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Model Simulation of "Sawah-Kolam" System for Rainwater Harvesting to Support Rainfed Paddy Production

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ABSTRACT

Model Simulation of "Sawah-Kolam" System for Rainwater Harvesting to Support Rainfed Paddy Production (S Triyono, Zeovany, Oktafri, and B Rosadi): The study was used to evaluate whether rainwater could be harvested and used to meet water demand of rainfed paddy. As generally known, yield of rainfed paddy was low compared to that of irrigated paddy. The study was performed by simulating a model of "Sawah-Kolam" system. Daily 10 year climatological data from Metro City of Lampung Province was used in the study. The program was written in Professional VisSim 4.0. Three scenarios of alternative planting schedules (January, February, and March) were tested. Results implied that without a collection system, rainwater might not be sufficient to grow rainfed paddy. It was demonstrated that "Sawah-Kolam" system was capable of sufficing water requirement of rainfed paddy. Huge rainwater of more than 90% could be saved, thus reducing a lot of runoff volume. In term of pond size, February appeared to be the most optimum growing season of all other months for Metro City, in that the pond area (1,400 m^2) required was the smallest.

Keywords: Model simulation, rainfed paddy, rainwater harvesting, "Sawah-Kolam" system.

INTRODUCTION

Since Indonesian people eat rice as the staple food, demand of rice is steadily increasing as the population increases. Now national consumption of rice reaches 30 million Mg per year, and in year 2030 the domestic consumption is predicted no less than 60 million Mg (Nainggolan 2007). Many efforts had been taken to meet the national need of rice. Import, even gaining controversy, was one of the efforts to supply the demand. Indonesia imported 2,895 million Mg of rice in 1998, but it was gradually reduced in the following years and in 2008 Indonesia was free from the importing (Abubakar 2009).

Another effort, more important step, to supply the national demand of rice was by increasing production. Indonesia produced rice by 52,137,604 Mg in 2003, then increased to 54,088,468 Mg in 2004, and 54,151,097 Mg in 2005. In 2006, Indonesia produced rice 54,454,937 Mg, and 57,157,435 Mg in 2007. At last, the production reached 60,279,897 Mg in 2008 (BPS 2009). Wet (irrigated) land was the backbone of the national production of rice, with the yield of 4.89 Mg ha^{-1} in 2008 (BPS 2009); while, rainfed (dry land) still had low production with lower yield.

Lampung Province is one of important contributors of national rice production. Similar figure of national rice production happened everywhere including Lampung Province. For example, average yield of wet land paddy in Lampung reached 4.56 Mg ha^{-1}, while yield of rainfed paddy was only 2.66 Mg ha^{-1} in 2006 (BPS Lampung 2007). It seemed that the rainfed lands functioned under suboptimal condition. The rainfed paddy covered a significant area to the total sawah in Lampung (13% of total area), but its production was only 8% of the total.

The yield gap was about similar for other locations in Indonesia and so was the cause. The low

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productivity of rainfed paddy was obviously caused by water availability. Irrigated paddy had never faced water deficit as rainfed paddy had. Rainfed paddy exclusively relies on rainwater to meet its consumption. When rainfall is abundant, its water consumption is satisfied. However, in dry days the crop may suffer from water stress, resulting in low yield or even harvest may fail. A lot of Indonesian farmers working on rainfed lands have been long time in such condition of water uncertainty.

Such high tropical rainfall in Indonesia seems to be overlooked and is not wisely managed. In contrast, there are some areas in the world are in water scarcity condition such as in Middle East and North Africa (World Bank 1992; Pereira *et al*. 2002). A lot of people live in areas under water stress condition, with availability of water resources less then 2000 m^3 per capita per year (UNEP 2003). Water crisis in the world was predicted to be more frequently to occur and in wider areas in the future. Within the last century, water demand had been increasing 6 folds (UNEP-DEWA 2003).

Rainwater harvesting systems have been a solution to the water scarcity in some locations in the world, whether for crop cultivations or other uses, particularly in areas where water crises frequently took place (Critchley and Siegert 1991; Pereira *et al.* 2002). If the rainwater harvesting systems are applied for rainfed paddy production (Wu *et al.* 2001) in Indonesia, the problem of water deficit could be resolved.

