observed GWL to test how effective the model is and to verify the model.

Data collection

Data collection included topographic data as ground level (NGL), flood data as river water level (RWL), and water budget components as rainfall (P), evaporation (E) and computed ET_c, and local streamflow. Some instrumental devices were installed that included an automatic pressure-type recorder for river stage (Dlog), water level recorder for each observation well (OW), and an automatic rainfall recorder (located at P3). Observations of flood depth and measurements of lateral streamflow were carried out. The ponding depths in the paddy field in this area were observed to be of 0.02-0.08 and 0.2-3.0 m (Figure 6). Local percolation was observed at 49 points in the investigation area, and the distribution of data is shown in Figure 7. Each infiltration point was measured using double ring infiltrometers with a coverage area of approximately 1.03 km^2. The observed data were used for studying and understanding the water cycle in this area and for model verification.

The testing area for the conjunctive surface water and groundwater model was 40 km^2 located in the inner zone (Figure 7) which is bounded by 11 observation wells (P3, 5, 7, 8, 9, 10, 12, 20, 21, 22, 24). The overall model area was 72 km^2 (10x7.2 km) comprised of 1800 unit-areas with square grids of 200 m (51 columns and 37 rows).

RESULTS AND DISCUSSION

From the altitudes and locations of ground levels, observation wells, and field experiments of infiltration in 2001-2003, infiltration (F), seepage (A_c), and hydraulic conductivities (K) were

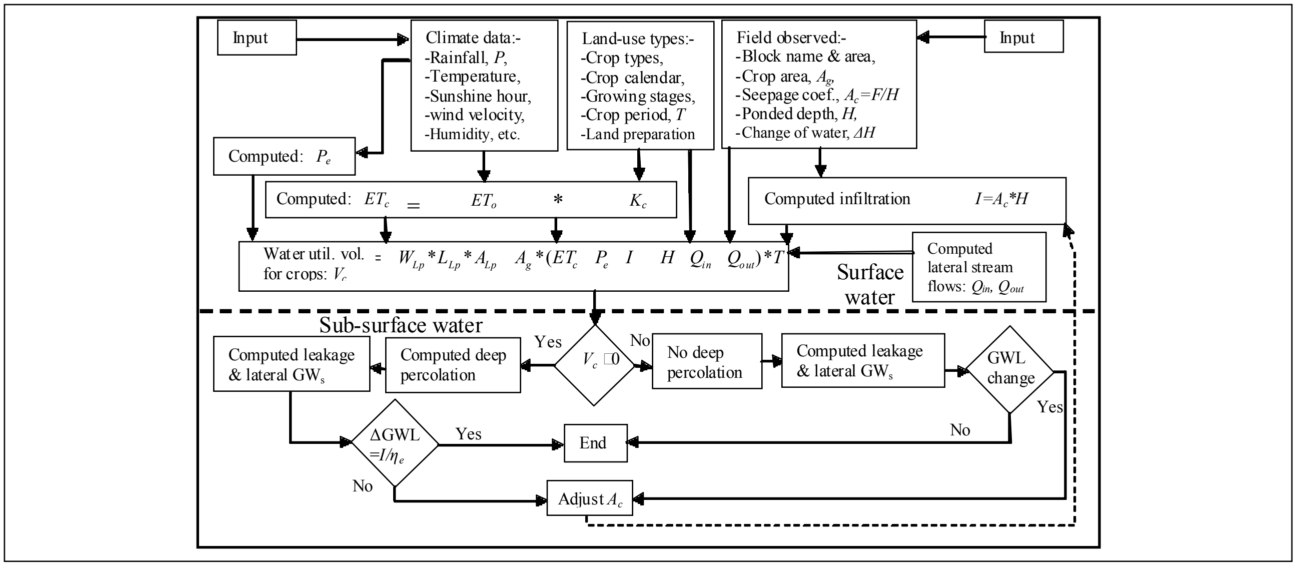

Figure 4. Flow chart for groundwater and surface water study in the floodplain paddy field.

