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Phreatic surface fluctuations within the tropical floodplain paddy field of the Yom River, Thailand

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Abstract

The fluctuation of phreatic surfaces in tropical floodplain was studied for the lower part of the Yom's river basin at Phichit Province in Thailand. The simple water balance budget model was applied to estimate the groundwater recharge. The hydrologic components i.e. average rainfall, surface runoff, and deep percolation were calculated by using climatologically recorded and measured data. The Penman-Monteith's evapotranspiration method was used to estimate potential evapotranspiration for crop water requirement based on climatic data. The 49-points of field infiltration and theirs distribution over the floodplain were measured using ring-infiltrometers. The surface water and phreatic surface deviations from the existing 22-observation wells nearby the Yom River daily observed continuously for 3 years. The observed river water levels and phreatic surface water levels were agreed very well with R^2 approx. 0.90. The rising or recessing of those fluctuations was depended on the inundated depth over floodplain or the amount of groundwater withdrawal for crop consuming. Understanding and quantifying the phreatic surface fluctuations in lowland paddy field is crucial for further floodplain management.

1. Introduction

In a large floodplain area of a large river in tropical-monsoon zone with high intense rainfall during rainy season, its hydrological parameters and components are difficult to determine due to complex physical conditions. Usually, flood occurs when there is too much water over specific area by rainwater, additional flow entering from adjacent upstream area, and overbank flow from the river itself. The period of inundation will be based on floodplain morphology, and hydrogeological characteristics. Moreover, the great amount of withdrawal of both surface and subsurface waters for crop consuming especially paddy in floodplain will affect the change of phreatic surfaces. Those physical behaviors over the specific floodplain catchments should be better investigated

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from the field. The infiltration which is one of the major hydrologic components of water penetrating from the ground surface into the soil that might percolates contribute, further and to groundwater storage, observations should be investigated using field experiments. It is an indicator that can be used to estimate potential loss by mean of soil hydraulic conductivity if a long period of time of the field measurement was undertaken. The relationship of penetrated water and testing period can be fitted using the simplest Kostiakov's model (Chow et al., 1988). The most common model for estimation of parameters is the water budget model.

This paper aims to contribute to the hydrological knowledge of a river reach within a tropical floodplain, particularly the relations between the surface water and the phreatic surface of the river's interconnecting aquifer.

2. Study area

A 3-year programmed of water table monitoring and supplementary experiments were undertaken from the years 2001 to 2004 at Phopratabchang District, a paddy field area was situated on floodplain of the Yom River in Phichit Province, Thailand (Fig. 1). The lower part of the main river is occupied by an extensive alluvial plain which flood usually occurs in this part during the rainy season from July to September corresponding to monsoon and typhoons effects. It is the typical season characterized by a pronounced long rainy season and produces around 90% of the annual rainfall amount. Its average annual rainfall over the overall basin is 1434 mm, and rainy day equals 80 days. The focused site covers an area of 153 km^2 (inner zone in Fig. 1 and Fig. 2) lying on the west of the Yom River bounded by 3-local roads (no. 117 on the west, no. 1276 on the north, and no. 1070 on the south) and flood protection dikes (RID's dike on the east) which was chosen to conduct investigation of gains and losses from flood and water table fluctuations. It was located in a larger basin (1698 km^2) in Fig. 1 included 7 major catchments are namely Banglai, Dannoi, Huaipakwan, Lamnang, Rangnok, Saichanuanyai, and Thainam and 7 floodplain's catchments along the Yom River which was lying between 2 sites of observed river stages belonging RID (Royal Irrigation Department) namely Y17 (Samngam) at upstream and Y5 (Phothale) at downstream with the river length between those 2 stages of 71 880 km.

The inundated area occupies by some 50% of the inner area (153 km^2) in Fig. 3 which occurs by overbank flowing from the river and overland flow from upstream catchment's runoff (Fig. 2). Moreover, its topography is very flat with average ground surface level of +32.88 m above mean sea-level (MSL) and average slope of 0.000138. There are 3-local streams flowing through this area and connecting to the Yom river namely Phairob (catchment's area of 74 km^2), Nongkla (catchment's area of 92 km^2), and Dongsualuang (catchment's area of 59 km^2) with average stream slope of 0.000286. The streams have regulated structures namely Dannoi, Saichanuanyai, and Lamnang near the river's confluences, respectively.

Its geomorphology conforms by shallow clay or silt at the ground surface as the top layer and thick sand layer as unconfined aquifer beneath the top soil (Fig. 3). The effective porosity (η_e) of this aquifer was averaged to 0.083 (Mekpruksawong et al., 2004). There were 22-observation wells (OW) ranged 15–30 m depth which was constructed by KTU (Kyushu Tokai University, Japan) and RID (Royal Irrigation Department) to monitor the change of phreatic surface levels (GWL) every 10 min. Some 15-OWs lying on floodplain (50.414 km^2) were namely P3, P7, P8, P9, P10, P11, P12, P13, P14, P15, P20, P21, P22, P23, and P24, respectively. Moreover, there was a river stage (Dlog) lying at the right bank of the Yom river upstream of Phopratabchang Bridge in order to recorded the change of daily river water level (RWL).

High-yield-variety (HYV) paddy (86% of total area) was grown 2 times a year. There were many shallow groundwater wells drilled and groundwater is utilized as supplementary water requirement for crop. The cropping pattern is shown in Fig. 4.

3. Material and methods

3.1. Topographical map and conceptual model

Unfortunately, due to lack of topographical data, contour-lines were constructed based on available data which were collected from RID, Highway Department (HWD), Royal Thai Survey Department (RTSD), Department of Land Development (DLD), and Department of Environmental Quality Promotion (DEQP) and geographic information systems (GIS)'s maps with 1:50 000 scale. The existing ground surveyed was done during the construction of OWs. Moreover, the inundated mapping was sketched using aerial and satellite imaging maps which used to verify those contour-lines. The relations among inundated extents versus pool levels were plotted which used to estimate daily flooded storage changed. This paper applied Arc-View's GIS and surface programs as the tools for plotting those contour-lines and flood extensive over floodplain. The conceptual blocks model was applied using Thiessen's polygon for drawing each OW's serviced area (Fig. 5) which were used for infiltration and phreactic surface changes estimation by applying the water budgeting equations. The overall floodplain area (50.414 km^2) was bounded by surrounding roads with the average ground surface elevation of 32.88 m (MSL). Most land-uses in this area is paddy (89.6%), others were residential areas included upland crop and orchard (7.4%), and water body and bare land (3.0%).

