Water Balance of Small-Farm Reservoir for Rainfed Irrigation under Tropical Monsoon Climate

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(熱帯モンスーン気候下の天水灌漑における小規模圃場貯水池の水収支解析)

2015

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SUMMARY

Indonesia is an agricultural country that is influenced under tropical monsoon climate which consists of dry seasons and wet season or rainy season in a year. Almost all of area in Indonesia has high annual rainfall, included Central Java where much area is cultivated for paddy field and annual crops. But some areas have main problem in water scarcity, especially for irrigation in rainfed area because rainfall is water source for irrigation and distributed unevenly during a year. Besides during dry season, uneven distribution is occurred as short drought during rainy season. Short drought is some period without or under limited rainfall in several days during rainy season and cause water shortage in irrigation than impact to decrease in crop yield or harvesting failure.

Small-farm reservoir (SFR) is a method to overcome water shortage by collecting and storing (harvesting) rainwater during rainfall from narrow catchment area with small volume and used for individual or small group farmers. SFR construction is often expensive for individual farmers. Therefore it is preferable to optimize the SFR storage capacity. However, the optimum capacity depends on numerous factors including sizes and characteristics of the catchment and irrigation areas, crop types, and climate conditions. While the catchment area and climate conditions are factors that cannot be controlled by farmers, the irrigation area and crop type can be controlled together with the SFR capacity in order to design a successful irrigation scheme. Hence, the series of research about water balance of small-farm reservoir was conducted with following objectives:

1) To evaluate the efficacy of SFRs as a method of supplemental irrigation through the water balance analysis.

2) To propose the principle for estimating the optimum SFR capacity and the irrigation area size for rainfed agriculture.

To achieve the objectives, field experiments were constructed five SFRs where were conducted at rainfed agricultural fields located in Gondangrejo, Karanganyar, Central Java Province, Indonesia. The investigations analyzed data that was recorded from October 2013 to June 2014. The Climate or weather data was collected by Automatic Weather Station which installed at field experiment.

The first objective was achieved by conducting five SFRs constructs which were designed so that it was able to store the total runoff from catchment area based on the daily maximum rainfall during 2012-2013. The design accorded to the runoff curve number method (Conservation Engineering Division, 1986). Based on the reference SFR volumes, actual SFR volumes were determined through discussion with farmers and the field owners. Areas of SFRs were calculated from the volume and the limitation of the depth to < 2 m in order to prevent fall accident by users and children. Five SFRs were constructed by digging soil and coating the floor by plastic tarps (tarpaulin) to prevent water infiltration into soil. SFR1 and SFR3 were smaller than the reference volumes due to the restriction of the field area. On the other hand, SFR4 and SFR5 were larger than the reference volumes. In particular, the farmer of SFR5 requested to construct a larger SFR than the reference volume because of the larger irrigation area than the catchment area. The irrigation methods were classified to three types, manual (SFR1), pump (SFR2, SFR3, and SFR5), and siphon (SFR4). Water levels of each SFR were recorded every 10 minutes by a water level data logger by Onset Corporation installed at the bottom. In order to calibrate evaporation losses that were variable among SFRs, pan evaporation was measured beside each SFR. The results showed that an SFR was capable of irrigating a paddy field during short droughts in the rainy season and during the early dry season even in the critical period of rice cultivation. SFRs were advantageous because they enabled farmers to cultivate rice in CS2. Nevertheless, it was also indicated that a proper design of the SFR volume and the size of the irrigation area was important in order to get the most out of an SFR. For example, the size of SFR1 was smaller than the reference volume for the catchment area, and a large fraction of the harvested water was lost as outflow. The irrigation area of SFR5 was too large for the catchment area to be irrigated by the SFR alone.

The second objective was achieved by estimating the optimum SFR capacity and the irrigation area size using the model. The model consists of three sub models that collectively simulate the water budget of the rainfed agricultural system. Each sub model describes the daily runoff water volume from the catchment area (catchment area sub model), the daily increment of the SFR water volume (SFR sub model), and that of the soil moisture content (SMC) of the irrigation area (irrigation area sub model). In the simulation, the daily increments are computed as a result of inputs and outputs that take place during the day. Simulation periods are either from October 2013 to February 2014 that covers CS1, or from October 2013 to June 2014 that covers CS1 and CS2 (CS1-CS2). The simulation introduced two indexes WSI (Water Storage Index) expresses the amount of rainfall stored by the SFR and WDI (Water Demand Index) indicates the demand of irrigation water. If a simulation continues until the end of the simulation period, the SFR capacity is considered to be adequate under given conditions. If a simulation fails, the SFR capacity is considered to be inadequate. The adequate and inadequate ranges are created by correlation of WSI and WDI. The adequate cases are located at the left-hand side of a boundary line if it exists. The boundary line intersects the origin with a positive slope until a critical WDI value where the line curves to an opposite direction. The critical WDI indicates the theoretical limit of the size of an irrigation area with supplemental irrigation by an SFR for a given catchment area. The boundary line was absent in the positive cone when rice was cultivated with the daily percolation 0 and 2 mm. These results indicate that the rainfed agriculture can be adequate without supplemental irrigation if rice is cultivated under flooding condition in the rainy season. Farmers cannot control climate and the catchment area. The simulation results provide directions of how to design a rainfed agricultural system. The optimum SFR capacity and the irrigation area are obtained from the model simulation. Because the aim of this study was the model development, the simulations were conducted only with the climate data in 2013-2014. The design of the rainfed irrigation system should be based on more extensive simulations based on multi-year climate data. Further simulation and experimental studies are needed in order to verify the model framework presented in this study. The advantages of SFR are the farmers could cultivate rice twice in a year which was previously difficult. Besides that, the farmer can decide to cultivate early after SFR filled water during the uncertainly rainfall as impact of climate change so that water scarcity during short drought and critical period of rice in dry season can be avoided.

PREFACE

This dissertation is a part of fulfillment of the requirement for the degree of Doctor of Philosophy (PhD) undertaken by the writer through Basin Water Environmental Leadership (BWEL) Program under the supervision of Prof. Dr. Masateru Senge, of the United Graduate School of agricultural Science, Gifu university, Japan.

This thesis is a compilation of the result of field experiments, which was conducted since 2013 until 2014. The result had been published in Journal of Rainwater Catchment Systems. The constructing of a small-farm reservoir (SFR) is a common practice of rainwater harvesting especially in developing countries, and was shown to be effective for supplemental irrigation during consecutive days without effective rainfall in crop season. Advance investigation based on five SFRs that were constructed at rainfed agriculture area was capable of irrigating a paddy field during first to second crop season and advantageous because they enabled farmers to cultivate rice in second crop season which could not be done before construction. Nevertheless, a proper design of the SFR volume and the size of irrigation area were important in order to get the most out of an SFR. The simulation can obtain optimum SFR capacity and the maximum adequate irrigation area with considered climate data.

Alhamdulillah, this dissertation has been successfully completed following suggestion, invaluable aid and encouragement from many people whom cannot mention one by one. I would like to take this opportunity to extend my appreciation to:

1) Professor Dr. Masateru Senge: my honorable teacher, supervisor and guarantor; I acknowledge my indebtedness, best gratitude, deepest grateful, greatest thankfulness, and sincere appreciation for given me the opportunity to pursuing my education in

Gifu University Japan, for his concern to my study and also my daily life, for his patience, guidance, suggestion, comment and all kindness that were given me during my present study in Japan.

2) Associate Professor: Dr. Takeo Onishi; I am gratefully indebted for his valuable instructions, comments, guidance and great patience during my study in Gifu University.
3) Assistant Professor: Dr. Kohei Yoshiyama, for his excellence correction, suggestion and support on my scientific paper writing and his kindness.
4) Associate Professor: Dr. Kengo Ito, for guidance, support, comment and great patience during my study and investigation on my experiments in Irrigation and Drainage Laboratory, Faculty of Agricultural, Gifu University, Japan.
5) Professor: Dr. Satoshi Tsuchiya, for guidance, support and comment on my presentation and study in Gifu University.
6) Dr. Komariah, my friend in Soil Science Department, Faculty of Agriculture, Sebelas Maret University, Indonesia, as well as our team project leader in bilateral research between Sebelas Maret University and Gifu University; for great help and support on my study and life both in Indonesia and Japan.
7) The Basin Water Environmental Leadership (BWEL) Program for the financial assistance by providing free tuition for my study in the Doctoral Program of Gifu University. Also the support scholarship of Gifu University providing scholarship for my education and supporting my daily life.
8) The Directorate General of Higher Education (DGHE), Republic of Indonesia and The Japan Society for the Promotion of Science (JSPS) for the financial support by

providing collaboration research fund between Gifu University and Sebelas Maret University that was included my experiment.

9) My father and mother, for all kindness and prayers which never I give back along of my life, also my parents in law, my brother and sister (Mas Sigit and his family, Mas Benny and his family, and Nita) for well wishes and prayer during my study.
10) My lovely wife: Betta Dwi Isti Ferela, for her great love, patient, motivation, prayers on the successfulness of my life, study and career and give me energy to finish my study and her well wishes during my absence from her.
11) Member of bilateral research project: Dr. Dewi, Mrs. Sumani, Yudhi, Zuhud, Mr. Waluyo and his family and all students whom join in that research, for helping me to get the data. Special thank you for Arief Noor Rahmadiyanto, for helping, assisting and accompany during research.
12) My colleagues in the Irrigation and Drainage Laboratory, Faculty of Applied Biological Science, Gifu University, for helping me to enjoy my life in Japan. Also to my Indonesian friends in the Gifu city for their warm friendship during my stay here.