This research was to evaluate the potential of a rainwater harvesting system to supply irrigation water for rainfed paddy using a model simulation of “Sawah-Kolam” in Metro City, Lampung. Some researches on water movement and water dynamic in paddy rice fields have been conducted (Chen and Liu 2002; Arora 2006) but use of “Sawah-Kolam” system in rainfed paddy fields has not been reported. Reduction of runoff volume (Bosch *et al.* 2005) is among many advantages that can be obtained from the rainwater harvesting system. Besides assurance of water availability for paddy; other advantages include fertilizer (Feng *et al*. 2004; Seo *et al*. 2005; Gilley *et al.* 2007) and pesticide residue (Nakano *et al*. 2004; Matsui *et al*. 2006) transport, erosion (Rachman *et al.* 2008; Yin *et al.* 2009), flood, and environmental pollution can be prevented (FAO 1996; Carpenter *et al*. 1998; Pitois *et al*. 2001; Brachmort *et al.* 2006).

MATERIALS AND METHODS

Location and Data

This research used daily rainfall and pan evaporation data from 1999 to 2008 taken from the Meteorological Office, Metro City Lampung. The City of Metro was chosen due to its completeness of the Meteorological data. In order for the modeling to work, daily climatological data was continuously arranged from day 1 (Julian day) in a file. The first day was 1 January 1999 and the end time was 30 December 2008. Correction was carried out to the evaporation data because there were some blanks. The blanks were filled by interpolating the adjacent days (before and after the blanks). The rainfall data; however, was complete.

Soil samples from the location were taken for analyses of texture, bulk density, and field capacity. The sample was analyzed at the Laboratory of Soil Science, College of Agriculture, University of Lampung. Field measurement was mainly to determine percolation rates by using lysimeters with and without bottom. Other constants such as crop coefficient (Kc), saturation point, wilting point, and pond evaporation coefficient were taken or adjusted with some literatures, for example from FAO.

Description of the Rainwater Harvesting System

The model of rainwater harvesting system consists of a unit paddy field “sawah” and a unit collection pond “kolam”, so named as “Sawah-Kolam”. The model is visualized as on Figure 1. Water level of the paddy field moves upward when rainfall comes or irrigation water is added, and downward due to evapotranspiration and percolation. Percolation occurs when soil water content over the field capacity. If rainwater exceeds the field water holding capacity, overflow will occur and the runoff water is collected in the pond. Conversely, if the field water decreases to the allowable level (halfway between wilting point and field capacity), the field is irrigated to saturation level by pumping the pond water. If the pond water is not sufficient, the irrigation water will be taken from other sources, such as groundwater, but this is just for the model works properly without disturbances.

Slightly different, pond water level moves just similar to the paddy field water. The pond water surface will rise because of rainfall and overflow from the paddy field, and decrease when pumped for

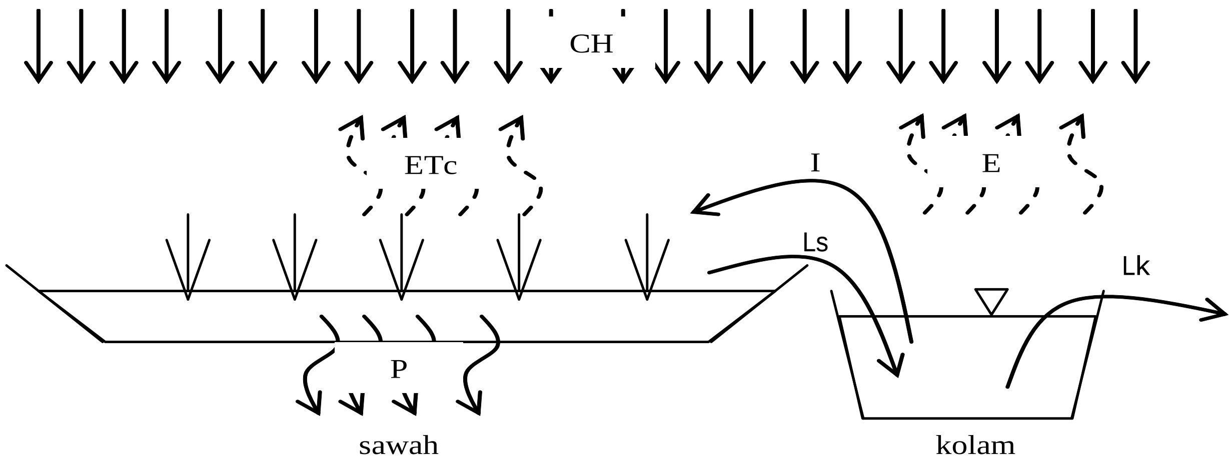

Figure 1. Description of "Sawah-Kolam" for rainwater harvesting system.