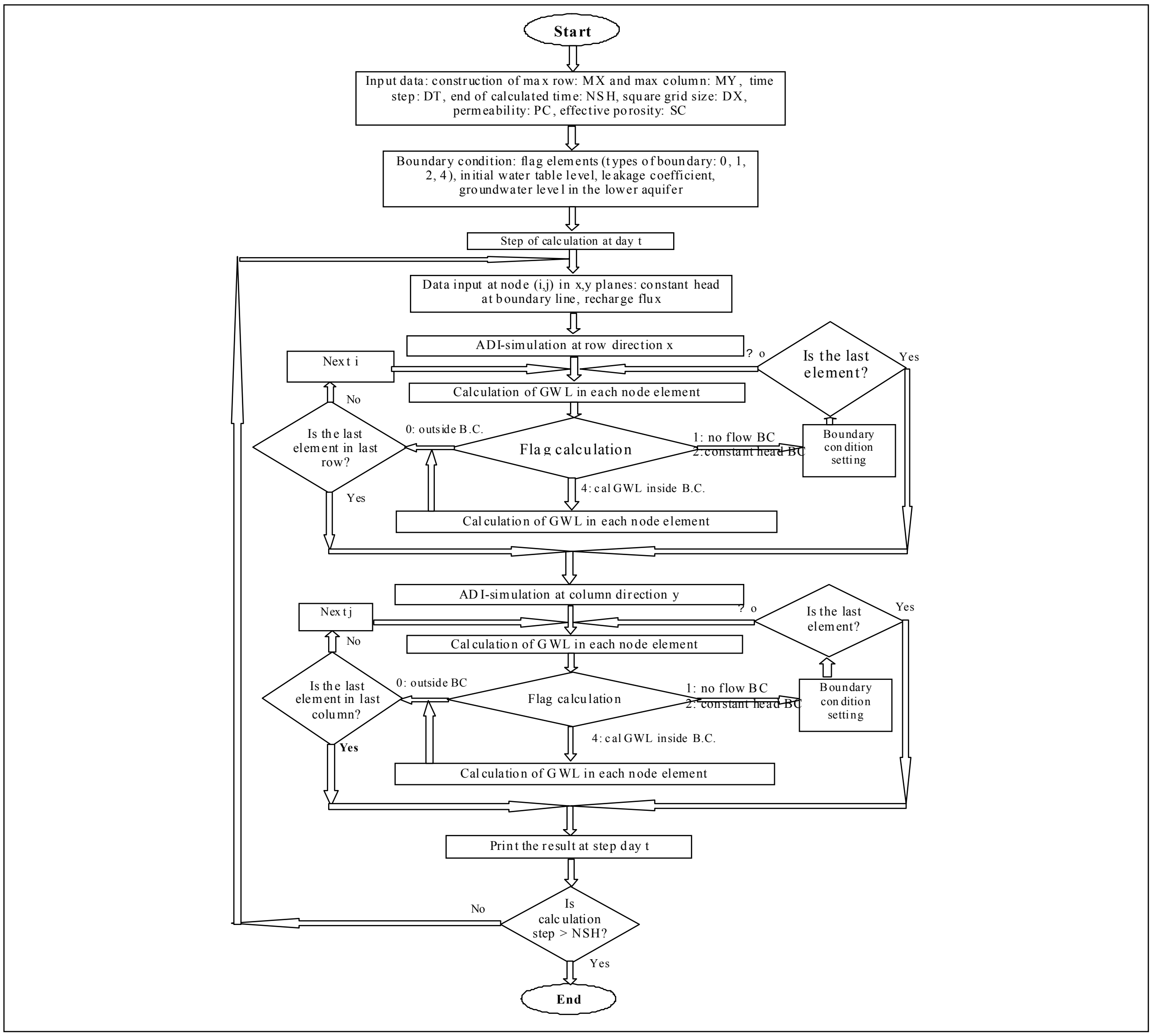

Figure 5. Flowchart of the model using the ADI solution.