And also for all the people that I cannot mention one by one for their helps, support and prayers for me.

Gifu, December 2015

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I. INTRODUCTION

1.1 Short Drought in Agricultural

Agriculture is important sector for Indonesia because Indonesian people depend on agricultural productions. Based on statistics of agricultural land in 2012, Indonesia had 39,594,537 ha that was used for agricultural land and 3,714,764 ha or 9.38% was non-irrigated wetland or rainfed agricultural land (Ministry of Agriculture of Republic of Indonesia, 2013). The main problem in rainfed agricultural land is water availability, especially for irrigation, because irrigation in rainfed agricultural land depends on rainfall (Notohadiprawiro, 1989; Arsyad, 2006). Central Java Province as one of paddy field areas of Indonesia, has annual rainfall more than 2,000 mm that is located in tropical area and influenced Monsoon climate that has significant difference about dry season and rainy season or wet season. Dry season occurs during April or May to September or October and wet season occurs during October or November until March or April (Mamenun et al., 2014). This rainfall is actually enough for cultivation during a year, like paddy cultivation, but the distribution is uneven. In 2000-2010, average rainfall during November to February was 1,582 mm (BPS, 2010) and during November 2013 to February 2014 was 1,360 mm. It means most of rainfall occurs in November until February.

Uneven rainfall has been pushing farmer to divide crop pattern into three crop seasons which is a common crop season in Indonesia (Setiyowati and Rusdiansyah, 2008; FAO, 2005). The 1st crop season is started from November until February when water irrigation is available during crop season, even exceed of water available as reason for many farmer to cultivate paddy in 1st crop season. The 2nd crop season is started during March until June when early of dry season occurs in the end of 2nd crop season. Farmer cultivates annual crop (like peanut and green bean) or paddy if their field near river or downhill where water for irrigation is easy to acquire. The 3rd crop season occurs in dry season when it is difficult to get water for irrigation and many fields are not cultivated or fallowed.

However, water shortage is also a problem in the rainy season due to the occasional short droughts that cause decreases in crop yields. Short drought is a period time without rainfall during wet season. Indonesian Agency for Meteorological, Climatological, and Geophysics separate each month into three blocks to classify season or climate in Indonesia. Short drought is defined as an isolated block in wet season where rainfall is less than 50 mm/block. Wet season is started from two consecutive blocks where rainfall is greater than 50 mm/block. Vice versa, dry season is started from consecutive blocks where rainfall is less than 50 mm/blocks (Anonim, 2009).

The main problem is that short drought often impact to harvest failure, especially rice crop which need much irrigation, because short drought in Indonesia sometimes occurred during critical period of rice crop. To overcome water shortage in rainfed area, collecting water during rainfall and being used when irrigation is needed, which is known as rainwater harvesting, is effective.

1.2 Small-Farm Reservoir for Irrigation

Supplemental irrigation through rainwater harvesting is one of resolutions to the problem. Groundwater storage also is used for irrigation and has many advantages, like as little evaporation loss, ubiquitous distribution or can be constructed near or under the point of use, and good water quality because water filtrated by soil. But, groundwater storage has disadvantages like environmental issue withdrawal exceeds long-term recharge and result the rapid decline of water table (Keller et al., 2000).

Beside those, reservoir is a method to harvest and collect rainwater into artificial basin. Many types of reservoir can be divided based on scale, area or capacity volume (Komariah and Senge, 2013). Reservoir used to moisture soil is classified as a small reservoir or a pond. A small reservoir has capacity volume less than 100 m^3. Small-Farm Reservoir (SFR) is a method of rainwater harvesting from local catchment for irrigating of a rainfed farm to supply crop water requirement during a short drought. Whether an SFR is beneficial to farmers or not depends on the integrative design of the location and size of an SFR, irrigation area, and catchment area.

SFR can be divided into three areas: catchment area; water body area or volume; and irrigation area. Catchment area is located at upstream of a pond collecting rainfall and supplying it to a pond. Water body area or volume is a pond where water is stored. Irrigation area is cultivation field which is irrigated by pond water, which is usually located downstream of a pond, but some cases, can be located upstream of SFR, or similar with catchment area which need pump or other method to irrigate.

Each irrigation source method has advantages and limitation. SFR can be constructed by individual or small group farmer because need lower cost than large reservoir, even though capacity volume and irrigation area smaller. On the other hand, high evaporation is a limitation of SFR that impact to water loss and absence of year to storage or cannot fulfil during a year (Keller et al., 2000). This means main purpose of SFR construction is to irrigate during short drought and not to be used for long drought during dry season. It should be constructed in non-sloping or slightly sloping area using plastic trap (tarpaulin) to reduce seepage losses (Abebe et al., 2012).

Design of SFR volume is influenced by many factors, i.e. catchment area, irrigation area, vegetation or crop type, climate etc. Climate condition is a factor which cannot be changed artificially, so it could be considered as a given factor to decide SFR volume. Catchment area is also important factor to estimate the quantity of collected water used for irrigation, which can be necessarily determined from the location of SFR. Whereas, SFR volume and irrigation area are two important factors which can be designed for optimum irrigation planning by rainwater harvesting method. Evaluation of the SFRs efficacy can be used to estimate for SFR volume that is needed to store sufficient water for irrigation.

1.3 Research Objectives

From the above description, the series of research about water balance of small-farm reservoir was conducted with following objectives:

1) To evaluate the efficacy of SFRs as a method of supplemental irrigation through the water balance analysis.
2) To propose the principle for estimating the optimum SFR capacity and the irrigation area size for rainfed agriculture.

II. MATERIALS AND METHODS

2.1 Study Site Condition

Five SFRs were constructed at rainfed agricultural fields located in Gondangrejo, Karanganyar, Central Java Province, Indonesia (Figure 2.1). The climate condition of the site is classified as tropical monsoon having a dry season from April/May to September/October and a rainy season from October/November to March/April in a typical year. Just like the season in Indonesia, Gondangrejo has rainy season and dry season. Annual rainfall during 2013 was 2,043 mm and mean annual rainfall during 2000-2010 was 2,042 mm (BPS, 2011). Mean air temperature was 26.3^{o}C with maximum air temperature of 29.5^{o}C and minimum air temperature of 21.5^{o}C. The humidity range was between 57.2-97.0% with mean humidity of 83.6%.

The site lies between 108-132 m above sea level and consists of *Association of Dark Grey Grumusol and Reddish Brown Mediterranean* soils. The landform was hilly with dominated rainfed and non-irrigation farm that was cultivated annual crop (peanut and green bean) and rice (BPS, 2011). Almost all farms depend on rainwater as a main source for irrigation, although few farmers pump ground water and river water for the supplement irrigation. This condition forces farmers to cultivate twice in a year with rice crop only once in a year and other crops such as peanut or green bean. This means crop pattern in Gondangrejo was rice – annual crop (peanut or green bean) – fallow (Pratono et al., 2008).