irrigation and because of evaporation. If rainwater and runoff water from the paddy field exceed the water holding capacity of the pond, then the water will overflow and discharged from the "sawah-kolam" system.

Water Balance Model

Simulation simultaneously operated two water balance models, in the paddy field and in the collection pond. The water balance model in the paddy field is presented on Equation 1.

$$\left(\frac{\Delta H}{\Delta T}\right)_s = CH + I - ETc - P - Ls \qquad (1)$$

where (ΔH/ΔT)s is change of water level per day in the field, CH is rainfall, I is irrigation, ETc is evapotranspiration, P is percolation, and Ls is overflow from the field. Evapotranspiration is estimated using Equation 2 as proposed by Doorenbos and Pruitt (1977),

$$ETc = Kc x ETo \qquad (2)$$

where, Kc is crop coefficient and ETo is potential evapotranspiration or measured pan evaporation data. The equation has been used in many researches (Vu *et al*. 2005; Yoder *et al*. 2005; Hunsaker *et al*. 2007).

Water balance in the collection pond is presented as on Equation 3.

$$\left(\frac{\Delta H}{\Delta T}\right)_k = CH + Ls - I - E - Lk \qquad (3)$$

where (ΔH/ΔT)k is change of water level per day in the pond, E is pond evaporation, and Lk is overflow from the pond. Pond evaporation was as on Equation 4;

$$E = K x ETo \qquad (4)$$

where K is pond evaporation coefficient.

Simulation run continuously, from day to day, and compute water level at day i+1 (Hi+1) based on water level at day i (Hi) and change of water level at day i (ΔH/ΔT)i as presented on Equation 5.

$$H_{i+1} = H_i + \left(\frac{\Delta H}{\Delta T}\right)_i \qquad (5)$$

Equation 3 works for both the paddy field and the collection pond. In the water balance models, all variables are water levels in mm. Hence, in order for the models to work properly, all soil water contents such as wilting point, lower limit, field capacity, saturation level were converted to water level in mm. The program was written in Professional VisSim (Visual Simulation) 4.0. Similar simulation techniques have been used in Cathcart *et al*. (1999) and Cathcart *et al*. (2007).

Assumptions and Limitations

Assumptions and limitation of this models as follows (1) Simulation was continuous, in growing and non-growing/off seasons, with daily intervals, for 10 years (1999-2008). So, there was one growing season per year, or total of 10 growing seasons within 10 years, (2) growing season lasted 105 days with irrigation period of 90 days, (3) Initial soil water content of the paddy field was assumed at saturation, while initial water level of the collection pond was 1 m, (4) the area of paddy field was 1 ha (10,000 m^2), mud thickness/root zone was 20 cm, and maximum water levels (inundate) were zero for first 10 days from planting, and 10 cm thereafter, (5) in growing season, evapotranspiration was maximum at field capacity and above, and decreased when soil water content decreased to the allowable lower limit (middle between wilting point and field capacity) at which irrigation was applied, (6) in off season, the field was assumed to be bare or covered by grass or organic litters, so maximum evapotranspiration was assumed to be the potential evapotranspiration for field capacity and above. Evapotranspiration decreased when soil water depleted bellow field capacity and stopped at halfway of wilting point (Allen *et al*. 2005), (7) pond evaporation stopped when the pond was empty, (8) because the model was used to evaluate the maximum potential of rainwater harvesting, the pond was assumed to be an ideal system, or the percolation of the pond bottom was zero. Minimum percolation of pond bottom could be really obtained to some extends if the bottom was layered with some impervious materials (Teichert-Coddington *et al*. 1989; Lentz and Kincaid 2008).