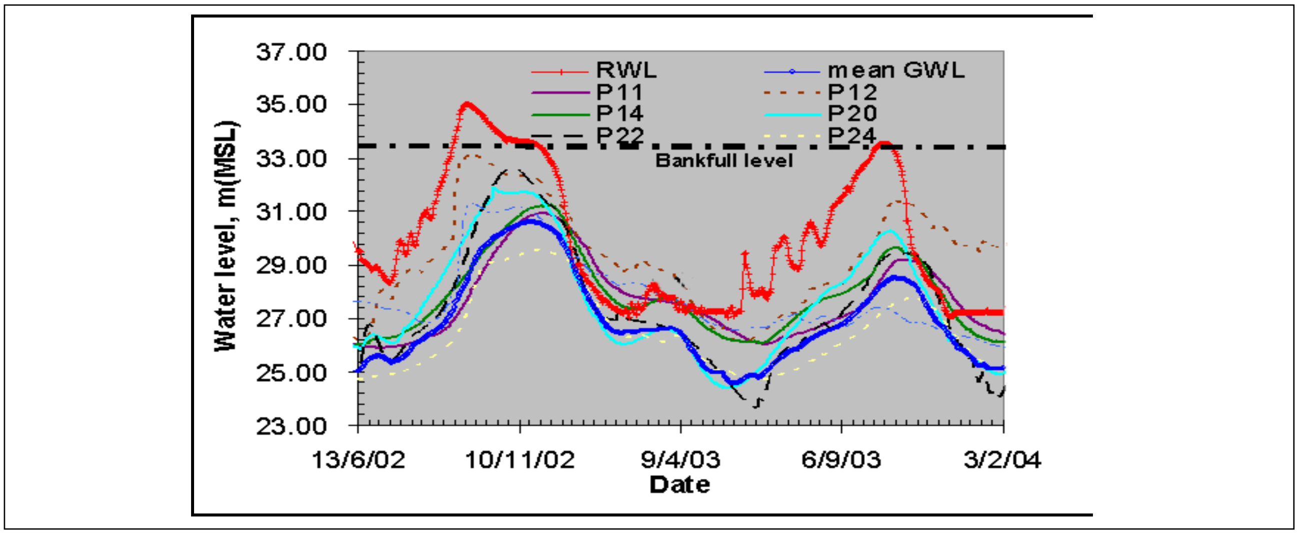

Figure 6. Daily groundwater level (GWL) and river water level (RWL) in 2002-2003.

assigned to each service area of each observation well (Table 1). An aerial view of the distribution of 49 infiltration points transformed to seepage coefficient (A_c) is presented in Figure 7.

The catchment's characteristics of area (A), slope (S), and stream length (L) were used to compute each catchment peak discharge (q_p) to the inner zone, lag-time (t_p), and shape using Snyder's synthetic hydrograph. The procedure is summarized in Table 2.

The surface flux in the inner zone resulting from infiltration in 2001-2003 is shown in Table 3. If a larger flood occurs as shown in Figure 6, the amount of recharge during the inundated period will be a higher volume. The mean GWL hydrograph in 2002-2004 increased and receded according to the river water level (RWL) hydrograph. Therefore, it is clear that the rise of groundwater level in this area is mainly the result of flood. However, the GWL is continues to be