3.2. Model description and existing parameters

The water budget model for studying surface and subsurface waters over the considered floodplain was applied (Fig. 6). The losses by infiltration (I) and evapotranspiration (ET), and inundated extensive over the catchment's area were models within 3 categories: 1) non-flooded (upland), 2) semi-flooded, and 3) fully flooded (lowland). Firstly, if the value of effective rainfall (P_e) was less than the amount of infiltration capacity during the same period of time, then there was no flood occurred and upper soil surface would be unsaturated. The actual infiltrating water would be equaled to such effective rainfall value and would be flown downward as gaining as raising water table in such considered block. Secondly, in case of continuing rainfall and infiltration with less than the amount of effective rainfall, then flood extensive would be occurred over the considered block. For both cases, the daily river water stage in the Yom River was less than the ground surface elevation (upland). Thirdly, if the river water level (RWL) was higher than ground surface elevation and the riverbank or levee (floodplain), flood discharge could be estimated as the flow over broad crested weir. The flood extensive would be occurred on a consequence of the RWL. The actual potential infiltration capacity could be the rate of final infiltration value that nearly equaled to the rate of hydraulic conductivity (K) because of ground surface was saturated. The keeping water depth in paddy field in each block during growing season was averaged by 0.05 m with 0.02–0.08 m in variant. However, during wet season and flood period, depth of water above ground was varied and ranged from 0.2 to 3.0 m. The amount of infiltration would be varied by head of water according to Darcy's Law as the rate of seepage.

In case of none flooded (Fig. 7), the continuity equation for the hydrological processes measured over a certain period of time (t) will be budgeted as:

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

P-ET can be considered as effective rainfall volume (P_e). Whereas Q_{in} is the total volume of upstream runoff water from every lateral streams and over-bank flow from the river, Q_{out} is the total volume of runoff water flow out from the considered downstream boundary through the regulators at the end of lateral streams, I is the infiltration or seepage volume, and ΔS is the change of storage volume. The stream discharges via those regulated structures will be considered as the flow volume via their channels.

For the case of flooded, it is assumed that there is no any plant grown in such period, and then ET can be considered as existing evaporation (E). The extra-inflow (Q_{in}) can be computed as the discharge across the levee or roads along the river.

The total amount of infiltrated water from surface to subsurface of the 3-cases over the year will be recharged to the unconfined aquifer and increased phreatic surface level during inundated period. However, during growing season, if rainfall is less than crop water requirement withdrawal of groundwater from shallow wells will be occurred which affects the recessing of phreatic surface levels.

The first parameter, P, was the weighted values from actual daily rainfall amount at every rain gauge which was estimated by the Thiessen polygons method which located at the districts namely Phichit, Samngam, Saingam, Phopratabchang, Phothale, and Kanuworalaksaburi. There was an automatically rain gauge with 5-min time interval recorded and located at Neonkwang School (P3) in the middle part of the inner zone. It was used for the study of rainfall intensity-duration-frequency and surface runoff over the catchments.

To estimate crop water requirement (ET_c), the FAO's potential evapotranspiration (ET_o) using combined Penman-Monteith's (P-M) equation (Doorenbos et al., 1977) was applied. Whereas all parameters for this equation were applied by using standard climatologically data recorded by the MD (Thai Meteorological Department) at the Phichit Agricultural Research Station in Phichit Province. Those included daily solar radiation (sunshine hour), air temperature (maximum and minimum), humidity and wind speed data. Then ET_c for each kind of crop during growing season in none flooded catchments could be estimated as ET_o multiplied by crop coefficients (K_c) at each growing stages which assumed to be the amount of groundwater consumed.

The loss from surface water was considered as flux over the catchments (I) getting from field infiltration experiment using ring-infiltrometer and fitted by empirical Kostiakov's infiltration model. The accumulated depth into the soil (D) versus recording times (t) would be equaled to the amount of infiltrated water (F). However, during the saturated condition or longer time of infiltration has been taken, F can be replaced by saturated hydraulic conductivity (K) [mm/d] varied by head. The seepage coefficient (A_c) [mm/d/m] was introduced as the rate of infiltrated per head of ponded water above the ground surface (Mekpruksawong et al., 2004).

$$A_c = K/H \tag{2}$$

The results of field infiltration would be weighed by Thiessen Polygon's area of each observation well to represent the spatially distribution of fluxes and A_c over the catchment's area.

To estimate lateral inflow (Q_{in}) from upstream sub-catchments entering the inner zone, the method of ungauged basin with lack of rainfall and stream flow data was applied using the neighboring catchment's data of topographical and watershed characteristics. The synthetic hydrograph using Snyder and US Army Corps of Engineers method (US.ACE, 1994; Chow et al., 1988) was applied to compute the peak discharge (q_p) and the hygrograph shape. The basin characteristics including the stream length (L) [km], stream length measure from the centered of basin to outlet point (L_c) [km], average stream slope (S), catchment's area (A) [km^2], effective rainfall (P_e) [mm] and C_t, C_p, a_1, a_2 getting from those relationships in linear regression from the neighboring basins were applied to compute the peak discharge, lag-time from the duration of rainfall to the peak discharge(t_p) [h], and base time (t_b). Therefore, lateral inflows (Q_{in}) and their hydrographs entering the inner zone could be sketched. However, the extra Q_{in} that might be spilled out from the river across the levee or road along the river entering the inner zone with length of 3.95 km and altitude of 33.58 m (MSL) during flood season. Q_{out} as discharge via the open channel of the streams, road structures, and tail regulators was considered (Chow et al., 1988).

The area of flood extensive over the floodplain was studied according to daily river stage recorded at the middle reach of the Yom River (Dlog). Moreover, occasional field water stage observation during flood period at the upstream boundary (Wangjik) along the main road (Rd.#1276) through the feeder roads and observation wells in the inner zone and down to the last section at downstream boundary (Phaitapho) along the other main road (Rd.#1070) was investigated and used to sketch the water surface profiles. Therefore, the relationship among flooded height above natural ground surface versus inundated area and temporary flood storage would be fitted. Due to the limitation of the numbering of observation points in floodplain, the assumption of water surface level at every point along each cross sectional profiles would be the same value as the river water surface level (RWL). Therefore, flood flow patterns could be presented at each return period of flood occurrences using the Gumbel's distribution. Then the inundated depth at any point along floodplain cross-section would be used as flux head in the infiltration model and used to study the change of phreatic surface level (GWL). Moreover, the standard-step method in the river hydraulic analysis's HEC-RAS model (US.ACE, 2001) was applied during the first year that without the stage recorder at Dlog yet. The cross-sectional profiles with average step length of 5–6 km which the upstream boundary water level at Y17 was used as initial condition and for computing stages along the Yom River at cross-sectional profiles, through the inner zone and down to the last section at Y5.