Scenario and Output Data

Growing season was started in wet months; January, February, and March. Planting in other moths were not observed because it was uncommon as rainfall gets less. Area of the collection pond was changed until an optimum size (all irrigation water was sufficed by the pond water or the pond was empty already) was obtained.

The output data includes: (1) volume of rain water falling in the system, (2) volume of irrigation water, (3) volume of water pumping from the pond, (4) overflow from the pond, and (5) efficiency of the rainwater harvesting "sawah-kolam' system.

RESULTS AND DISCUSSIONS

Parameters

Some parameters used in the modeling are listed on Table 1. Field capacity and bulk density of soil were results of laboratory analysis. Saturation and wilting point were taken from the list of FAO (1998) after cross checking the soil texture. Percolation was measured directly on the field. Crop coefficient (Kc) maximum (at field capacity and above) was also taken from FAO (1998) after comparing to other literatures. Actual crop coefficient, at which the crop was in water stress periods, was regressed between halfway of wilting point (the lowest water content by sun drying) and the field capacity.

Irrigation Water

Table 2 shows irrigation water pumped from the collection pond when the paddy needs irrigation

Table 1. Paremeters used in the modelling.

Parameters	Values	Sources
Saturation point	54%	(FAO 1998)
Field capacity	40%	Lab analysis
Wilting point	24%	(FAO 1998)
Percolation of paddy field	2.68 mm day^{-1}	Field measurement
Soil bulk density	1,377 kg m^{-3}	Lab analysis
In growing season:		
Kc for field capacity and above	1.1	(FAO 1998)
Kc for bellow field capacity	Y= 0.0143X-0.4714	Interpolation
In off season:		
Kc for field capacity and above	1	(Allen *et al*. 2005).
Kc for bellow field capacity	Y= 0.013X-0.4286	Interpolation
Kc for halfway of wilting point	0	(Allen *et al*. 2005).
Pond evaporation coefficient (K)	0.8	(Boyd 1985)

water. Of the three different planting scenarios (January, February, and March), all the irrigation water can be satisfied by the collection ponds with different surface areas of ponds but with the same depths (1.5 m). January, February, and March were chosen to test the model because they had highest rainfall depths among any other months. In addition, farmers traditionally start planting in these months because they are in raining season.

For January planting, total amount of irrigation water was 4,106 m^3 or 6 times of pumping for 10 years of growing season. This irrigation water can be satisfied by the collection pond with surface area of 1,800 m^2. For February planting, the irrigation water was 5,444 m^3 or 8 times of pumping, and can be served by the pond surface area of 1400 m^2. For March planting, the total irrigation water was 9,926 m^3 or 16 times of pumping, and can be served by the pond surface area of 2,500 m^2. Hence, in term of the pond surface area required for the surrounding areas of Metro City, February first was the optimum planting start because it needed the smallest size of pond surface. If the planting was started on other times, it would need larger pond surface areas.

From Table 1, it can be seen that even if the planting was started on the wettest month (January or February), paddy still needed irrigation water to satisfy its consumption. It implied that the rainfed paddy could not sometimes exclusively rely on rainfall, or otherwise the plant would suffer from drought. It might be the answer why productivity of rainfed paddy was low so far. If the plant experienced in long period of drought, harvest might fail. In this modeling, irrigation water was applied when soil water content dropped to the allowable lower limit which was 32%, between the wilting point (24%) and the field capacity (40%), to the saturation point (54%). Should the irrigation water was not applied; the soil water content would deplete possibly below the wilting point.

Figure 2 shows water level (after the soil water content was converted to water depth in mm) on the paddy field, for February planting in 1999. For the first 10 days after planting maximum limit of weter level was controlled to be saturated (150 mm or not inundated). It might be required for land preparation or because the paddy was still too short. After the 10 days of planting to 90 days, the water level was allowed to the maximum level of 250 mm (100 mm inundated). It can be seen that most of the time paddy was inundated, and no irrigation water was needed. The irrigation water was to bring the water from the allowable lower limit (88.1 mm or 32% soil water content) back to saturation level. After 90 days of planting and in off season, there was no need to control water level, so the water could drop to the minimum level, half of the wilting point (12% or 33 mm).

Table 3 shows volume of rainwater falling in the "Sawah-Kolam" system per year for a 10 year pe-

Table 2. Irrigation water pumped from the collection pond.