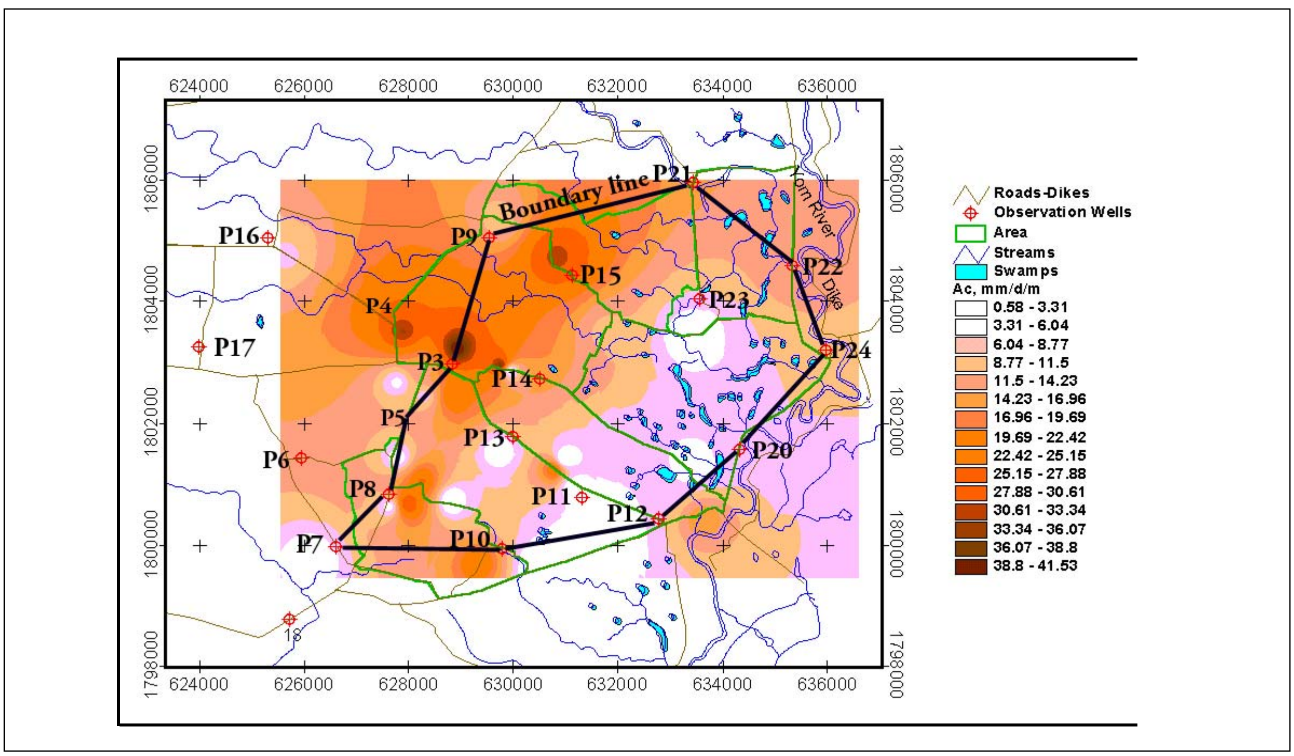

Figure 7. Aerial view of A_c contours, location of OW_s, and model area.

Table 1. Infiltrations, seepage, and hydraulic conductivities at each observation wells.

OW's name	A [km^2]	Elevation[m(MSL)]	F[mm/d]	A_c[mm/d/m]	K[mm/d]
P03	4.23	33.72	12.4	30.9	2.1
P07	0.62	33.67	0.1	9.6	0.003
P08	3.96	33.82	2.8	10.9	0.6
P09	3.35	34.07	0.9	9.8	0.04
P10	3.67	33.45	13.2	14.5	4.9
P11	3.70	33.16	3.9	4.3	0.9
P12	2.25	32.12	3.9	37.6	0.7
P13	3.18	33.54	3.5	4.7	1.5
P14	4.35	32.74	3.9	51.1	0.9
P15	4.82	32.57	7.6	23.7	2.2
P20	3.65	31.62	2.8	4.7	1.6
P21	2.81	32.19	9.7	14.8	2.7
P22	2.29	32.08	0.3	6.3	0.02
P23	5.92	32.16	1.0	2.8	0.04
P24	1.56	32.37	0.3	6.3	0.02

Table 2. Basin characteristics to use with Snyder's synthetic hydrograph.

Basin name	A, km^2	L, km	S	q_p, m^3/s/mm	t_p, h	Location
Rangnok	526.18	71.65	0.00031	3.266	19.0	upstream
4-Yom's floodplain-u/s	84.14	7.85	0.00017	0.914	5.6	u/s floodplain
Dannoi (Phairob)	73.93	32.86	0.00032	0.589	12.2	Inner zone
Saichanuanyai (Nongkla)	92.42	38.47	0.00031	0.703	13.3	Inner zone
Lamnang (Dongsualuang)	58.78	26.51	0.00020	0.496	10.8	Inner zone
Huaipakwan	367.12	130.42	0.00044	1.809	26.8	downstream
Banglai	347.47	54.25	0.00038	2.374	16.2	downstream
Thainam	126.66	32.67	0.00023	1.011	12.1	downstream
3-Yom's floodplain-d/s	21.35	13.02	0.00004	0.212	7.3	d/s floodplain

Table 3. Recharge flux through ground to aquifer during flood using existing A_c.

Item in each year	2001	2002	2003
Average RWL, m(MSL)	32.13	32.51	31.50
Average NGL, m(MSL)	30.30	30.30	30.30
Ponding period, day	129	118	63
Flooded area, km^2	22.0	29.5	12.0
Average flooded depth, m	1.83	2.21	1.20
Average A_c, mm/d/m	16.245	16.245	16.245
surface flux, mm	3848.28	4247.9	1225.78
flux volume million cu.m (MCM)	84.66	125.31	14.71

drawn down during the dry season by groundwater use for crops. The withdrawal exceeds the recharge during the flood season. The recharge during the flood season, and ponding water in paddy fields during the dry season averaged to 70-75 % and 25-30%, respectively.