The change of phreatic surface levels in sub-surface water part (Fig. 7) would be compared to the computed recharge over the effective porosity. The effects from lateral groundwater inflow (GW_{in}) and outflow (GW_{out}) from adjacent blocks and leakage to the lower aquifer might affected the change of phreatic surfaces which could be further computed using Darcy's equation based on the change of the slope of the water table between the blocks (Mekpruksawong et al., 2004).

4. Results and discussions

The summary of the configuration of 15-OW Thiessen blocks are namely P03, P07, P08, P09, P10, P11, P12, P13, P14, P15, P20, P21, P22, P23, and P24, and 49-field infiltration points (Fig. 5) were shown in Table 1. These included the serviced area (A) of each OW, ground elevation, F, A_c, K whereas the isohyets of field A_c before block averaging was presented in Fig.8. The final infiltration (approx. K) in the upstream basins connecting the inner zone (153 km^2) was averaged to 9.386 and 3.375 mm/d for the first day and longer period (30 days) of ponded water, respectively. The average infiltration rate (F_{avg}) and time relationships in Kostiakov's model was shown to be $F = 9.386\,t^{-0.3007}$ [mm/d] with $R^2 = 0.9947$. The initial infiltration (F), however, in the inner zone (50.414 km^2) was averaged 4.925 mm/d and the final infiltration in the floodplain zone was 1.355 mm/d (1.568×10^{-6} cm/s) with A_c of 16.245 mm/d/m of head of ponded water (Table 1).

The 4-years daily data recorded of P and elevation of river water stage (Fig. 9) was shown that flood peak in 2001 was less than flood in 2002 which was highest peak. The comparison between P, ET_o, F, and runoff in the inner zone from the upstream boundary at Wangjik via Dlog to the downstream boundary at Phaitapho were presented in daily (Fig. 10) and annually (Fig. 11) with annual P of 1103.6 mm, ET_o of 1515.8 mm, F at the upstream area of 723.1 mm (69.14% of annual rainfall), Q_{in} from upstream basins (225.137 km^2) entering the inner zone of 634.2 mm (57.5% of annual rainfall. Whereas the mean daily of ET_o, F were equaled to 4.15, 2.12 mm, respectively.

The average characteristics and results of Snyder's synthetic unit hydrographs for 3-subbasins in the inner zone were; the average slope of 0.000286, unit discharge (q_p) of 1.788 cu.m/s/mm, and lag time (t_p) of 12.3 h, respectively. The local stream discharge was very small compare to the river and floodplain flow that will not affect the flood extent. However, it contributed and combined to the overbank flow from the Yom River during inundated period.

The characteristic of flooded elevation, inundated extent, and temporary storage volume between Wangjik to Phaitapho was presented (Fig. 12). The result of flood extent was used to draw flood flow patterns in Fig. 13 (Chuenchooklin et al., 2003) and comparative of inundated extent in 3-years (Fig. 14). The comparison between RWL and GWL was presented in Fig. 15 and Fig. 16. The lag-time between rising and recession limbs of those hydrographs in the year 2002 and 2003 were 75 days and 105 days (during rising limb), and 10 days and 6 days (during recession limb), respectively. Those trend lines in Fig. 16 during rising and recession limbs were fitted with R^2 equal to 0.90 (Chuenchooklin et al., 2004). The difference on slope of those trend lines and time delayed during rising and falling limbs were shown because of flood volume and ponded time in the year 2002 was more and longer than in the year 2003. However, the data of water table hydrographs of some OWs along the river e.g. P20, P22, and P24 were less affected by the change of river water levels.

The computation of recession constant (K_{rb}) for baseflow separation into groundwater flow (K_{rg}) and interflow (K_{ri}) during the years 2000–2003 were fitted average of 0.783 and 0.936, respectively and R^2=0.9672. The amount of annual baseflow per total runoff via the measuring point was averaged to 0.107. However, during dry season (January to May), there is no baseflow in the river because of the withdrawal for crop and human consumption has been taken by farmers and communities using small pumping machines along the river. Therefore, the baseflow is decreasing as the result showed that the trend line of the minimum GWL in dry season (P7, P11, and P14) is slightly decreasing with the rate of 0.10 m per year (Fig. 15).

The simulation using water budget for each polygon showed that the averaged losses rate from paddy field percolated to the uppermost aquifer layer was very high with 2650 $m^3/d/km^2$. Total annually infiltrated water was 26 million m^3 during inundated period (90 days) in year 2002 over floodplain paddy field area (50.414 km^2) with about 5730 $m^3/d/km^2$. The averaged daily P-M's ET_o was 4.1 mm which produced the total potential loss by this phenomenon and for dry seasonal crop water requirement computing of 34 million m^3 with about 75% of gross area.

5. Conclusions

From the study using water budget model, the distributions of infiltration fluxes over floodplain have a directly effect to the phreatic surfaces through flood extent over the land surface during inundated period. The daily flood storage and inundated area in the study site could be estimated from the corresponding local lateral inflows, overflow from the bank-full level. The generated database from existing topographic contours and basin characteristics using GIS techniques coupling to hydrologic models could be applied to compute flood. Most of the floods were produced by overflowing from the riverbank because of total sub-catchments area were smaller than whole river basin sizing. Flood risk map could be developed corresponding to hydrological statistics, and hydrodynamic model, should be extended to the local administration officers and farmers in order to change or shift cropping pattern in floodplain for avoiding flood.

The main cause of inundated extent in this study area was over-bank flow from the river rather than the flow from surface runoff over its catchment's area. The influences from inundated zone leaded to the increasing of phreatic surface too. If higher inundated depth by flood occurred then the slope-line of GWL on the rising limb would be steeper than fewer floods which were already discussed on Fig. 15 and Fig. 16. On the other hand, the downward slope of trend line of GWL occurs which might be influenced by the greater amount of groundwater withdrawal than amount of flood recharging. The fluctuation of phreatic surface was mainly influenced by flooded recharge and groundwater withdrawal. For the conservation of phreatic surface in flooded zone, further study about flood reduction through artificial recharge from the zone with high infiltration flux e.g. farm-ponds and sandpits should be carried out. Understanding and quantifying the phreatic surface fluctuations in lowland paddy field is crucial for further floodplain management.

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Table 1. Summary of 15-observation well (OW)'s configuration resulted by Thiessen Polygon.

