Jurnal
Teknologi

Full Paper

RICE HARVESTED AREA ESTIMATION MODEL FOR RAIN-FED PADDY IN MEKONG RIVER BASIN

Article history
Received
15 July 2015
Received in revised form
2 August 2015
Accepted
26 August 2015

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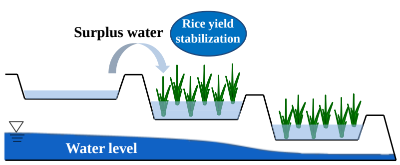
Graphical abstract



Abstract

In Mekong river basin, productivity of rice is still low and unstable because more than 70 % of paddy fields were classified as rain-fed paddy. In addition, future global climate change and land use change will make negative impact on rice production in this region. In order to analyze the stability of rice production quantitatively, it is important to consider the rice farming management such as strategy of rain-fed rice yield stabilization. This management was defined as control their acreage under rice cultivation depended on rainfall amount. In drought year, farmers abandoned some paddies to cultivate rice and collect rain water from abandoned paddies to planted paddies. In this way, statistic data of rice yield was more stable than that of harvested area. In this study, rice production model was developed combined with distributed type water circulation model. This model consists of three sub models, harvested area estimation model used of FAO-33, yield estimation model used of Monteith equations and FAO-56 and rainfall runoff model used of TOPMODEL. Developed rice production model was applied to Mekong river basin. Mekong river basin was divided in 10km mesh grids, and model simulation was conducted in 10km resolution from 1986 to 1995. Simulation result of rice harvested area, yield and production were verified with the statistic data of northeast Thailand. As a result, rice harvested area, yield and production was good agreement with statistic data, and especially error in rice yield was improved by considering the strategy of rain-fed rice yield stabilization.

Keywords: Mekong river, TOPMODEL, harvested area ,rice yield, water stress

1.0 INTRODUCTION

World population has increased from 3 billion in 1960 to 6 billion in 2000. Furthermore, by 2050, it is expected to increase up to 9.5 billion. Along with population growth, global grain production has also increased, owing to breed improvement, application of chemical fertilizers, and the expansion of irrigated farmlands. According to the United Nations' World Food Programme (WFP), in 2013, approximately 870 million people were undernourished. Approximately 98% of the undernourished people live in developing countries; about 560 million belong to Asia and the Pacific Ocean region.

According to the Fourth Assessment Report published by the Intergovernmental Panel on Climate Change (IPCC), in low-latitude regions, especially tropical regions, even a 1–2°C-rise in the average temperature has a negative impact on grain productivity; starvation risk has also been predicted to increase. In addition, because of increasing water circulation rate, flood and drought damage is of major concern.

Asian Agriculture is mainly of paddy rice cultivation. Most of the agricultural land is occupied by rain-fed paddy fields that depend only on precipitation. Irrigation rate in the Mekong River basin is low (30%) (the ratio of the dry season cultivation area to the rainy season cultivation area) [1]. Therefore, the effect of the above-mentioned problems on food production is pronounced.

The impact of climate change on crop production has been extensively studied. Tanaka *et al*. (2011) developed a tool for predicting the possibility of rice cultivation by using the rice growth simulation model [2]. And previous study indicated that assessment of the impact of climate change in the near future on rice production in Asia [3] [4] [5]. These analyses are mainly concerned with the evaluation of potential rice yield.

Therefore, in this study, we developed a rice production model combined with a distributed-type water circulation model, including the estimation of harvest acreage model. And we evaluated its impact (harvest acreage) on yield and production.

2.0 STUDY AREA

Mekong river is located in the Indochina peninsula in Southeast Asia, and it flows in six countries. Its length is approximately 4,400 km, and the catchment area is 790,000 km^2 (Figure 1). Basin land use, forest was 41.5%, agriculture land mainly paddy field was 37.8%. In 1993, irrigation rate was only 8.6%; the rest of paddy field was rain-fed. Generally rain-fed paddy was vulnerable and unstable with respect to the weather conditions.

In this study, the verification region was selected to be northeast Thailand (Figure 2), where reliable rice production data existed. Northeast Thailand includes the Moon Chi river basin.