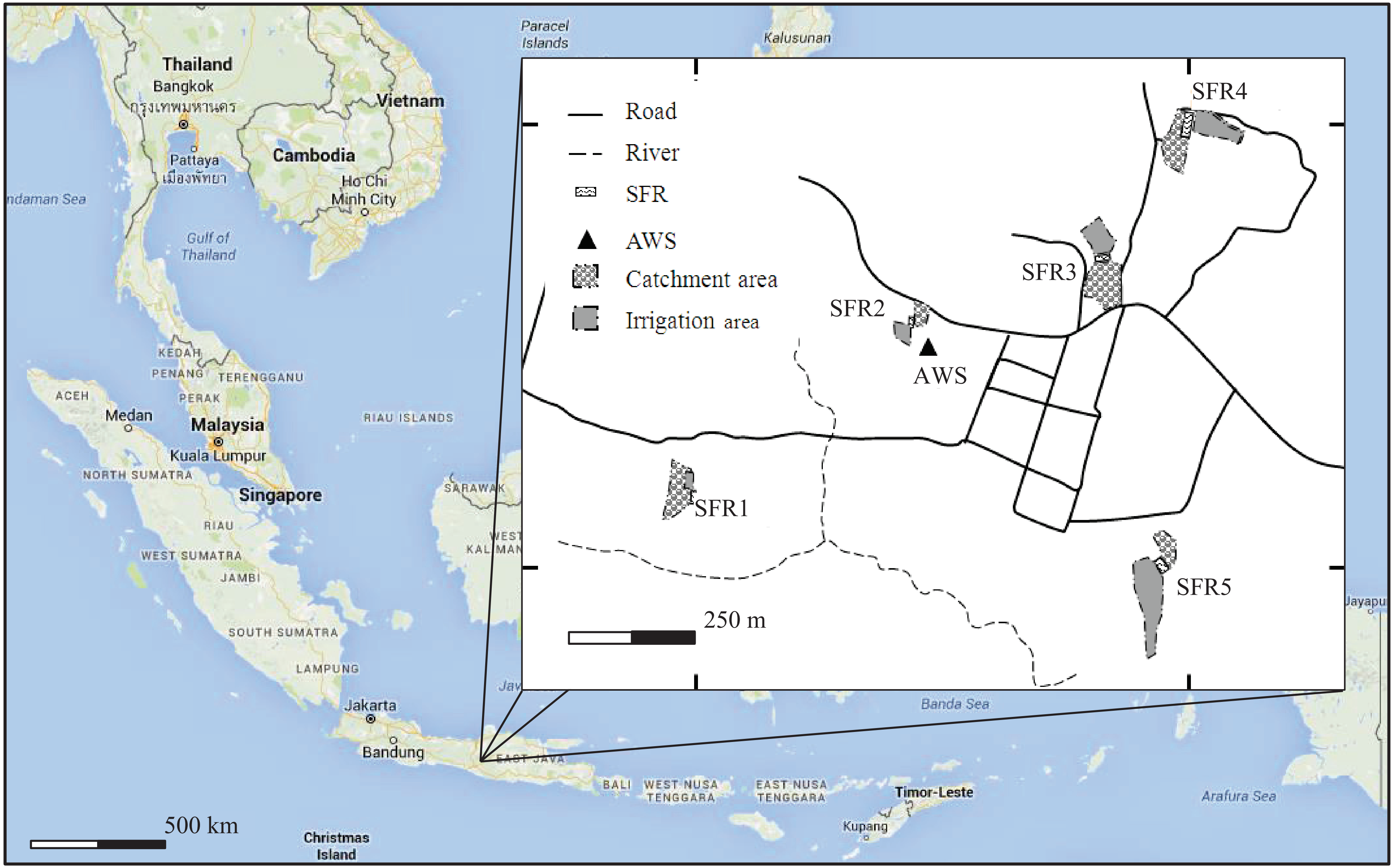


Figure 2.1 Location of five SFRs at Gondangrejo, Central Java Province, Indonesia

2.2 Construction of SFRs

Five SFRs were constructed in Gondangrejo, Indonesia and designed so that it was able to store the total runoff from catchment area based on the daily maximum rainfall during 2012-2013. The design accorded to the runoff curve number method (Conservation Engineering Division, 1986; Mishra and Singh, 2003; Soulis et. al., 2009; Soulis and Valiantzas, 2012; Wang et al., 2008), runoff Q (mm) is expressed as a function of rainfall P (mm):

$$Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \tag{2.1}$$

where S (mm) is the potential maximum soil moisture retention after runoff begins, which is expressed as a function of the curve number CN (a dimensionless value from 0 to 100):

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2.2}$$

CN was determined to be 78 from the land characteristics (good hydrology, field infiltration 9.72 cm/h and permeability rate is 4.73 cm/h), the soil type (C, sandy clay loam), the cover type (row crops), and the land treatment (contoured and terraced). With the maximum rainfall P = 87.1 mm, the runoff Q was obtained as 36.7 mm. The reference SFR volume (SFR_{ref}, m^3) was estimated as a product of Q and catchment area A (m^2):

$$SFR_{ref} = \frac{Q \cdot A}{1000} \tag{2.3}$$

Five SFRs were constructed by digging soil use Backhoe (Figure 2.2 and Figure 2.3) and coating the floor by plastic tarps to prevent water infiltration into soil. Based on the reference SFR volumes, actual SFR volumes (SFR_{act}) were determined through discussion with farmers and the field owners. SFR1 and SFR3 were smaller than the reference volumes due to the restriction of the field area. On the other hand, SFR4 and SFR5 were larger than the reference volumes. In particular, the farmer of SFR5 requested to construct a larger SFR than the reference volume because of the larger irrigation area than the catchment area. Consequently, the ratio of the actual volume to the reference volume ranged between 0.63 and 1.7 (Table 2.1). Areas of SFRs were calculated from the volume and the limitation of the depth to < 2 m in order to prevent fall accident by users and children.

SFR1 was surrounded by cashew plantation and was fully (100%) shaded by the canopy (Figure 2.4). SFR3 was surrounded by cashew and teak plantation and was partly (25%) shaded by the canopy (Figure 2.6). SFR2 was located at 1 meter from 3-meter tall teak plantation (Figure 2.5). SFR4 and SFR5 were located at open space (Figure 2.7 and Figure 2.8). All dimensions and location of SFRs are shown in Table 2.1.

Table 2.1 Land and SFR characteristic based on estimation and actual constructing

	SFR No.	SFR1	SFR2	SFR3	SFR4	SFR5
(1)	Catchment area (m^2)	2,877	817	4,184	4,068	1,826
(2)	Irrigation area (m^2)	232	781	1,733	2,968	3,270
(3)	Area ratio [(1)/(2)]	12.4	1.05	2.41	1.37	0.56
(4)	SFR_{ref}^{a} (m^3)	105.48	29.95	153.4	149.15	66.95
(5)	SFR_{act}^{b} (m^3)	66	31.2	132.5	182.6	113.6
	W(m)•D(m)•H(m)	10•5•1.32	9•3•1.3	25•5•1.06	22•5•1.66	20•4•1.42
(6)	SFR ratio [(5)/(4)]	0.63	1.04	0.86	1.22	1.7
(7)	Specific volume [(5)/(2)](mm)	284	40	76	62	35
	Characteristics of catchment area					
	Location	110.851° E 7.495° S	110.854° E 7.493° S	110.857° E 7.492° S	110.858° E 7.490° S	110.858° E 7.496° S
	Gradient of slope (%)	5.6	2.9	8.0	10.8	6.3
Land use (%)	Farm land	100.0	0.0	65.4	100.0	63.2
	Teak plantation	0.0	90.8	33.2	0.0	36.8
	Asphalt road	0.0	9.2	0.0	0.0	0.0
	Residence	0.0	0.0	1.4	0.0	0.0

Note: [a] : SFR reference is calculated from Eq.(2.3) with 36.66 mm runoff; [b] : SFR actual is real SFR size in the field

Figure 2.2 SFR2 was constructed by Backhoe

Figure 2.3 SFR3 was constructed by Backhoe

Figure 2.4 SFR1 was constructed under cashew canopy

Figure 2.5 SFR2 was constructed beside of tall teak plantations

Figure 2.6 Teak and cashew canopy shaded some part on SFR3 construction

Figure 2.7 SFR4 was constructed on open space

Figure 2.8 SFR5 was constructed on open space

Figure 2.9 Automatic Water Station was installed near SFR2

The Climate or weather data was collected by Automatic Weather Station (Davis Instrument Wireless Vantage Pro2 plus 6162 weather link type) installed at 110.8542^{o} E and 7.493289^{o} S (Figure 2.9 and Figure 2.10) where was located around of SFR2. The climate was recorded every ten minutes during 2013 to 2014.

2.3 Small-Farm Reservoir Contribution to Annual Crop Cultivation in Rainfed Paddy Field under Tropical Monsoon Climate

2.3.1 Catchment and irrigation area

The locations of the catchment area and the irrigation area of each SFR were classified into two types, whether the irrigation area was located inside of the catchment area (SFR1) and other SFR (SFR2, SFR3, SFR4, and SFR5) was located outside of the catchment area. The owner of each SFR and the irrigation area was the same except for SFR2. The owner of the irrigation area of SFR2 was different because the owner of SFR2 cultivated peanuts that did not need irrigation but other farmer near SFR2 whose cultivated rice that need irrigation from SFR.

The ratio of the catchment area to the irrigation area (area ratio) ranged between 0.56 and 12.4 (Table 2.1). The area ratio of SFR1 was the highest (12.40) because the farmer intensively cultivated onion within a small area due to the limited capital and labour. The area ratios were greater than a unity except for SFR5 with the area ratio (0.56). Accordingly, the SFR volume per unit irrigation area (specific volume, mm) ranged widely from 35 mm in SFR5 to 284 mm in SFR1 (Table 2.1).

(a) (b)

Figure 2.10 (a) Automatic Water Station instrument and (b) wireless data logger

The irrigation methods were classified to three types, manual, pump, and siphon. Siphon irrigation was applied to SFR4 where sufficient potential energy was obtained through the difference in elevation between SFR4 and the irrigation area. The outlet of the siphon was equipped with a faucet. It was usually located at a level of 100 cm from the bottom of SFR4 with the faucet closed (Figure 2.11). When the farmer withdrew irrigation water, it was moved lower than the bottom with the faucet opened. Pump irrigation was applied to SFR2, SFR3, and SRF5 where the elevation difference was not sufficient to provide potential energy for siphon. Manual irrigation was applied to SFR1 that was located lower than the irrigation area because of the relatively small irrigation area (232 m^2) and irrigation water volume (2 m^3 per irrigation).

2.3.2 Water balance analysis in SFR

Water balance estimation was used water level of SFR and climate data. Water levels of each SFR were recorded every 10 minutes by a water level data logger by Onset Corporation, Hobo U20-001-04 (Figure 2.12a) installed at the bottom and in the air to compare air pressure. Evaporation was computed from the FAO Penman-Monteith method for climate conditions provided by the automatic weather station and was multiplied by crop coefficient and a water reflection coefficient. In order to calibrate evaporation losses that were variable among SFRs, pan evaporation was measured beside each SFR.

The daily increment in the storage water volume of SFR (ΔW_{sfr}) is expressed by the water balance equations (Eq.(2.4)). Water inflow (W_i; Eq.(2.5)) is either due to direct rainfall (W_{rain}) or runoff from the catchment area (W_{run}), and water outflow (W_o; Eq.(2.6)) is due to evaporation (W_e), irrigation (W_{ir}), and overflow through the spillway (W_{ov}). Water leakage through plastic tarps was neglected in the water analysis.