OW's name	A [km^2]	Elevation [m(MSL)]	F [mm/d]	A_c [mm/d/m]	K [mm/d]
P03	4.233	33.727	12.4275	30.988	2.1328
P07	0.623	33.675	0.0606	9.595	0.0033
P08	3.968	33.824	2.7883	10.941	0.6015
P09	3.350	34.074	0.8771	9.799	0.0372
P10	3.674	33.455	13.2486	14.555	4.8885
P11	3.704	33.160	3.9618	4.284	0.9247
P12	2.248	32.126	3.9296	37.661	0.7095
P13	3.182	33.546	3.4740	4.722	1.5381
P14	4.356	32.744	3.8949	51.089	0.9424
P15	4.825	32.570	7.6243	23.693	2.2082
P20	3.653	31.626	2.8464	4.698	1.6496
P21	2.814	32.198	9.6890	14.810	2.7641
P22	2.297	32.080	0.2869	6.303	0.0225
P23	5.922	32.166	0.9923	2.788	0.0415
P24	1.566	32.370	0.2869	6.303	0.0225

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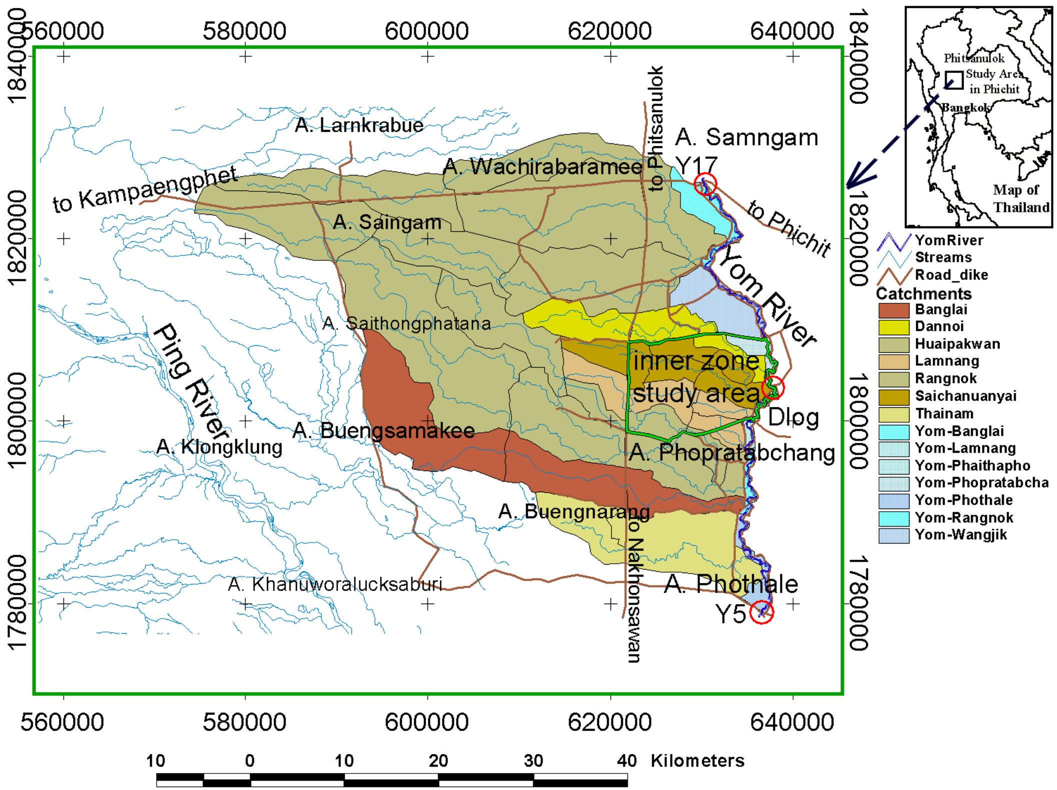

Fig. 1. Location of study area, streams and catchment's systems, inner zone, and river's gauging stations.

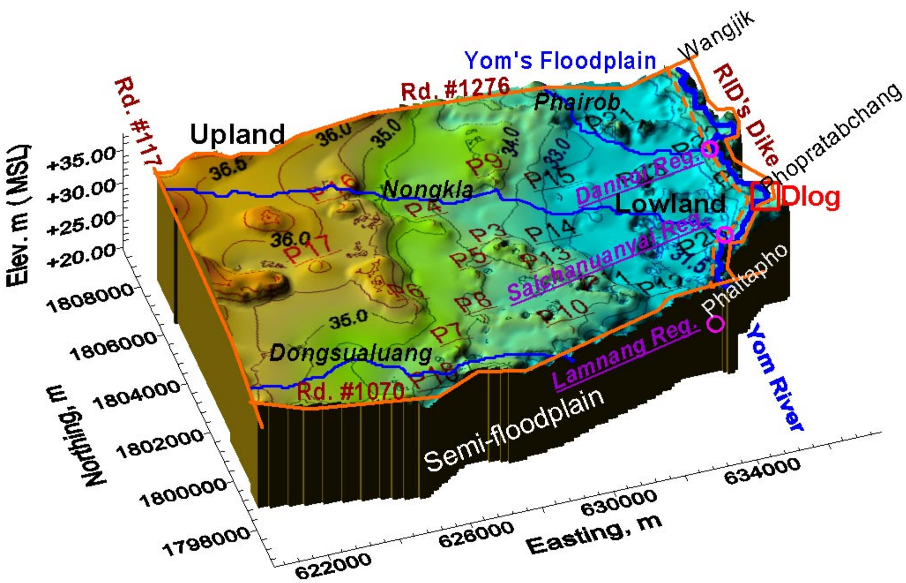

Fig. 2. 3-D view of the inner zone (153 km^2) included contour-lines, roads boundaries, dike, Yom-River, 3-local streams (Phairob, Nongkla, and Dongsualuang) with regulated structures (Dannoi, Saichanuanyai, and Lamnang), location of river stage recorder (Dlog) and 22-observation wells (P3 to P24).