3.0 MATERIALS AND METHODS

The rice production–water circulation model consists of three sub models—runoff analysis model, harvested area estimation model, and plant growth model. These models are based on hydrometeorological and topographical data. In this study, data on precipitation, temperature, and cloud cover were obtained from the Climate Research Unit (CRU TS2.10, resolution 0.5°monthly). Shortwave radiation data were obtained from the Solar Radiation Budget (SRB, resolution 1.0°monthly). Digital elevation map and land use data were obtained from U.S. Geological Survey (USGS Hydro1k and Land Cover Institute, resolution 0.01°), and data on soil nitrogen content and saturated soil water content were obtained from Food and Agriculture Organization (FAO GeoNetwork, resolution 0.5°). These data were integrated 10km resolution from each resolution.

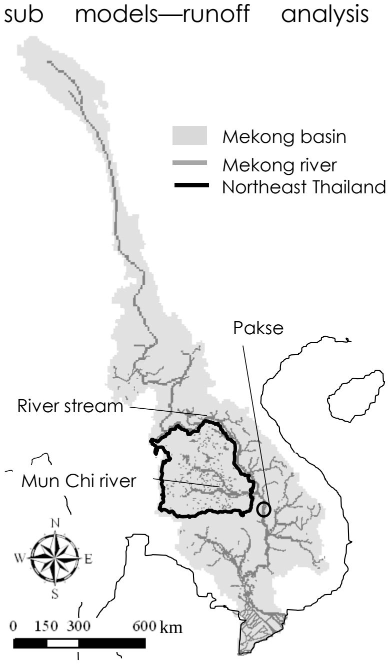


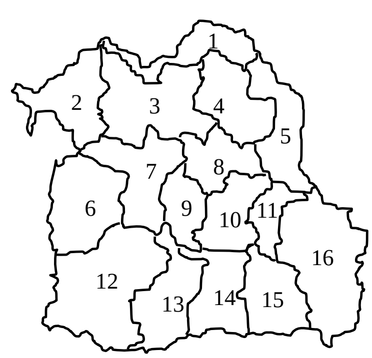
Figure 1 Mekong river basin

3.1 Water Circulation Model

TOPMODEL, which was proposed by Beben *et al*. [6], was used for the water circulation model. The TOPMODEL is a rainfall–runoff model that uses the concept of hydrological similarity based on the topography. With the help of TOPMODEL, some corrections that consider the physical properties were added to the conceptual model. These were applied in large- and small-scale basins all over the world [7] [8]. Thus, the general versatility and applicability of TOPMODEL has been assessed. The circulated volume of water was estimated. Based on the water budget, there are three zones—root, unsaturated, and saturated zones. In general, root and unsaturated zones are calculated as the distribution type, but saturated zone is the lumped type. In this study, a fully distributed TOPMODEL was used to calculate the water budget in each grid lattice and the saturated zone. The estimation of accuracy of the water budget will affect the calculation result of crop production model.

3.2 Rice Production Model

The rice production model consists of two sub-models—harvested area estimation model and plant growth model. Estimation of the harvested area is calculated by the ratio of actual evapotranspiration to potential evapotranspiration based on FAO-33 [9]. Harvested area reduction ratio is calculated by the following equations [10].



Province No.	Name
1	Nong Khai
2	Loei
3	Udon Thani
4	Sakon Nakhon
5	Nakhon Phanom
6	Chaiyaphum
7	Khon Kaen
8	Kalasin
9	Maha Sarakham
10	Roi Et
11	Yasothon
12	Nakhon Ratchasima
13	Buri Ram
14	Surin
15	Si Sa Ket
16	Ubon Ratchathani

Figure 2 Provinces of Northeast Thailand

(i) When $Ka_i<ka_{i-1}$

$$Ka_i = \frac{(\sum_{j=1}^{i} ETa_j + a)\cdot APr}{(\sum_{j=1}^{i} ETp_j + a)\cdot APr} \quad (1)$$

(ii) When $Ka_i>ka_{i-1}$

$$Ka_i = Ka_{i-1} \quad (2)$$

where the subscript *i* indicates the current day, the subscript *j* indicates the day the calculation was started (May 1). Ka_i is harvested area reduction rate [-], ETa_j is the actual evapotranspiration [mm], ETp_j is the potential evapotranspiration [mm], *APr* is the after-correction paddy area [km^2], and *a* is the relaxation constant [mm]. In order to determine the initial water depth, in this study, a = 30mm. Ka_i means ratio of the required amount of water to the available actual amount of water during the total cultivation period. The harvested area is calculated as follows

$$AH_i = APr \cdot Ka_i \quad (3)$$

$$APr = AP \cdot C \quad (4)$$

where AH_i is the harvested area [km^2], *AP* is the paddy-cultivated area [km^2] plotted in a 1 km scale land-use map published by USGS, *C* is the correction coefficient [-]. *APr* should be corrected by multiplying *C* (*C* = 0.47) because *AP* has a different statistical value in north-eastern Thailand.