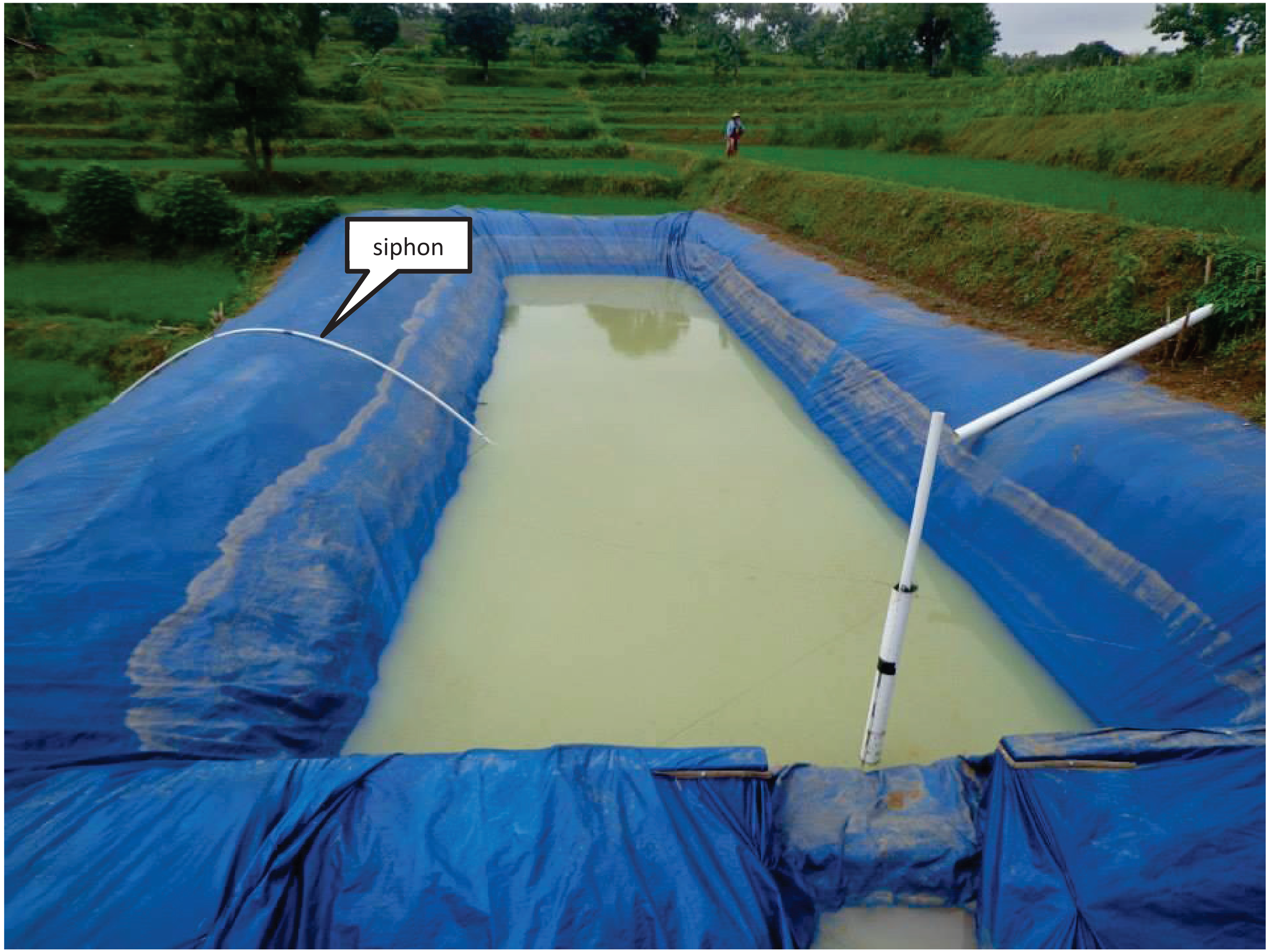


Figure 2.11 Siphon in SFR4 was used to irrigate the rice field

(a)

(b)

Figure 2.12 Water level recording instruments, (a) Hobo U20-001-04 which was used for water level logger and (b) Optic USB interface to retrieve data

$$\Delta W_{sfr} = W_i - W_o \tag{2.4}$$

$$W_i = W_{rain} + W_{run} \tag{2.5}$$

$$W_o = W_e + W_{ir} + W_{ov} \tag{2.6}$$

ΔW_{sfr} was directly obtained from the water level changes (from midnight to midnight) multiplied by the SFR area. W_{rain} was estimated from rainfall recorded at the automatic weather station.

W_e was estimated for two cases. In days when rainfall, runoff, irrigation, and overflow events were absent ($W_{rain} = W_{run} = W_{ir} = W_{ov} = 0$), it was directly estimated from the water level decrease of SFR. The estimations corresponded well to the pan evaporation values. If the above condition was not met, evaporation was estimated through several steps. First, potential evaporation from an SFR was calculated by the FAO Penman-Monteith method (Eq.(2.7)) with a water reflection coefficient of 0.06 and data recorded at the automatic weather station. Second, an evaporation coefficient was obtained for each SFR as the ratio of pan evaporation to the potential evaporation during the measurement period from May 21 to Jun 22, 2014 (Figure 2.13). Then, W_e was obtained as a product of the evaporation coefficient and potential evaporation.

$$\mathrm{ET_o} = \frac{0.408\,\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 273} \mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma\,(1 + 0.34\,\mathrm{u_2})} \tag{2.7}$$

where ET_o (mm/day) is reference evapotranspiration (or evaporation in SFR surface area case). R_n ($MJ/m^2\ day^1$) is net radiation at the crop surface which is determined from the difference between the net shortwave radiation and the net longwave radiation, included water reflection coefficient as coefficient in the net shortwave radiation. G (MJ/m^2 day) is soil heat flux density which was ignored for daily calculations in this experiment because the magnitude of the flux is relatively small. T (^oC) is mean daily air temperature at 2 m height. u_2 (m/s) is wind speed at 2 m height. e_s (kPa) is saturation vapour pressure. e_a (kPa) is actual vapour pressure. Δ (kPa/^{o}C) is slope vapour pressure curve. γ (kPa/^{o}C) is psychrometric constant.

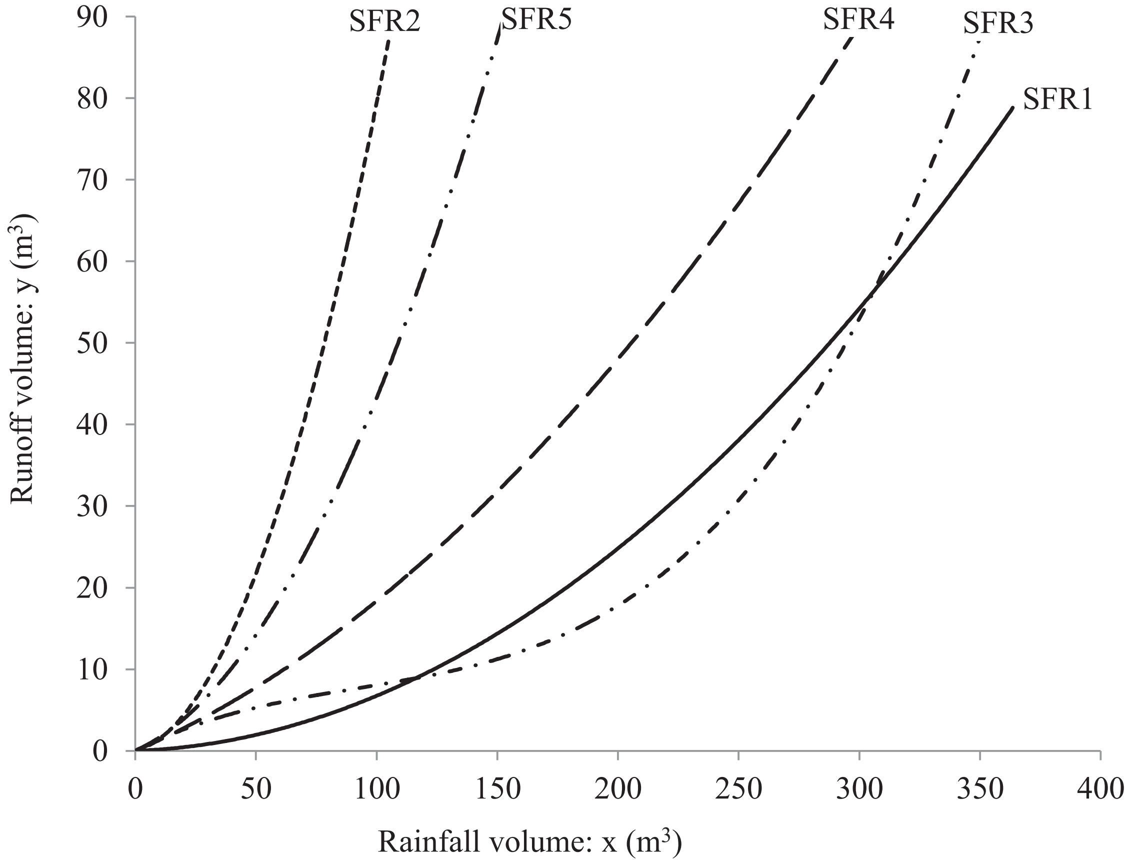
Irrigation was not practiced during rainfall. Therefore irrigation water uses were identified as water decreases greater than those by evaporation, and were calculated from the difference between the water decreases and evaporation losses. W_{ir} was given as the total during a day.