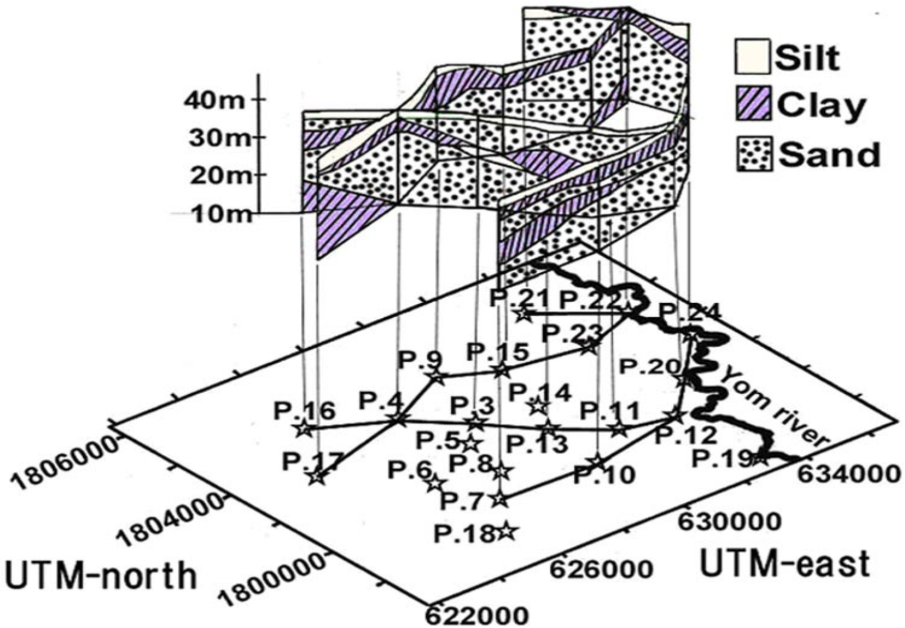

Fig. 3. 3-D view of geological profiles resulted by soil log data interpreting from 22-observation wells (OW)'s construction in the inner zone (after Mekpruksawong et al., 2004).

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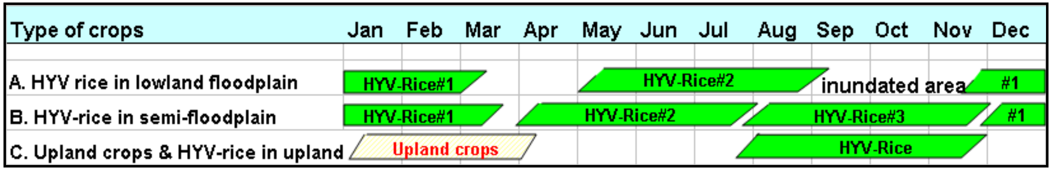

Fig. 4. Cropping pattern in the inner zone of study area.

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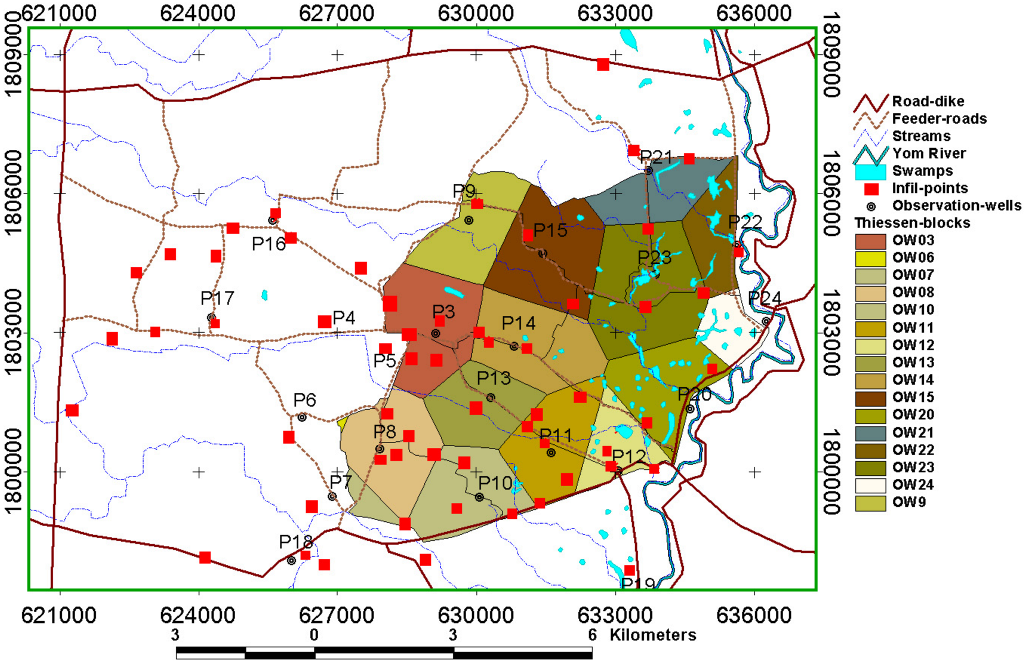

Fig. 5. View of 15-observation well's serviced area (OW) using Thiessen's polygon in study area (50.414 km^2) and location of 49-field infiltration experimental points located in floodplain.

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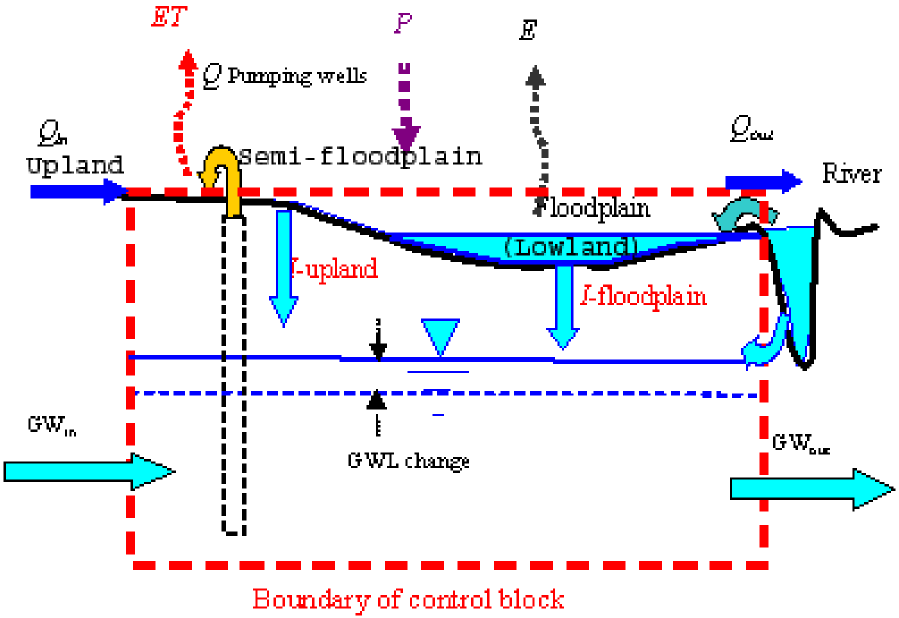

Fig. 6. Configuration of water budget model for the study interactions of floodplain-groundwater interactions.