The plant growth sub model can also be defined as the carbon assimilation model proposed by Monteith (1997) [11]. This model is widely used in hydrological models such as WEEP (Water Erosion Prediction Project) and SWAT (Soil and Water Assessment Tool). This model is based on the concepts of phonological crop development, daily heat unit accumulation, and harvest index for partitioning the gain yield.

$$HUI_i = \frac{\sum_{k=1}^{i}(T_i - Tb)_k}{PHU} \quad (5)$$

where HUI_i is the heat unit index [-], T_i is the average temperature [°C], *Tb* is the initial temperature for the crop [°C], and *PHU* is the potential heat unit required for maturity [°C]. *PHU* is one of the fitting parameters, for the minimization of the error in north-eastern Thailand province *PHU* = 1,700°C. HUI_i ranging from 0 to 1, HUI_i = 0 means planning, HUI_i = 0.5 means ear, HUI_i = 0.8 means reduction leaf, HUI_i = 1 is physiological maturity. Biomass production is accumulated through cultivation period as follows

$$Bm = \sum_{i=1}^{ndays} \Delta B_i \quad (6)$$

$$\Delta B_i = BE \cdot PAR_i \cdot REG \quad (7)$$

$$PAR_i = 0.5Rn_i \cdot (1.0 - \exp(-0.65 \cdot LAI_i)) \quad (8)$$

where *Bm* is the biomass production [kg/m^2], *ndays* is the total number of days from the starting day, ΔB_i is the increase in total biomass production [kg/m^2/day], *BE* is the crop parameter for the conversion of energy to biomass [g/MJ/day], *REG* is the crop growth regulating factor (the minimum of the temperature and water stress factors). PAR_i is the photosynthetic active radiation [MJ/m^2/day], Rn_i is the solar radiation [MJ/m^2/day], LAI_i is the leaf area index [-]. *BE* is one of the fitting parameters of the model, which was set as a function of the FAO soil nitrogen content map. The value of the identified *BE* varied from 0.58 to 1.12. When the future changing of the fertilizer amount or varieties, it is possible to express the increased production by adjusting the *BE*. Interception PAR_i is estimated with Beer's law; it is expressed as a function of Rn_i and LAI_i.

The temperature and water stress factor are calculated as follows

$$TS_i = \sin\left[\frac{\pi}{2}\frac{T_i - Tb}{Ta - Tb}\right] \quad (9)$$

$$WS_i = \frac{TAW_i - SWD_i}{TAW_i - RAW_i} \quad (10)$$

$$SWD_i = SWD_{i-1} - AW_i + ET_i + Per_i \quad (11)$$

where TS_i is the temperature stress factor [0-1], *Tb* is the initial temperature for crop [°C] (*Tb* = 15°C), and *Ta* is the optimum temperature [°C] (*Ta* = 30°C) [12]. KS_i is the water stress factor [0-1]. It is calculated by considering the water budget in the equation. The value of KS_i is predicted using the soil and water balance model (proposed by FAO-56, Crop evapotranspiration) [13], where TAW_i is the total available water in the root zone [mm], RAW_i is the readily available water in the root zone [mm], SWD_i is the soil water depletion at the end of the day [mm], AW_i is the available water [mm], and Per_i is the water loss from the root zone by deep percolation [mm]. TAW_i and RAW_i are the amounts of water that can be extracted from the root zone, and their magnitudes depend on the type of soil and rooting depth. Per_i is calculated based on the shallow groundwater level indicating moisture shortage in the saturated zone of the water circulation model.

Yield is calculated as follows

$$YLD = HIA \cdot Bm \quad (12)$$

$$HIA_i = HIO_j \cdot f(WS_i) \cdot f(HUI_i) \quad (13)$$

where *YLD* is the yield [kg/m^2], HIA_i is the adjusted harvest index at harvest [-]. HIO_j is the harvest index under favorable growing conditions for crop *j*; it is set to 0.5 for rice. HIA_i is represented by the function of the WS_i and HUI_i, please refer to the literature for details [11].

Rice cultivation schedule in rain-fed paddy field there is characterized that varies according to weather conditions. In this study, therefore, planting date is set to accumulation rainfall from May 1st that exceeds the 250mm. In order to ensure the cultivation period, the latest planting date is set on July 30.