In order to estimate W_{run}, all rainfall events and the corresponding water increases without overflow were identified from data for each SFR. Overflow was distinguished when the water level was greater than the height of the spillway of the SFR. A runoff water volume during each event was estimated by adding a volume lost by evaporation, and subtracting the direct rainfall to an SFR from the water increase. Then volumes of runoff and total rainfall on the catchment area were related by linear and polynomial (from 2nd to 4th order) equations with zero intercepts, and the best-fit equation was selected for the SFR according to AIC (Akaike information criterion, Burnham and Anderson, 2004). As the result, a 2nd to 3rd order equation was obtained for each SFR that describes the runoff water volume as a function of the total rainfall on the catchment area (Figure 2.14). The equations were used to obtain runoff water volumes due to rainfall events with overflow. W_{run} was computed as the total runoff during a day.

Finally, W_{ov} was calculated based on the water balance equation (Eq.(2.8)).

$$W_{ov} = W_{rain} + W_{run} - W_e - W_{ir} - \Delta W_{sfr} \tag{2.8}$$

Figure 2.13 Evaporation pan was installed near SFR2



		$y = ax^3 + bx^2 + cx$			
		a	b	c	R^2
———	SFR1	0	0.0006	0.0104	0.9757
- - - - -	SFR2	0	0.0072	0.0744	0.7786
— · — · —	SFR3	$4 \bullet 10^{-6}$	-0.0011	0.1509	0.848
— — —	SFR4	0	0.0006	0.1271	0.7983
— · · —	SFR5	0	0.003	0.1348	0.9004

Figure 2.14 Best equation models in each SFR based on AIC test that is used to estimate volume inflow (y)

2.4 The Optimization Principle of Storage Capacity of Small-Farm Reservoir for Rainfed Agriculture

2.4.1 Model description

The model consists of three sub models that collectively simulate the water budget of the rainfed agricultural system. Each sub model describes the daily runoff water volume from the catchment area (catchment area sub model), the daily increment of the SFR water volume (SFR sub model), and that of the soil moisture content (SMC) of the irrigation area (irrigation area sub model), respectively (Figure 2.15). In the simulation, the daily increments are computed as a result of inputs and outputs that take place during the day. In the followings, three sub models are described in detail.

Two assumptions are made for the simplification. First, the runoff water volume from the catchment area is assumed to be related linearly to the total rainfall on the catchment area. The relationship can be replaced by more detailed nonlinear functions (Conservation Engineering Division, 1986), however, a linear function is presumed to be sufficient for the current purpose. Second, the runoff water flows into the SFR within the day when a rainfall event takes place. This assumption holds when the catchment area is relatively small, which is a typical case in Indonesia. With the above assumptions, the runoff water volume at day d ($Q_r^{[d]}$, m^3) is expressed as a function of the total rainfall at the day ($R^{[d]}$, m):

$$Q_r{}^{[d]} = H_r \cdot A_c \cdot R^{[d]} \tag{2.9}$$

where H_r is the harvesting ratio and A_c, the catchment area (m^2). In this study, H_r is assumed to be a constant during the simulation period, although it is influenced by the amount of rainfall, and soil and landscape characteristics of the catchment area (Thompson, 2006).

The SFR water volume at day d ($V_{sfr}^{[d]}$, m^3) is evaluated at the end of the day, and the change is a result of water inputs and outputs during the day. The inputs consist of daily runoff water, $Q_r^{[d]}$, and direct rainfall, $A_{sfr} \cdot R^{[d]}$, where A_{sfr} (m^2) is the surface area of the SFR. In the simulation, the depth of an SFR is set to 1.67 m and hence $A_{sfr} = \frac{V_{sfr}}{1.67}$. The depth was determined through the agreement with farmers in order to prevent the risk of falling accidents. The outputs consist of irrigation water, $Q_i^{[d]}$ (m^3), evaporation loss, $A_{sfr} \cdot Ev^{[d]}$, where $Ev^{[d]}$ (m) is the daily amount of evaporation from the SFR, and overflow from the SFR, $Q_{o1}^{[d]}$ (m^3). In this study, the SFR is assumed to be sealed at the bottom, and water leakage is ignored, where plastic tarps were applied at the bottom of SFRs. In order to obtain $V_{sfr}^{[d]}$, the following water balance equation is evaluated:

$$V_{sfr}^{[d]} = V_{sfr}^{[d-1]} + Q_r^{[d]} + (A_{sfr} \cdot R^{[d]}) - Q_i^{[d]} - (A_{sfr} \cdot Ev^{[d]}) \tag{2.10}$$

The obtained $V_{sfr}^{[d]}$ from Eq. (2.10) is employed if it is within the range of 0 and V_{max} (m^3, the storage capacity of SFR). If the value is negative, then SFR is empty, that is,

$$\text{if } V_{sfr}^{[d-1]} + Q_r^{[d]} + \left(A_{sfr} \cdot R^{[d]}\right) - Q_i^{[d]} - (A_{sfr} \cdot Ev^{[d]}) < 0,$$

$$\text{then } V_{sfr}^{[d]} = 0 \tag{2.11}$$

If the value exceeds Vmax, then SFR is full and water overflows, that is,

$$\text{if } V_{sfr}^{[d-1]} + Q_r^{[d]} + \left(R^{[d]} \cdot A_{sfr}\right) - Q_i^{[d]} - \left(E_v^{[d]} \cdot A_{sfr}\right) > V_{max}, \text{ then}$$

$$V_{sfr}^{[d]} = V_{max} \text{ and } Q_{o1}^{[d]} = V_{sfr}^{[d-1]} + Q_r^{[d]} + \left(A_{sfr} \cdot R^{[d]}\right) - Q_i^{[d]} - \left(A_{sfr} \cdot Ev^{[d]}\right) - V_{max} \tag{2.12}$$

$Q_i^{[d]}$ is determined by the irrigation area sub model described below.

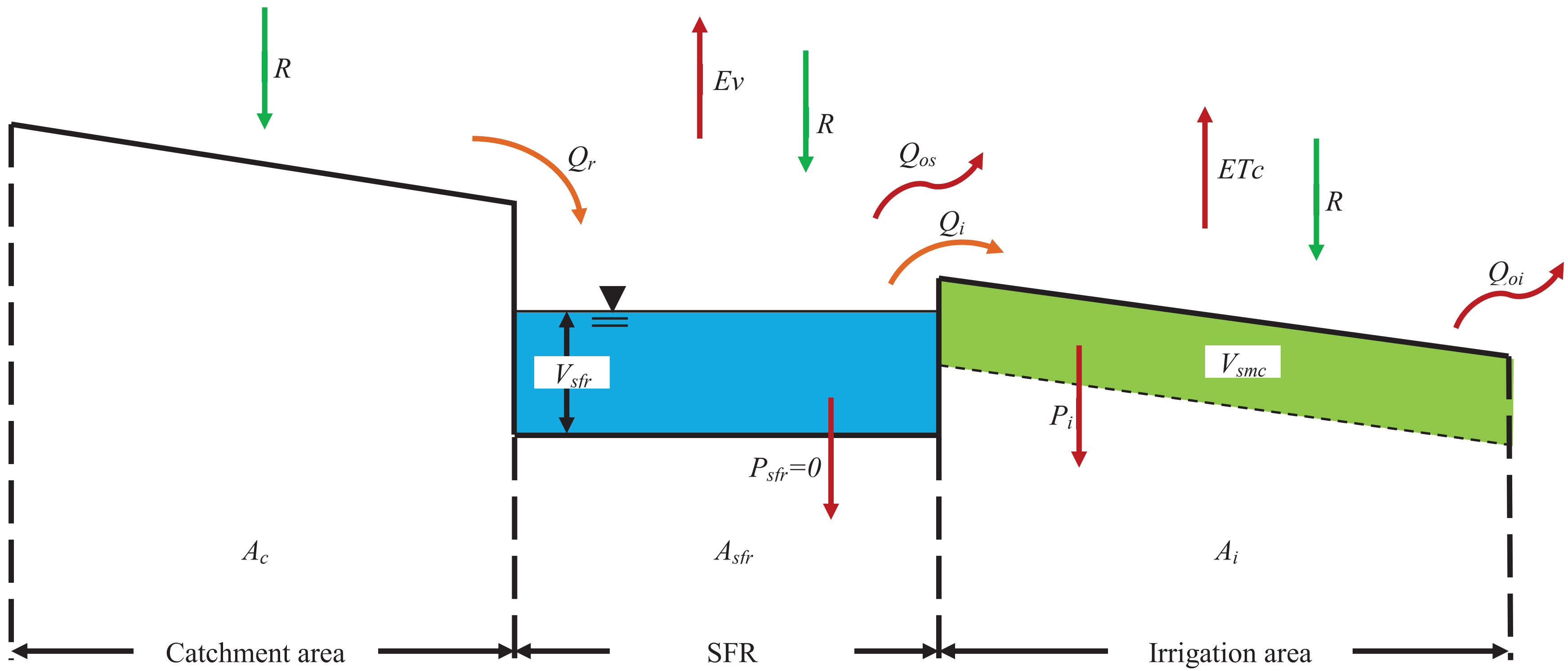


Figure 2.15 The schematic diagram of the simulation model; descriptions of symbols are found in the text, green arrow is input, red arrow is output, orange arrow is output from a submodel before and input for other submodel, blue coloured area is SFR water, green coloured area is soil moisture