Year	Months of Planting Starts					
	January*		February**		March***	
	m^3	times	m^3	times	m^3	times
1999	0	0	0	0	634	1
2000	2,234	3	1,113	1	1,227	2
2001	0	0	1,854	3	3,103	5
2002	613	1	613	1	612	1
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	610	1	1,841	3
2006	0	0	0	0	635	1
2007	623	1	624	1	1,246	2
2008	635	1	630	1	627	1
Total	4,106	6	5,444	8	9,926	16

Pons area: *1,800 m^2, **1,400 m^2, and ***2,500 m^2.

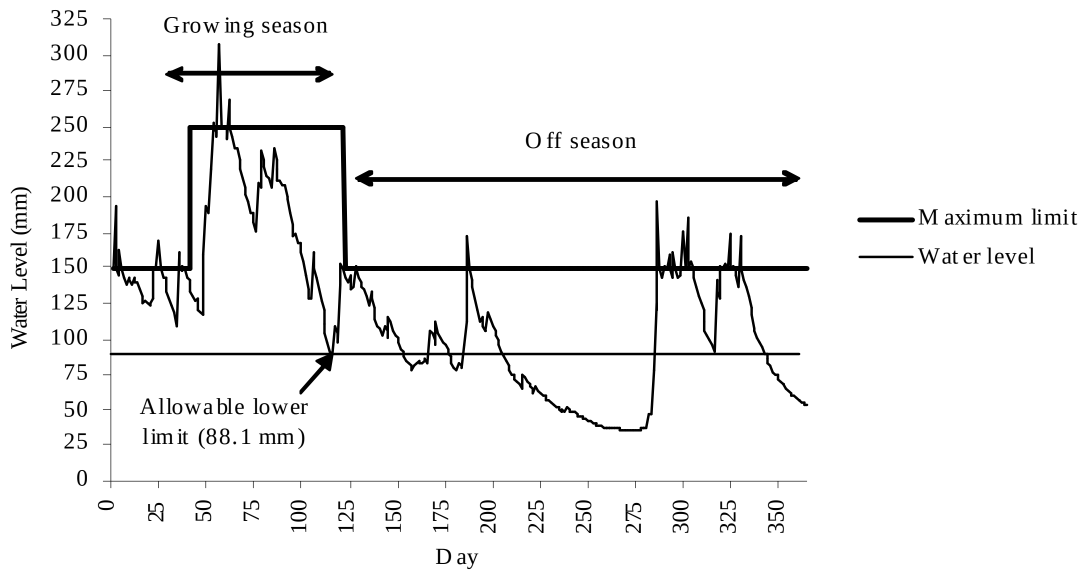

Figure 2. Water level on the paddy field for February planting in 1999.

riod. For January, February, and March planting, total amounts of water were 249,152 m^3, 240,706 m^3, and 263,935 m^3, respectively. The amounts of the rainwater were different for every scenario because of different sizes of the pond surfaces. The different sizes of the collection ponds were required by the paddy to meet its water consumption as discussed before. It can be seen that the amount of water used for irrigation (Table 4) was just small portion, and most of the times the water remained in the collection pond. Hence, the rainwater collected in the collection pond was very potential for other uses such for aquaculture.

Table 3. Volume of rainwater falling in "Sawah-Kolam" system (m^3).

Year	Months of Planting Starts		
	January	February	March
	----------- m^3 -----------		
1999	25,535	24,670	27,050
2000	20,638	19,939	21,863
2001	21,688	20,953	22,975
2002	20,544	19,847	21,763
2003	22,212	21,459	23,530
2004	29,620	28,616	31,378
2005	21,825	21,085	23,120
2006	30,076	29,056	31,860
2007	23,738	22,933	25,146
2008	33,276	32,148	35,250
Total	249,152	240,706	263,935

As discussed before, February was the most optimum planting start in that it required the least size of the collection pond. On Table 5, for February planting, we can see that rainfall in 2001 (20,953 m^3) was higher than that in 2000 (19,939 m^3) or 2002 (19,847 m^3). However, even rainfall was higher in 2001, the crop needed more irrigation water (1854 m^3) than in 2000 (1,113 m^3) or 2002 (613 m^3). If we look at Figure 3, there were slightly different distributions of rainfalls among the three years. In 2000 and 2002, there were more rainfall events occurring in the growing seasons, while in 2001, less rainfall events occurred in the growing season. Thus, this simulation demonstrated how rainfall characteristics (not only total amount of rainwater) affected the amount of irrigation water needed. This is also to show the importance of using collection pond so that rainwater falling outside growing season can be collected and used for irrigation in the next growing season. Without using collection pond, rainfall occurring outside the growing season would be discharged as runoff and not be useful for cultivation.