3.3 The Strategy of Rain-Fed Rice Yield Stabilization

In order to quantitatively analyze the stability of rice production, it is important to consider the rice farming management such as strategy of rain-fed rice yield stabilization. This management was defined as control their acreage under rice cultivation depended on rainfall amount. In drought year, farmers abandoned some paddies to cultivate rice and collect rain water from abandoned paddies to planted paddies [14] [15]. In this way, statistic data of rice yield was more stable than that of harvested area. To represent this farming management, the amount of available water altered, depending on the variation of the harvested acreage as follows:

$$AW_i = P_i \cdot \frac{1}{Ka_i} \quad (14)$$

Where P_i is the daily precipitation [mm/day]. In general, available water is only precipitation in rain-fed paddy field, but available water is increased by representing the strategy of rain-fed rice yield stabilization.

4.0 RESULT AND DISCUSSION

4.1 Verification of the Water Circulation Model

The verification of the water circulation model was used river flow rate that observed by MRC. The observations were verified for the following locations: Chiang Saen, Vientian, Savannakhet, and Pakse. Model parameters were identified so that the error is minimized. Figure 3 shows the hydrograph of Pakse, which is located downstream from the Mun Chi River confluence. The estimated river flow was in good agreement with the statistical values over the analysis period. It can be said that hydrological processes are adequately present in the land surface. The harvested area reduction rate and paddy percolation water were calculated from the findings of the water circulation model.

4.2 Verification of the Harvested Area Estimation Model

The verification of the harvested area estimation model was based on the harvested area statistic value issued by The Office of Agricultural Economics in Thailand. Verification scale is not each province but whole province (Figure 4). Because land use data for the harvested area were different from statistic data in the whole province, this rate is *C*. As a result, this model generally reproduced the secular change of the harvested area. Harvested area of reduced 1986, 1987, and 1993 is smaller than 40,000 km^2, it can be seen that has decreased by about 20% relative to the whole province paddy area in northeast Thailand.

4.3 Verification of the Plant Growth Model

The verification of the plant growth model was based on the rice yield statistic value issued by The Office of Agricultural Economics in Thailand. To examine the average yield level and year variation, Figure 5 shows calculated (farming management before and after) and statistic value for 8 provinces that have characteristics. In addition, to examine the effect of the strategy of rain-fed rice yield stabilization, it is shown in Table 1 that is calculation result for all provinces in northeast Thailand. The Root Mean Square Error (RMSE) was used to evaluate error function.

Reproducibility of the plant growth model was seen features in each area. In Loei and Chaiyaphum

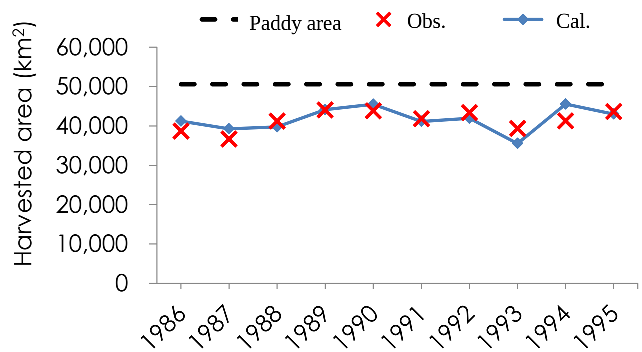


Figure 4 Verification of harvested area (All northeast Thailand)