The submodel describes the changes in the total volume of $SMC^{[d]}$ (m) in the irrigation area at day d. In this study, SMC is defined as available soil moisture, which is on the value of field capacity and permanent wilting point (Ayu et al., 2013), for plants in the root zone, and ranges from 0 (the wilting point) to the maximum SMC_{max} (m). With the irrigation area A_i (m^2), the total SMC volume ($V_{smc}{}^{[d]}$, m^3) is expressed by:

$$V_{smc}{}^{[d]} = A_i \cdot SMC^{[d]} \tag{2.13}$$

$V_{smc}{}^{[d]}$ changes as a result of inputs and outputs. The inputs consist of irrigation water ($Q_i{}^{[d]}$, m^3) and direct rainfall ($A_i \cdot R^{[d]}$, m^3). The outputs consist of evapotranspiration ($A_i \cdot ETc^{[d]}$, m^3), percolation ($A_i \cdot P_i{}^{[d]}$, m^3), and overflow ($Q_{o2}{}^{[d]}$, m^3), where $ETc^{[d]}$ (m) and $P_i{}^{[d]}$ (m) are the daily amounts of evapotranspiration and percolation, respectively. $P_i{}^{[d]}$ is assumed to be a constant if $V_{smc}{}^{[d-1]} > 0$, while $P_i{}^{[d]} = 0$ if $V_{smc}{}^{[d-1]} = 0$. In order to obtain $V_{smc}{}^{[d]}$, the following soil moisture balance equation is evaluated:

$$V_{smc}{}^{[d]} = V_{smc}{}^{[d-1]} + \left(A_i \cdot R^{[d]}\right) - \left(A_i \cdot ETc^{[d]}\right) - \left(A_i \cdot P_i{}^{[d]}\right) \tag{2.14}$$

The obtained $V_{smc}{}^{[d]}$ from Eq. (2.14) is employed if it is within the range of 0 and $A_i \cdot SMC_{max}$. If the value is negative, then irrigation water is supplied in order to compensate lost water through evapotranspiration:

$$\text{if } V_{smc}{}^{[d-1]} + \left(A_i \cdot R^{[d]}\right) - \left(A_i \cdot ETc^{[d]}\right) - \left(A_i \cdot P_i{}^{[d]}\right) < 0, \text{ then } V_{smc}{}^{[d]} = 0 \text{ and } Q_i{}^{[d]} = \left(A_i \cdot ETc^{[d]}\right) + \left(A_i \cdot P_i{}^{[d]}\right) - \left(A_i \cdot R^{[d]}\right) - V_{smc}{}^{[d]} \tag{2.15}$$

The above irrigation management, where soil moisture is kept at (or just above) the wilting point, is commonly practiced in Indonesia where water resource is occasionally limited during short droughts and dry seasons (Hasibuan, 2010).

If the value exceeds $A_i \cdot SMC_{max}$, then soil moisture is saturated and water overflows, that is,

$$\text{if } {V_{smc}}^{[d-1]} + \left(A_i \cdot R^{[d]}\right) - \left(A_i \cdot ETc^{[d]}\right) - \left(A_i \cdot {P_i}^{[d]}\right) > (A_i \cdot SMC_{max}),$$

$$\text{then } {V_{smc}}^{[d]} = (A_i \cdot SMC_{max}) \text{ and } {Q_{o2}}^{[d]} = {V_{smc}}^{[d-1]} + \left(A_i \cdot R^{[d]}\right) -$$

$$\left(A_i \cdot ETc^{[d]}\right) - \left(A_i \cdot {P_i}^{[d]}\right) - (A_i \cdot SMC_{max}) \quad (2.16)$$

2.4.2 Model simulations

In the simulation, there are two crop seasons which were computed, the first from November to February (CS1) and the second from March to June (CS2). In most cases, rice is cultivated in CS1, and annual crops such as green beans and peanuts are cultivated in CS2 although some farmers cultivate rice if irrigation water is accessible. Other crop season that is the third from July to October (CS3) which was not computed because cultivation in CS3 is generally impossible because it belongs to the dry season.

Daily rainfall $R^{[d]}$ was obtained from the data. $Ev^{[d]}$ was computed by the FAO Penman-Monteith method with the data. The harvesting ratio H_r is assumed to be a constant 0.3, which reflects the range of the actual values observed in the simulation site (0.10-0.31, Table 2.1). The simulated crop type was either peanuts or rice.

SMC_{max} is a difference between the wilting point and the maximum soil moisture content in the root zone (30 cm soil depth) or the amount of water above the root zone under flooded condition. In simulations where peanuts are cultivated, SMC_{max} is set to 30 mm. This value corresponds to the field capacity measured at the simulation site; 33.93 mm (SFR1), 31.52 mm (SFR2), 33.82 (SFR3), 32.30 mm (SFR4), and 32.28 mm (SFR5). In simulations where rice is cultivated, the paddy field is under flooded condition until two weeks before the harvesting (from November 1 to February 5 in CS1; from March 1 to June 6 in CS2). In the flooded condition, SMC_{max} is set to 140 mm, assuming that the saturated soil water in the root zone is 40 mm and the paddy field stores 100 mm of water above the soil surface. During two weeks before harvesting, the paddy field is drained and SMC_{max} is set to 30 mm as well as field capacity.

The simulation site has a hard soil layer with low percolation formed by plowing. Under flooded condition, the daily percolation was suggested to be less than 4 mm (Direktorat Jenderal Pengairan, 1986; Notohadiprawiro, 2006; Rizal et al., 2014). In this study, $P_i^{[d]}$ is set to 0 mm when the soil moisture content is below the field capacity (i.e., $SMC^{[d]}$ < 30 mm), and is either 0, 2, or 4 mm under flooded condition (i.e., $SMC^{[d]}$ > 30 mm). Therefore, $P_i^{[d]}$ = 0 (mm) for simulations where peanuts are cultivated, and $P_i^{[d]}$ depends on $SMC^{[d]}$ for simulations where rice is cultivated.

In this study, $ETc^{[d]}$ is approximated by the daily crop water requirement. In order to obtain the daily crop water requirement for each day and each crop type, the daily amount of reference evapotranspiration was obtained from the FAO Penman-Monteith method for climate conditions provided by the automatic weather station, and was multiplied by the crop coefficient (Allen et al., 1998, Direktorat Jenderal Pengairan, 1986). The obtained daily crop coefficient and crop water requirements are shown in Figure 2.16 and Figure 2.17 for the two crop types. The crop water requirements are assumed to be 0 during harvesting in CS1 and next cultivation in CS2 and during the rice ripening stage (two weeks before harvesting).

Simulation periods are either from October 2013 to February 2014 that covers CS1, or from October 2013 to June 2014 that covers CS1 and CS2 (CS1-CS2). Initial conditions are $V_{sfr}^{[0]}$ = 0 for the SFR volume, and $SMC^{[0]} = SMC_{max}$ for the soil moisture content, respectively, where day 0 is set to September 30. Peanuts are cultivated from November 1 to February 21 (CS1) and from March 1 to June 21 (CS2), respectively; rice is cultivated from November 1 to February 19 (CS1) and from March 1 to June 20 in the simulations, respectively.

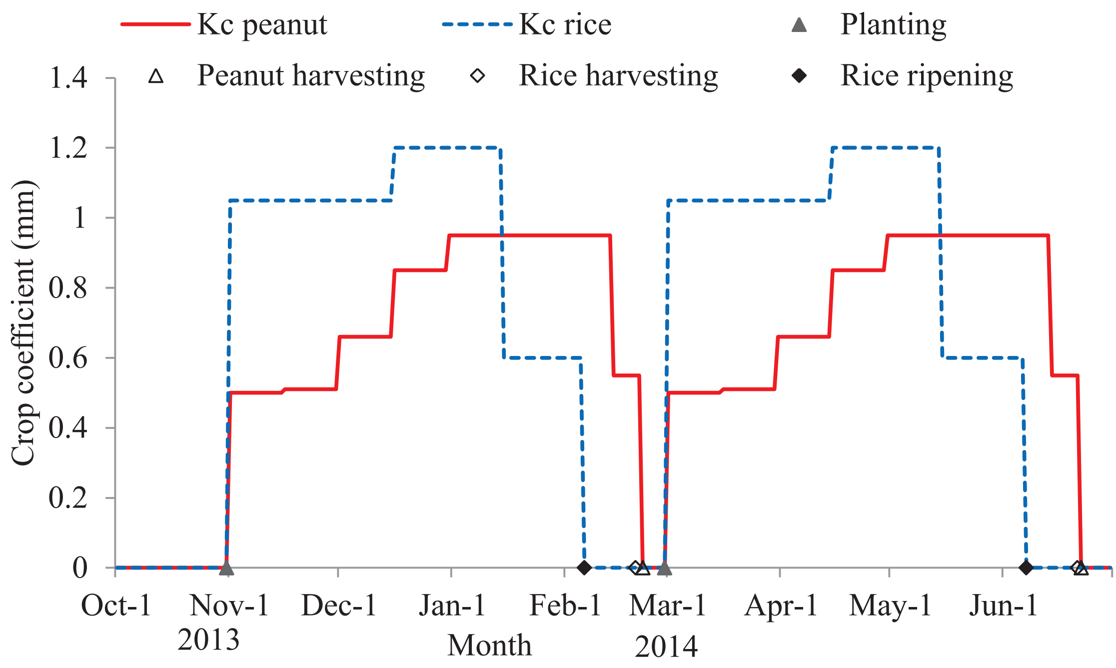


Figure 2.16 Crop coefficients of rice and peanuts from November 2013 to June 2014