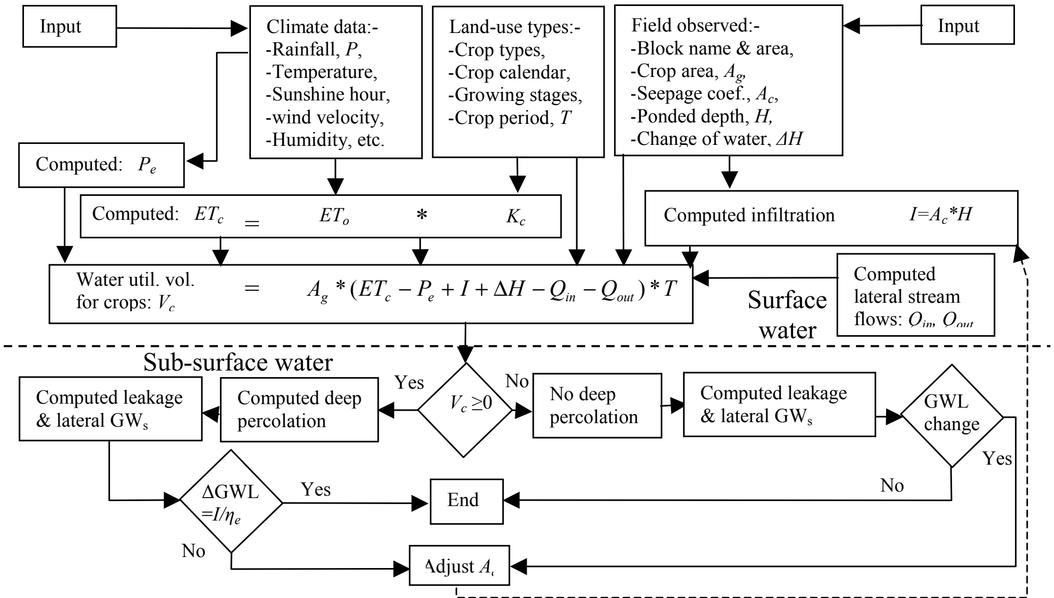

Fig. 7. Flow chart of computing the change of phreatic surface and ponding water in floodplain paddy field.

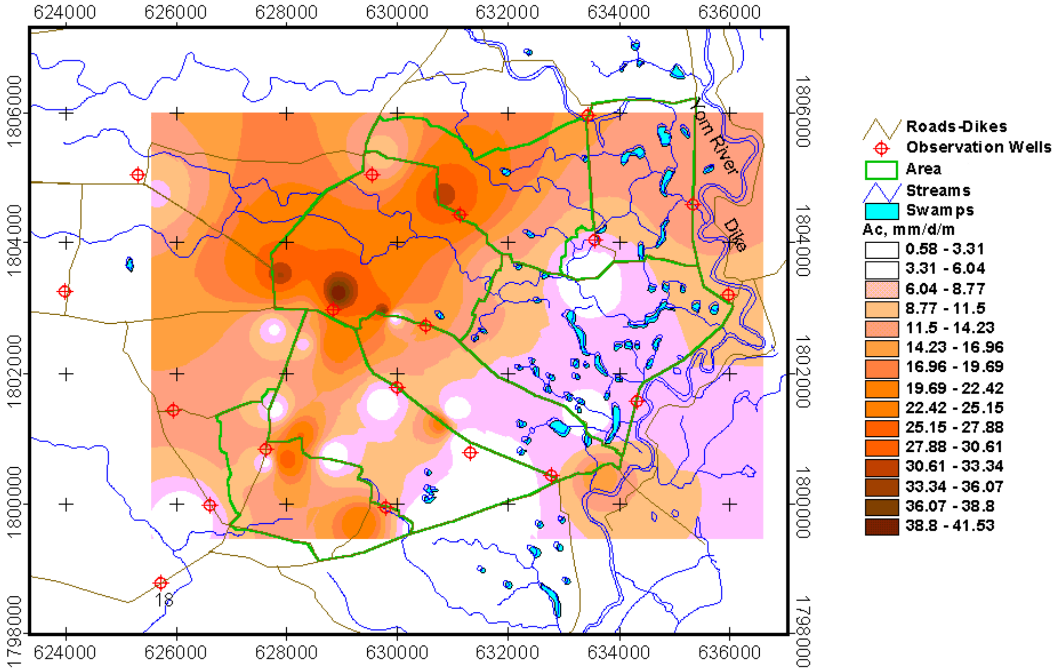

Fig. 8. The distribution of infiltration flux (A_c) over floodplain resulted by 49-points of field experiment.

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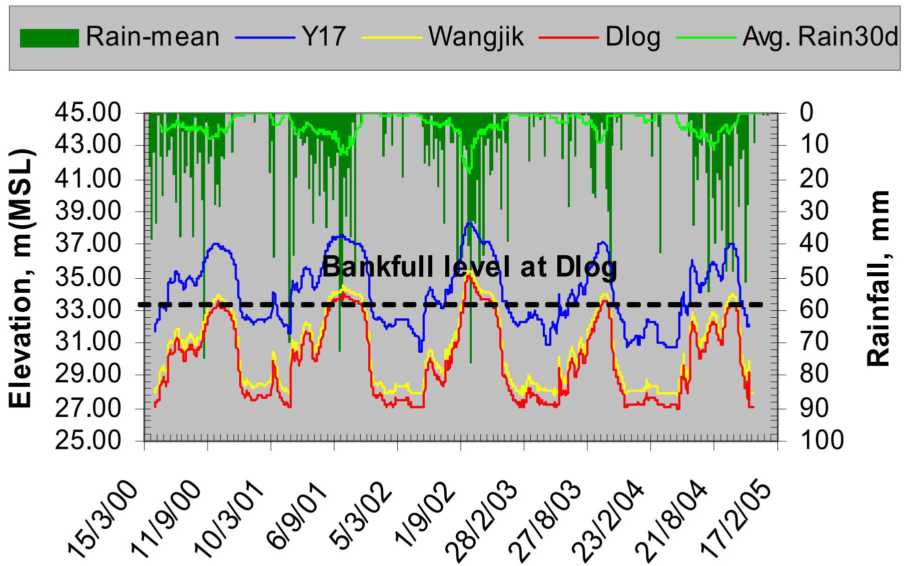

Fig. 9. Daily rainfall and water surface level in the Yom River (RWL) at observation stations during 2000–2004.