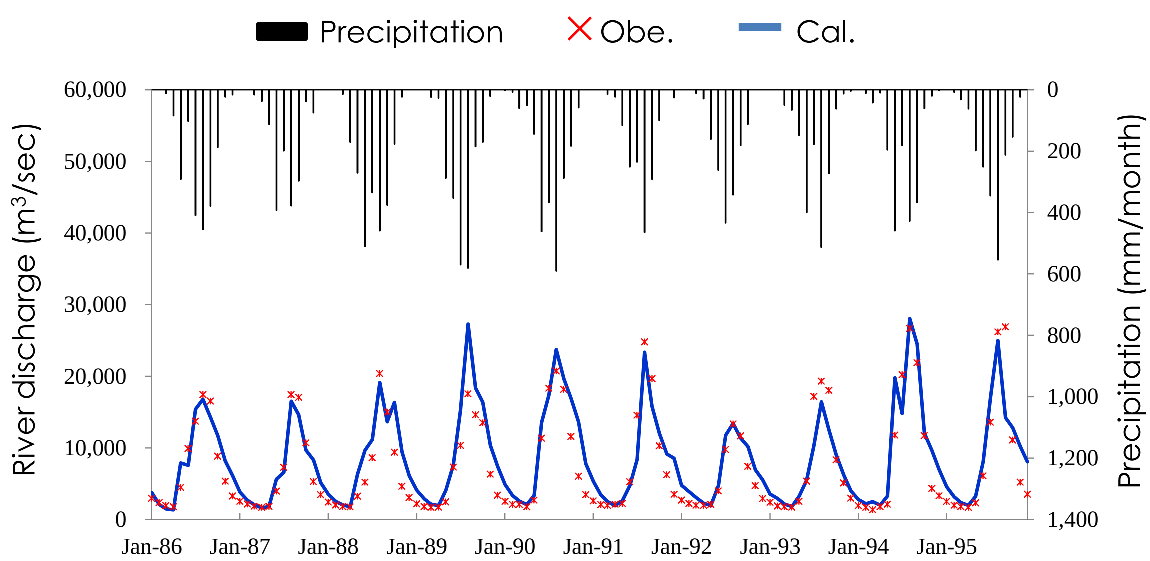


Figure 3 Verification of river discharge at Pakse point from 1986 to 1995

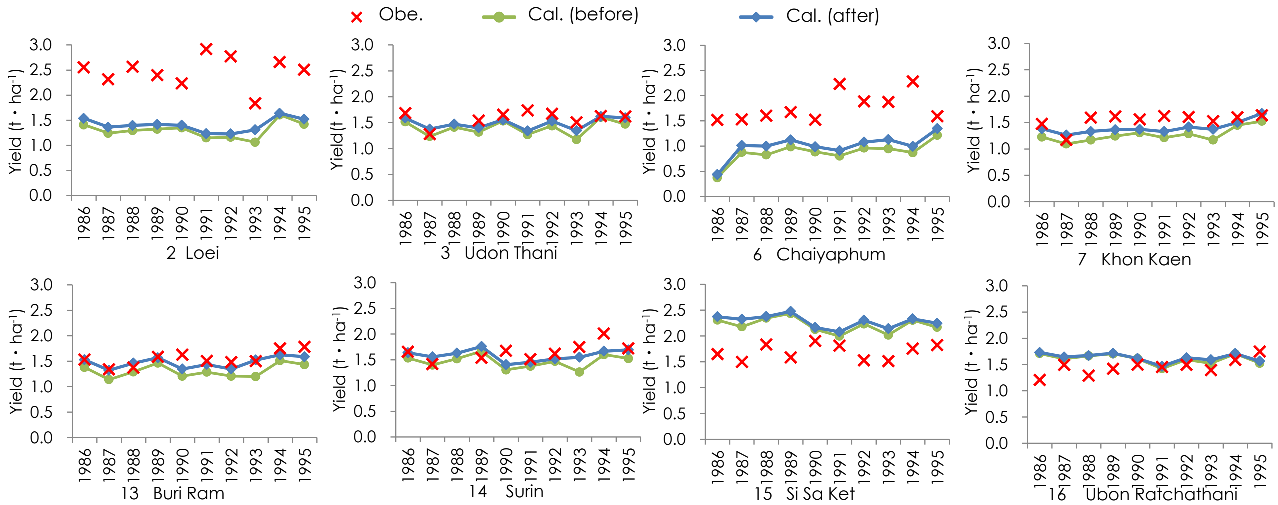


Figure 5 Verification of rice yield

provinces, calculated values were underestimated, as compared to the statistical yield level. These

Table 1 Calculation of rice yield values in northeast Thailand provinces

	Province	Ave. ($t\cdot ha^{-1}$)		S.D.($t\cdot ha^{-1}$)		RMSE	
No.	Name	before	after	before	after	before	after
1	Nong Khai	1.38	1.41	0.09	0.07	0.28	0.25
2	Loei	1.30	1.40	0.15	0.13	1.21	1.11
3	Udon Thani	1.40	1.48	0.14	0.10	0.24	0.17
4	Sakon Nakhon	1.50	1.54	0.13	0.11	0.23	0.20
5	Nakhon Phanom	1.64	1.66	0.09	0.07	0.31	0.30
6	Chaiyaphum	0.88	1.00	0.20	0.22	0.95	0.84
7	Khon Kaen	1.27	1.40	0.12	0.11	0.29	0.18
8	Kalasin	1.44	1.51	0.12	0.10	0.35	0.29
9	Maha Sarakham	1.28	1.41	0.10	0.08	0.21	0.16
10	Roi Et	1.50	1.58	0.10	0.08	0.25	0.23
11	Yasothon	1.46	1.52	0.12	0.10	0.24	0.23
12	Nakhon Ratchasima	1.15	1.29	0.23	0.25	0.35	0.27
13	Buri Ram	1.31	1.47	0.12	0.10	0.26	0.13
14	Surin	1.47	1.59	0.12	0.10	0.27	0.19
15	Si Sa Ket	2.21	2.28	0.13	0.12	0.56	0.63
16	Ubon Ratchathani	1.61	1.63	0.09	0.08	0.24	0.25