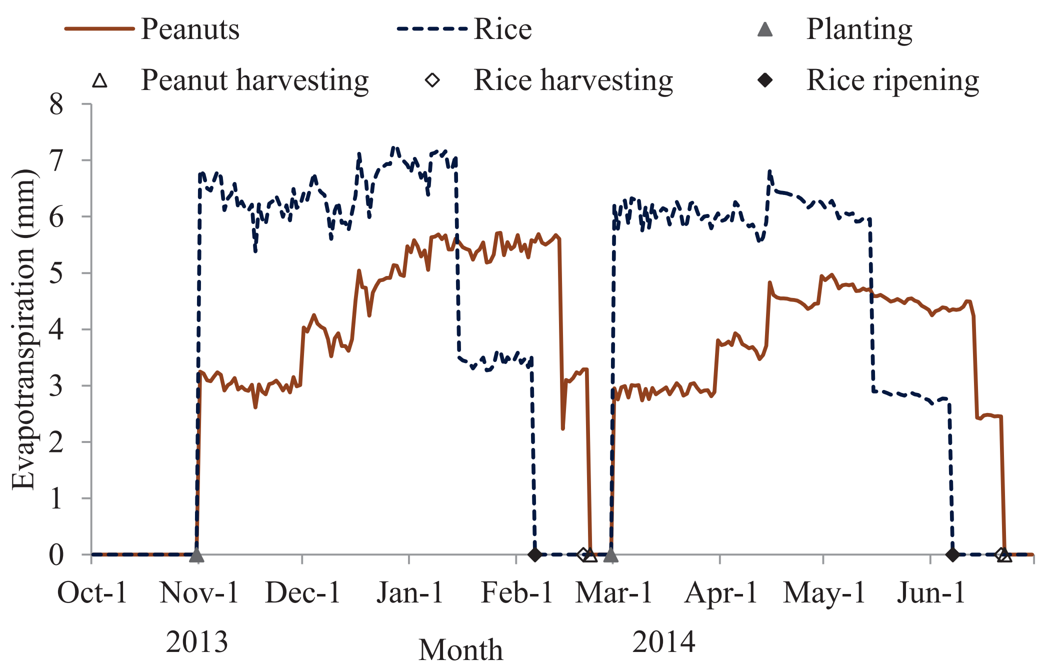


Figure 2.17 Evapotranspiration of rice and peanuts from November 2013 to June 2014

In the simulation procedure, $Q_r^{[d]}$ and $Q_i^{[d]}$ are first obtained by the catchment area submodel and the irrigation area submodel, respectively. Then, the values are adopted to the SFR submodel to obtain $V_{sfr}^{[d]}$. A simulation stops if $V_{sfr}^{[d]}$ obtained by Eq. (9) is negative when $Q_i^{[d]} > 0$. This case indicates the SFR cannot provide enough irrigation water at day *d*. Otherwise, a simulation proceeds to the next day. If a simulation continues until the end of the simulation period, the SFR capacity is considered to be adequate under given conditions. If a simulation fails, the SFR capacity is considered to be inadequate.

Following two indexes are introduced for the presentation of simulation results. A water storage index *WSI* (m) is a SFR storage capacity per a catchment area weighted the harvesting ratio, and expresses the amount of rainfall stored by the SFR (Eq. (2.17)).

$$WSI = \frac{V_{max}}{H_r \cdot A_c} \tag{2.17}$$

A water demand index *WDI* (dimensionless) is a relative extent of an irrigation area to a catchment area weighted by the harvesting ratio, and indicates the demand of irrigation water (Eq. (2.18)).

$$WDI = \frac{A_i}{H_r \cdot A_c} \tag{2.18}$$

Due to the linearity of the simulation model, results are identical for the same values of *WSI* and *WDI* under the same climate conditions. Table 2.2 shows the two indexes of five SFRs constructed in the simulation site. *WSI* values ranged from 0.13 to 0.32 m; *WDI* values from 0.58 to 5.87. The adequate range of *WSI* is computed for given *WDI* and climate conditions through the above procedure, and the minimum of the adequate *WSI*, if exists, corresponds to the optimal SFR capacity for the given irrigation and catchment areas, and climate conditions.

Table 2.2 The water storage and water demand indexes of five SFRs constructed in Gondangrejo, Central Java, Indonesia

SFR No.	SFR1	SFR2	SFR3	SFR4	SFR5
Water storage index (*WSI*)	0.16	0.13	0.32	0.19	0.20
Water demand index (*WDI*)	0.58	3.19	4.14	3.00	5.87

III. RESULTS AND DISCUSSION

3.1 Small-Farm Reservoir Contribution to Annual Crop Cultivation in Rainfed Paddy Field under Tropical Monsoon Climate

3.1.1 Rainfall patterns and crop cultivation

During the experiment, a dry season started from the beginning of May 2014 (Figure 3.1). Therefore, the experimental period included the rainy season from December 2013 to April 2014 and the dry season from May to June 2014. The rainy season contained four short droughts from December 21 to 31 (cumulative rainfall: 20.4 mm), from January 11 to 20 (30 mm), from February 21 to 28 (35.3 mm), and March 21 to 31 (34 mm). In general, there are three crop seasons in Gondangrejo, the first from November to February, the second from March to June, and the third from July to October. In most cases, rice is cultivated in paddy fields in CS1 and annual crops such as green beans and peanuts are cultivated in CS2 although some farmers cultivate rice in paddy fields if water for irrigation is accessible. Cultivation in the third crop season is generally impossible because it belongs to the dry season. The experiment was conducted during CS1 and CS2. Farmers of SFR2, SFR3, SFR4, and SFR5 could cultivate rice in their paddy fields both in CS1 and CS2 by utilizing SFRs, while the farmer of SFR1 cultivated (onion) in CS1 and did not cultivate crops in CS2 due to labour limitation.

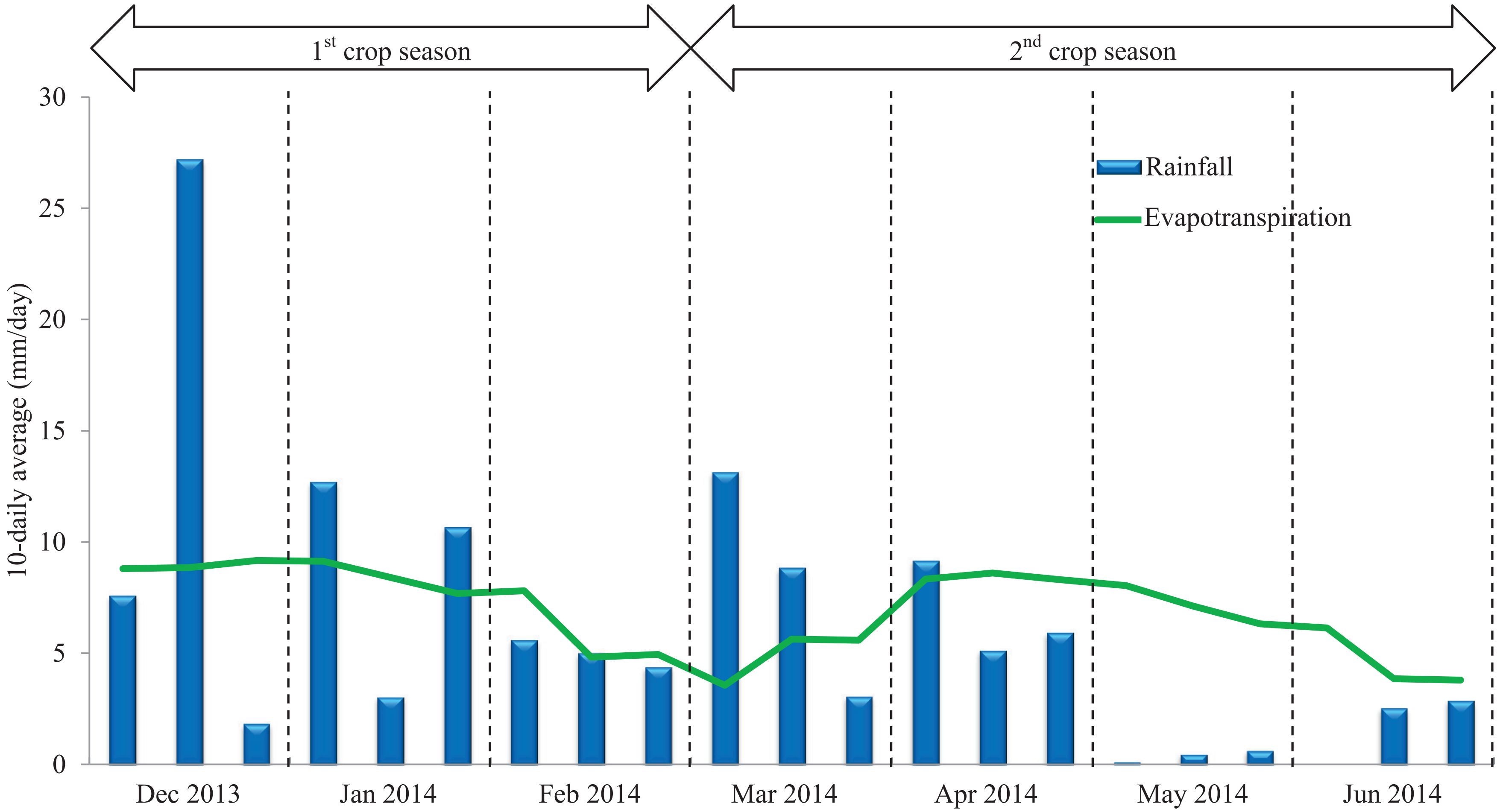


Figure 3.1 Rainfall and evapotranspiration in 10-daily average (mm/day) during experiment

3.1.2 Water balance of SFR

Time courses of SFR water levels and irrigation water volumes are depicted in Figure 3.2, and results of the water balance analysis are described in Table 3.1. Total inflow during the experiment ranged from 10.4% to 30.6% of total rainfall on the catchment area (harvesting ratio; Table 3.1). The harvesting ratio is generally influenced by the size and slope of the catchment area because rainfall is relatively more infiltrated or obstructed if it takes longer to drain into a reservoir with the larger and less steep catchment area (Critchley and Siegert, 1991; Chaudhary et al., 2013). Results of this study were consistent with the notion. Although the number of data was small ($n = 5$), most of the variation (adjusted $R^2 = 0.97$) in the harvesting ratio was explained significantly ($p < 0.05$) by the two factors, the size and slope of the catchment areas: (harvesting ratio) = -0.012 (size) + 0.018 (slope) + 26.5; $p < 0.05$ for all parameters.