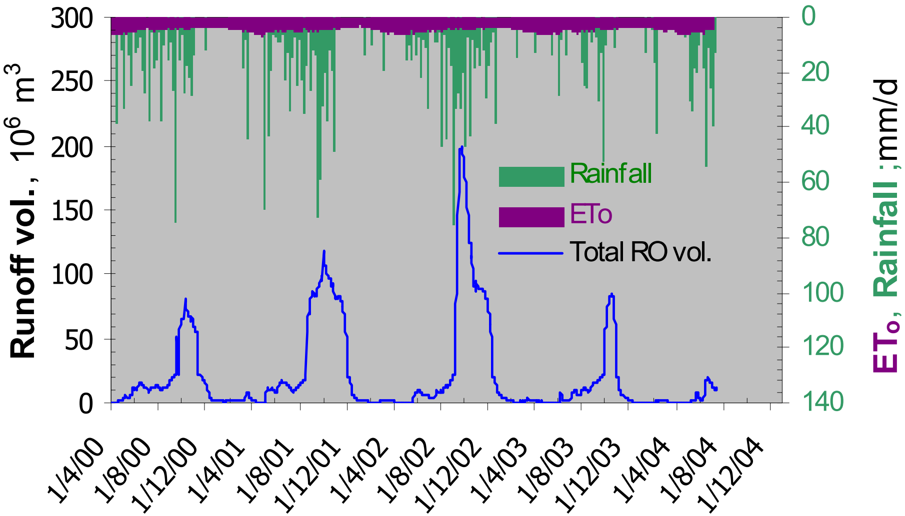

Fig. 10. Daily *P*, *ET*, runoff vol. (RO) on floodplain and river channel via study area during 2000–2003.

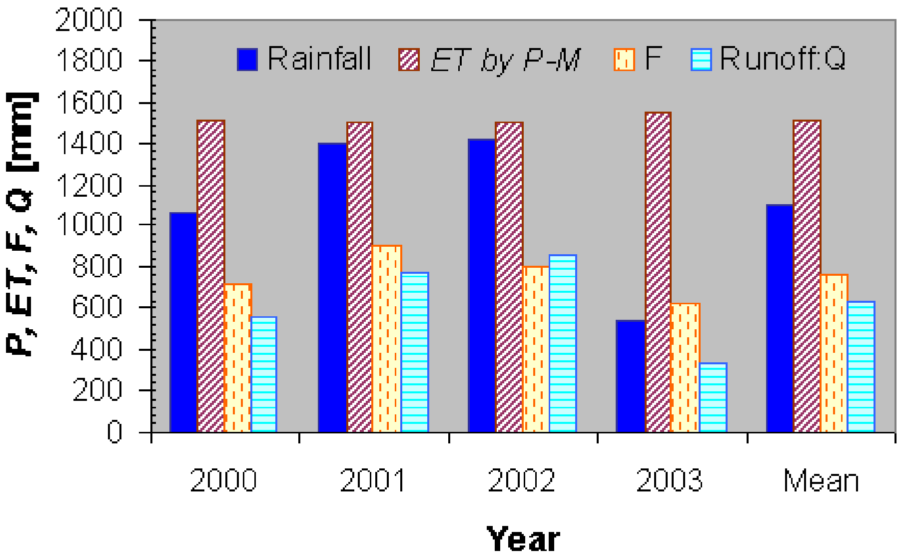

Fig. 11. Annual P, ET, F, Q_{in} [mm] at the upstream catchments to the inner zone during 2000–2003.

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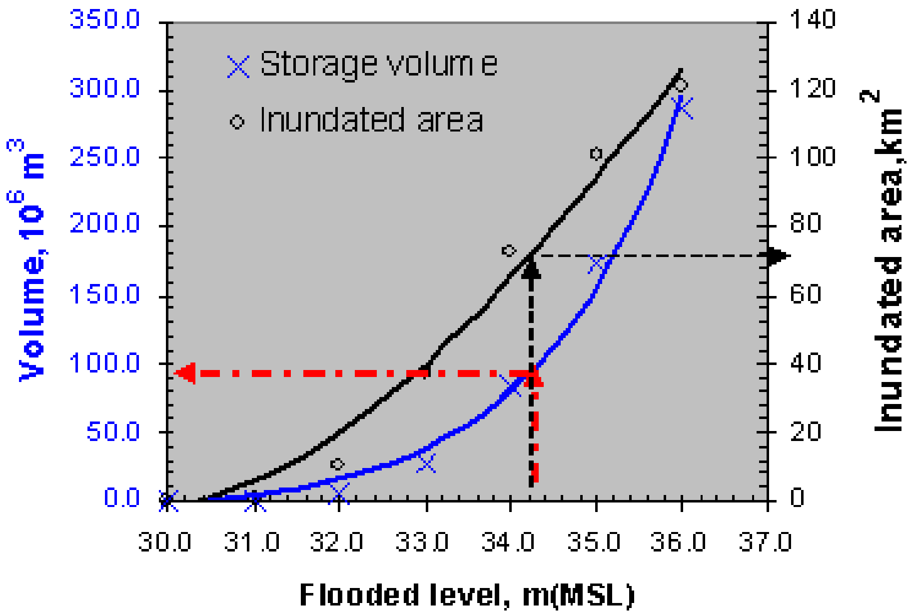

Fig. 12. Characteristic curves of flood pool level versus area, and flood pool levele versus storage volume in floodplain resulted by existing topography.

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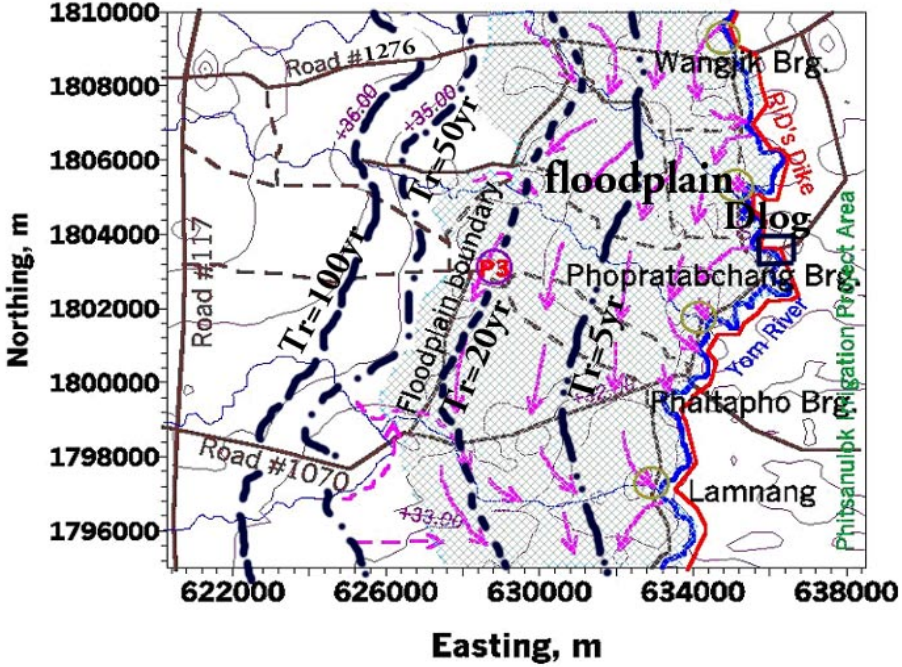

Fig. 13. Flood flow patterns in floodplain with the different frequencies (Tr) of 5 yr, 20 yr, and 100 yr, respectively.