The computed daily GWL and observed data in 2002 and 2003 were compared and fitted by using linear regression analysis with a correlation coefficient ($R^{2)}$ of 0.9995 (Figure 8). The examples of computed and observed GWL on 24 September 2002 and on 24 October 2003 are shown by different contour lines of computed and observed groundwater level (Figure 9).

The existing model computes groundwater flow based on the amount of ground surface flux to the ground through infiltration of 9.0 and 3.8 mm/d, recharge flux to the upper aquifer of 4.3 and

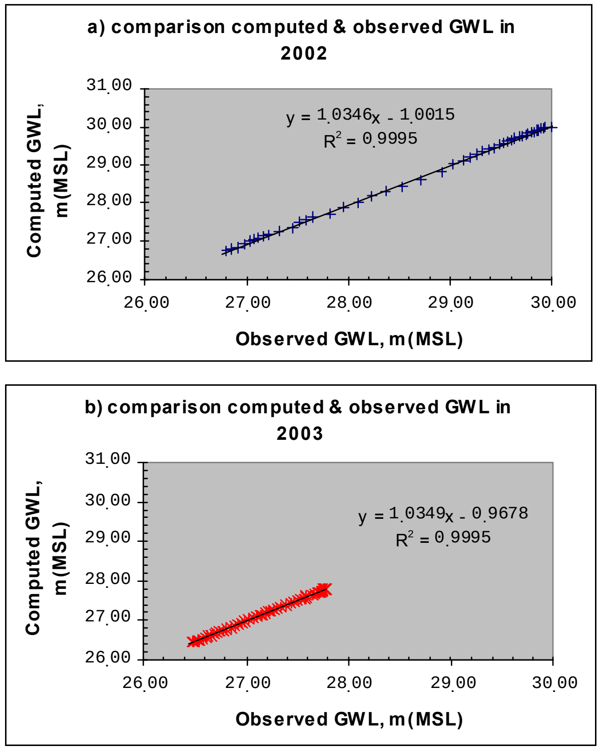

Figure 8. Comparison of computed and observed GWL in 2002 and 2003.

Table 4. Simulation results using conjunctive surface and subsurface flow model.

Results	Year 2002	Year 2003
Ground surface flux, m^3	59,067,400	15,407,800
Recharge flux to aquifer, m^3	28,238,999	4,857,139
Leakage to lower aquifer	11,229,448	3,634,858
Water stored in subsoil	30,828,401	10,550,661
Water stored in aquifer, m^3	17,009,551	1,222,280
Period of flood , days	91	57
Computed GWL, m(MSL)	29.463	27.262
Observed GWL, m(MSL)	29.445	27.278
Different in computed & observed, m	0.018	-0.016
Error in computed GWL, %	0.061	0.058
R^2 from the regression result	0.9995	0.9995

1.2 mm/d, leakage to the lower aquifer of 1.7 and 0.9 mm/d, storage water in subsoil of 4.7 and 2.6 mm/d, and storage water in aquifer of 2.6 and 0.3 mm/d, in 2002 and in 2003 (Table 4). Groundwater recharge in 2002 was greater than 2003 because it was a higher flood level, wider flooded extent, and longer flood period.

CONCLUSION

This study evaluated the effect of surface runoff on the change of groundwater level using field observation data in a paddy field. The amount of groundwater recharge from flooding was evaluated using field experiments of infiltration and interpreted as a distribution of seepage capacity over the ground surface in the study area. The infiltration flux over the floodplain during the inundated period is the major cause of the increase the water table elevation. Groundwater recharge would