Overflow

Table 4 presents the volume of overflow from the collection pond for the three different scenarios.

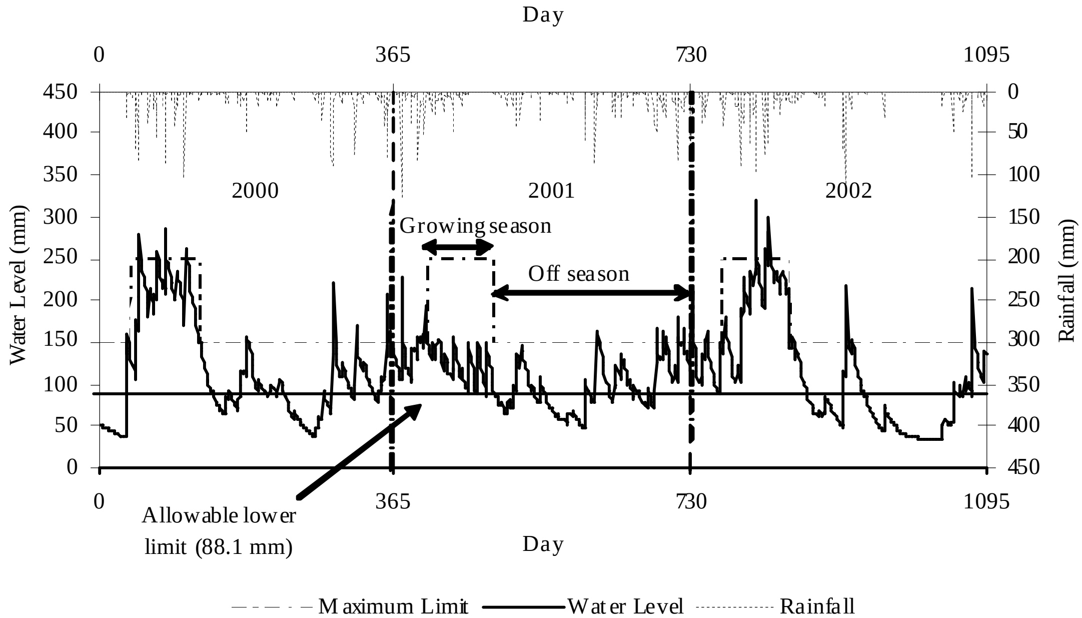

Figure 3. Field water level and rainfall for February planting in 2000, 2001, and 2002.

We can see that the largest amount of water discharged from the collection pond occurred on January planting. The amount was 23,816 m^3 or 280 times of occurrences. The second largest amount of overflow (21,521 m^3 or 234 time occurrences) took place in the March planting. The least amount of overflow which was 20700 m^3 or 274 time occurrences happened in the February planting. Therefore, the rainwater was actually more than enough if used to irrigate the rainfed paddy. After the pond water was pumped to irrigate the paddy, the overflow still occurred. The volumes of the overflow, however, were already far below the amount of rainwater falling in the system. In this case, the "Sawah-Kolam" system saved amount of rainwater by 90.44% for January planting, 91.44% for February planting, and 91.85% for March planting. If the runoff should be eliminated, certainly the sizes of the collection pond needed to be enlarged.

Table 4. Overflow from the collection pond.