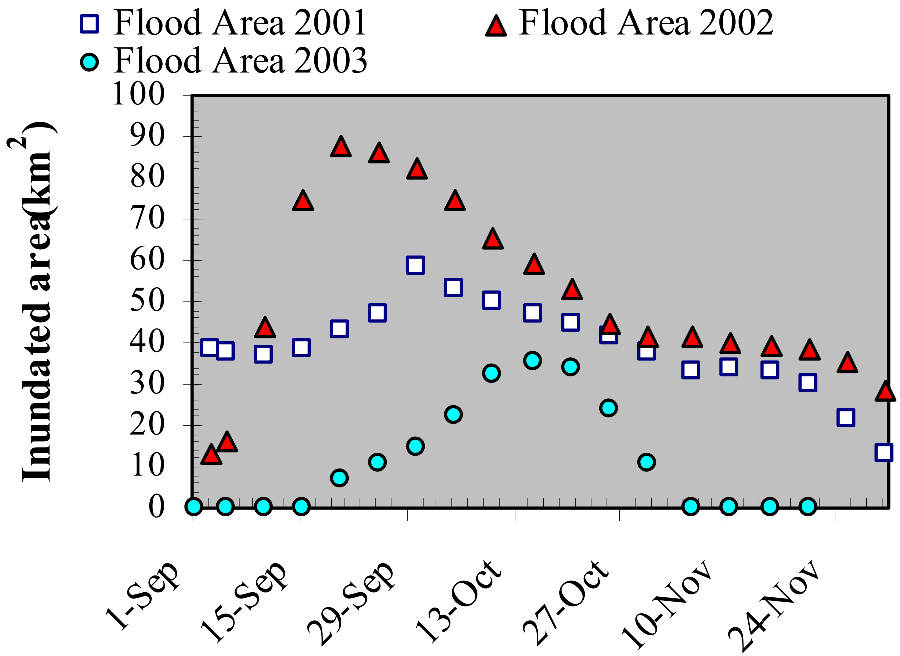

Fig. 14. Comparison of the inundated extents during 2001 to 2003.

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Phreatic surface fluctuations within the tropical floodplain

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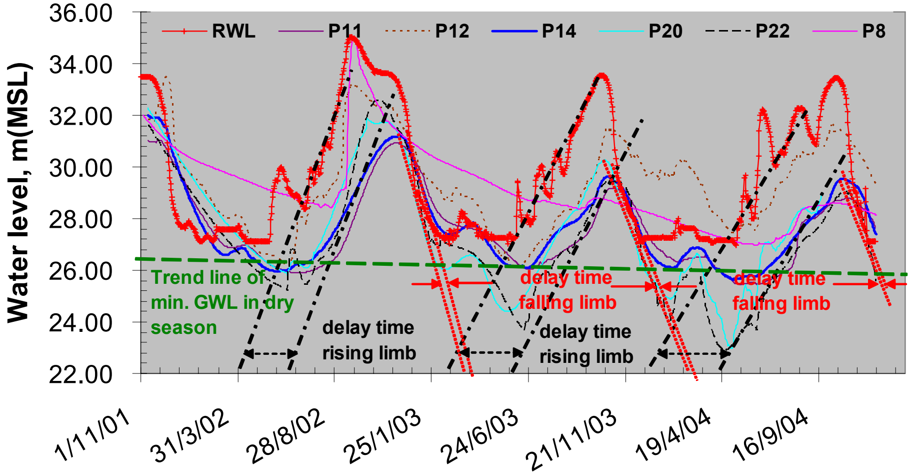

Fig. 15. Comparison between daily river stage (RWL) and phreatic surface (GWL) at some observation wells in floodplain with the downward slope of trend line during dry periods.

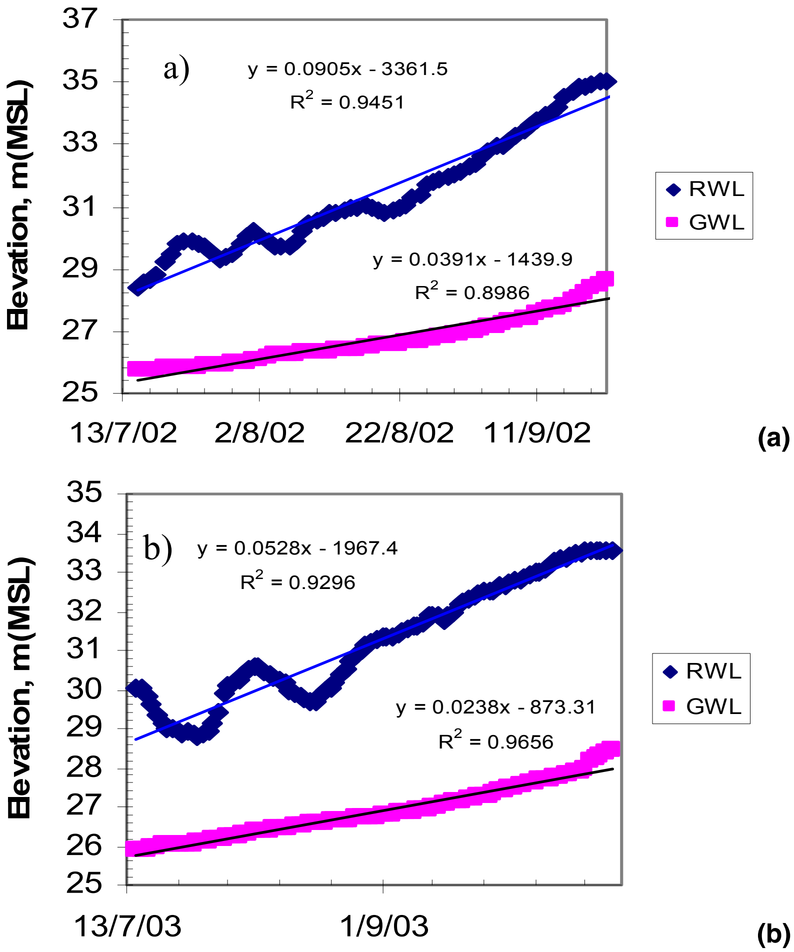

Fig. 16. Comparison between the trend lines of daily river stage (RWL) and phreatic surface (GWL) changed to the rising limbs of river hydrographs in the years: **(a)** 2002, and **(b)** 2003, respectively.