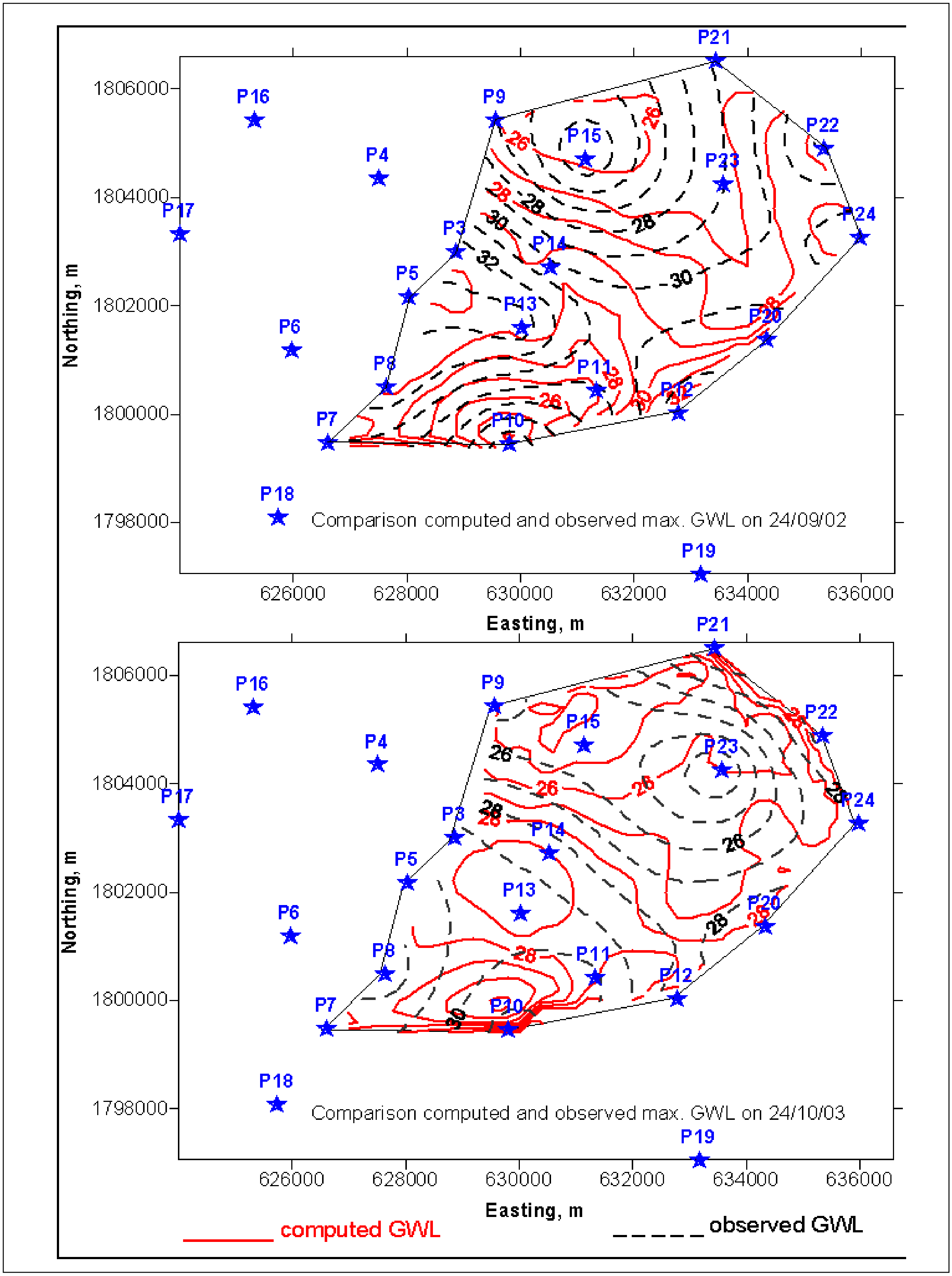

Figure 9. Comparison computed and observed daily GWL examples a) on 24/09/2002 and b) on 24/10/2003, respectively.

be more if higher flood depths occurred and there was a longer ponding period. However, groundwater level rapidly decreased during the drought after the flood which was caused by groundwater withdrawal for crop consumption, particularly paddy. There are many tube-wells in this floodplain with an irrigation area of 5-6 ha for each well. The lowering of the water table was also influenced by leakage to the lower aquifer but was less than water use during drought (Mekpruksawong et al., 2004). The numerical solution technique using the ADI method was effective and accurate enough to solve the problem of conjunctive use of surface water and groundwater in the inundated floodplain. This study will be useful for further development and to understand the phenomenon of floodwater and groundwater interaction in these floodplains.

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