Table 2 Compare of annual precipitation MRC with CRU

	Province	Annual Precipitation ($mm\cdot year^{-1}$)	
No.	Name	MRC	CRU
3	Udon Thani	1,390	1,400
7	Khon Kaen	1,320	1,360
15	Si Sa Ket	1,500	1,750

provinces are located in the upstream portion of the watershed, and thus, the forest ratio of Loei (57%) and Chaiyaphum (22%) provinces is higher than the northeast Thailand value (14%). The underestimation is attributable to the influence of fertile soil and spring water, which is supplied from the forest; however, in this model, their effect is not reflected.

On the other hand, in the Si Sa Ket province located downstream of the watershed, calculated value was overestimated as compared to the yield level of statistics. The overestimation is considered attributable to the influence of uncertainty of the input data such as precipitation. On comparing MRC statistic with CRU outputs of annual precipitation

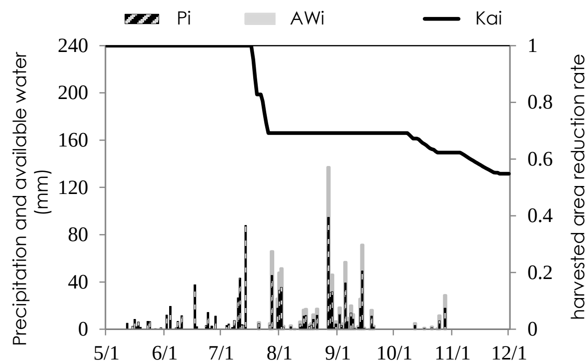


Figure 6 Relationship between Precipitation and available water

during the analysis period (see in Table 2), Udon Thani and Khon Kaen provinces showed good agreement, but Si Sa Ket province did not.

In Udon Thani, Khon Kaen, Buri Ram, and Surin provinces located in the central portion of the watershed, calculated values of rice yield were consistent with statistic values, and the secular changes were generally reproduced. In 13 provinces except for the under-overestimated 3 provinces, RMSE values were below 0.3, obtained good analysis accuracy (Table 1).

In this study, the strategy of rain-fed rice yield stabilization was reproduced. To examine its impact, we compared rice yield calculation values both before and after, the average value increased from 1.61 ton/ha to 1.65 ton/ha, and standard deviation decreased from 0.13 ton/ha to 0.11 ton/ha, which shows increase and stabilization of yield. RMSE values showed improvement in 14 provinces. Year in which the effect of farming management appeared is the 1993 drought year, this year the analysis accuracy was significantly improved. Specifically, the rate of yield increase was 12%, 15%, 21%, and 19% in the

Udon Thani, Khon Kaen, Buri Ram, and Surin provinces, respectively. In some provinces and years, the effect of farming management was not apparent. As a cause, this farming management expressed as equation 14, this method was not enough. Because, increasing the amount of available water were calculated depend on rainfall patterns. Thus in no rain day, it is impossible to collect rain water from abandoned paddies to planted paddies (Figure 6).

5.0 CONCLUSION

In this study, rice production model was applied to rainy rice cultivation seasons in Mekong river basin considering the strategy of rain-fed rice yield stabilization. Major achievements were obtained as follows

(1) The river discharge and harvested acreage calculated by the model were generally consistent with the statistic data.

(2) Rice yield was calculated by plant growth model. In a few provinces, calculated values were underestimated or overestimated as compared to the yield level of statistics, but in most provinces, the calculated values were in good agreement with statistic data.
(3) Reproducing the strategy of rain-fed rice yield stabilization showed rice yield increase and stabilization. Especially in drought year such as 1993, rice yield increased by 10–20%, analysis accuracy was improved. But calculation of amount of available water has a problem that does not depend on rainfall patterns.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 24780228.

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