Year	Planting Starts					
	January		February		March	
	m^3	times	m^3	times	m^3	times
1999	1,858	39	1,418	41	1,727	28
2000	7 40	8	858	11	1,090	10
2001	1,307	27	496	17	885	17
2002	2,268	19	2,501	23	1,223	20
2003	1,558	26	1,908	28	1,607	24
2004	3,580	51	2,709	49	3,631	47
2005	3,092	30	1,611	28	2,309	28
2006	4,761	31	3,128	26	2,583	19
2007	1,374	12	2,111	13	1,586	8
2008	3,279	37	3,959	38	4,879	33
Total	23,816	280	20,700	274	21,521	234

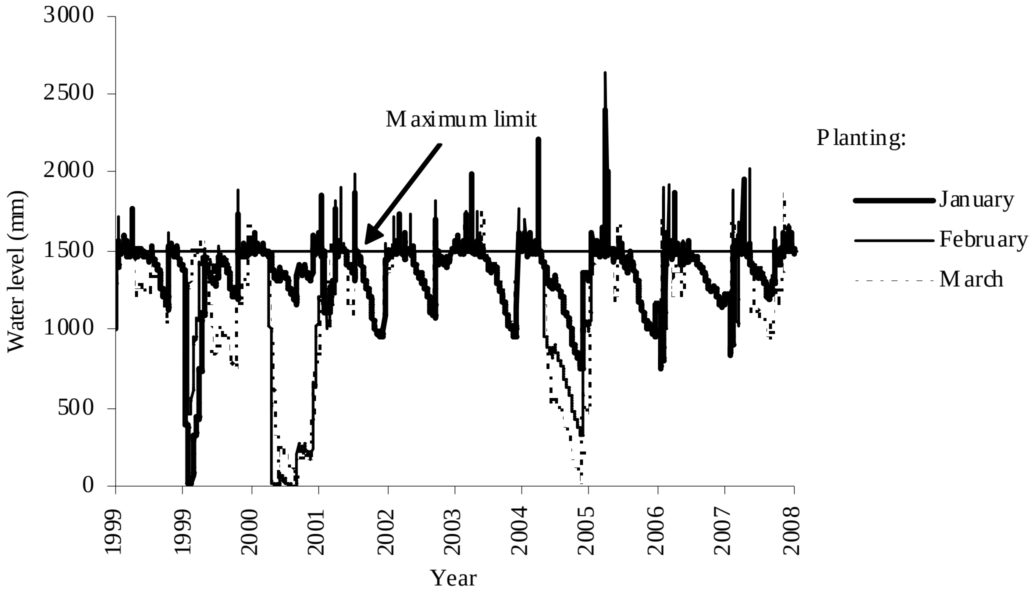

Figure 4. Pond water level.

Figure 4 illustrates pond water levels for the three different scenarios of planting starts. The pond water levels moved upward to the maximum limit (1,500 mm). The pond water above the maximum limit was discharged as runoff. On the Figure 4 it can be seen that the pond water levels more frequently approached the maximum limit rather then to the pond bottom (or dry). It was noted that the pond had never dried for January and March planting, while for February planting the pond dried 48 times and took place in 2001. However; most of the times the pond contained rainwater, implying it was very potential for growing fish for example. Adding the surface area of pond or slightly deepening the pond depth would be a very helpful solution to prevent the collection pond from drying if it was really used for aquaculture. Water use in aquaculture was known more productive than its use in agriculture (Boyd and Schmittou 1999).

CONCLUSIONS

Rainfed paddy still needed irrigation as an additional input of water budget. As demonstrated, rainfall alone without an engineering control was not always adequate to grow paddy for the best production. If the rainwater was collected, the water demand of paddy could be sufficed. The rainwater harvesting system of "Sawah-Kolam" was demonstrated to be adequate to satisfy the water needed by rainfed paddy.

For the surrounding areas of Metro City, February appeared to be about optimum time to start planting (in term of pond size required) because it needed the smallest area of the collection pond if compared to other times for planting.

In addition to meet the irrigation water, the "Sawah-Kolam" system could save a lot of water by more than 90% of rainwater, reducing a very significant amount of runoff volume.

Saving rainwater is a wise decision and needs to be promoted and spread. By using the "Sawah-Kolam" system, we can hopefully enhance the productivity of rainfed paddy. Besides satisfying irrigation demand, the rainwater collected was very potential for aquaculture. Environmental adverse effects created by runoff such as erosion and pollution can also be reduced

Such studies need to be spread in other locations, in order to get more complete figures of the "Sawah-Kolam" system performance. Economical feasibility of the system needs to be evaluated in that pond construction may be very costly and certainly burden to small farmers. For that reason, responses from government and private companies are required to develop the rainwater harvesting system.

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