The harvested water was either used for irrigation or lost by evaporation and overflow. Leakage from plastic tarps at the bottom was assumed to be negligible in this study. This assumption was supported by statistical results that water level decreases were not significantly greater than the corresponding pan evaporation values in all SFRs (paired one-tailed t-test; $\alpha = 0.05$). Total water volume of irrigation, evaporation, and overflow (total outflow) ranged from 81.1% (SFR2) to 93.4% (SFR1) of the total inflow (Table 3.1).

The irrigation water volume ranged from 91 m^3 (SFR1) to 883 m^3 (SFR4), which corresponded from 3.4% (SFR1) to 74.3% (SFR5) of total inflow (Table 3.1). The irrigation timing and amount were determined by farmers depending on their own consideration about the weather and crop conditions. SFR1 was used for manual irrigation of an onion farm of small area (232 m^2) intensively and sufficiently with 2 m^3 of water for each irrigation in the first crop season. As a result, SFR1 showed the highest amount of irrigation per area (394 mm). The different temporal pattern observed in SFR4 (Figure 3.2) was due to the unintended siphon irrigation through the leakage from the closed faucet located at 100 cm above the bottom. The leakage was included in irrigation water because it flowed into the adjacent paddy field. In CS2, the crop field was fallow and SFR1 was not used due to the labour shortage. Other 4 SFRs were used for irrigation of paddy fields both in CS1 and CS2. The amount of irrigation per area ranged from 28 mm (SFR3) to 118 mm (SFR4) in CS1 and from 88 mm (SFR5) to 179 mm (SFR4) in CS2. The increased amount of irrigation reflected the higher water requirement due to the dry season started during CS2. SFR2, SFR3, and SFR4 could irrigate sufficiently each paddy field both in CS1 and CS2. SFR5 could irrigate sufficiently in CS1, but not in CS2 because the irrigation area (3,270 m^2) was too large compared to the catchment area (1,826 m^2). The farmer of SFR5 used additional irrigation water of 55.3 m^3 (16.9 mm per irrigation area) by pumping up groundwater.

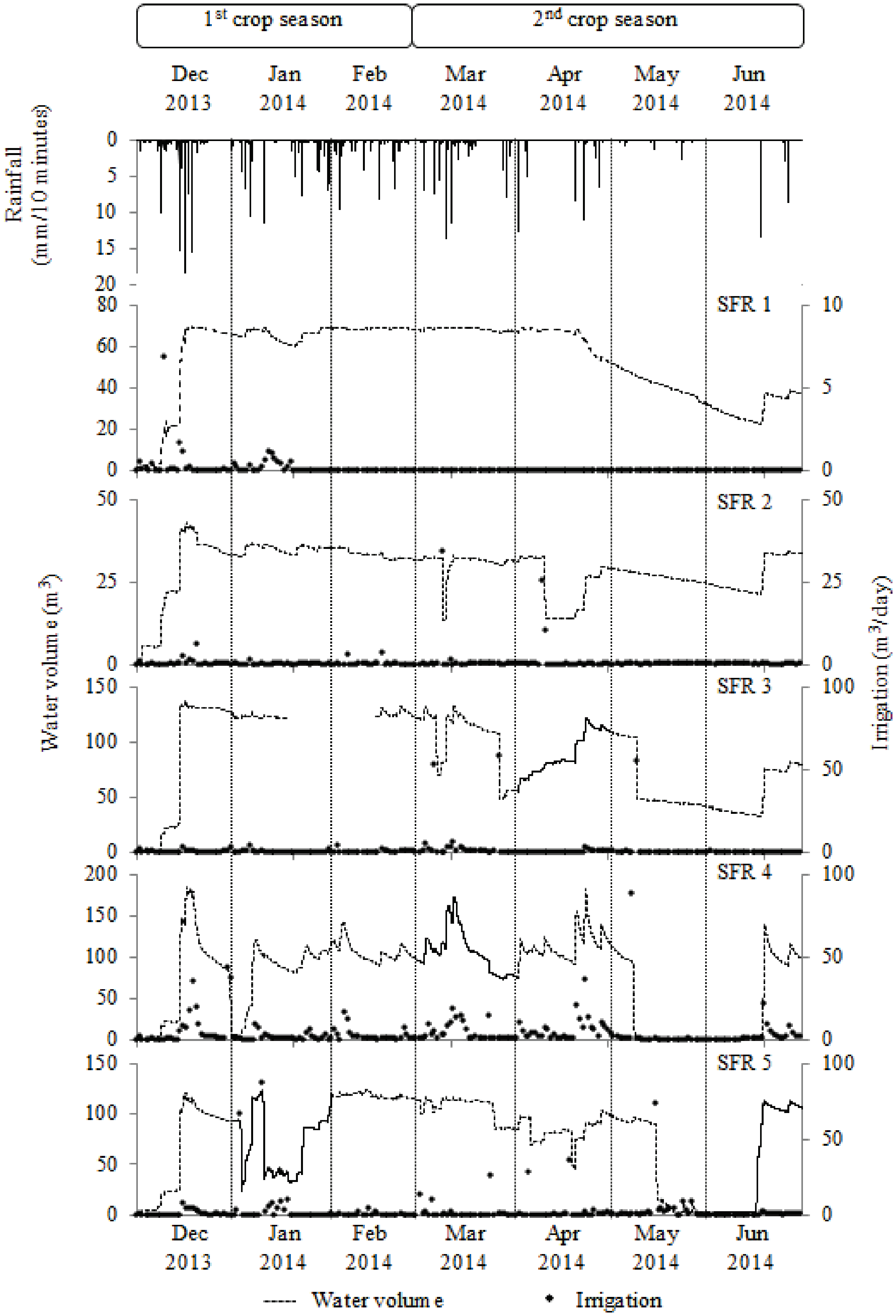


Figure 3.2 Rainfall, water volume and irrigation during experiment

Table 3.1 Total water balance in each SFR from December 2013 to June 2014

	SFR 1	SFR 2	SFR 3	SFR 4	SFR 5
(1) Rainfall (m^3)	3,774	1,072	5,489	5,337	2,396
(2) Total inflow (m^3)	530	328	573	1,296	729
(3) Harvesting ratio: [(2)/(1):(%)]	14.0	30.6	10.4	24.3	30.5
(4) Total outflow (m^3)=(5)+(6)+(7)	495	266	481	1200	668
[(4)/(2):(%)]	93.4	81.1	84.0	92.5	91.6
(5) Overflow (m^3)	445	96	94	207	44
[(5)/(2):(%)]	84.1	29.2	16.4	16.0	6.1
(6) Irrigation (m^3)	91	145	282	883	542
[(6)/Irrigation area](mm)	394	186	163	297	166
CS1; CS2 (mm)	394; 0	54; 131	28; 135	118; 179	78; 88
[(6)/(2):(%)]	3.4	44.2	49.3	68.1	74.3
(7) Evaporation (m^3)	31	25	105	110	82
[(7)/SFR area] (mm)	628	935	838	997	1,022
[(7)/(2):(%)]	5.9	7.7	18.3	8.5	11.2
(8) Final storage (m^3)	35	62	92	97	61
[(8)/(2):(%)]	6.6	18.9	16.0	7.5	8.4

Note: CS1 and CS2 stand for the first crop season and the second crop season, respectively

Evaporation during the experiment ranged widely from 628 mm (SFR1) to 1,022 mm (SFR5), which corresponded from 5.9% (SFR1) to 18.3% (SFR3) of total inflow (Table 3.1). While the potential evaporation was 1,035 mm, the actual evaporation was noticeably lower in some SFRs. Evaporation is influenced by climatic factors such as temperature, humidity, wind speed, and solar radiation that vary locally (Allen et al., 1998). The wide variation in this experiment was due to micro-climate condition of SFRs. A cover placed over a free water surface affects both heat and mass exchanges, and thus causes the lower evaporation rate (Assouline et al., 2010). In the experiment, evaporation was the smallest (628 mm) in SFR1 that was fully shaded by tree canopies, and was the second smallest (837 mm) in SFR3 that was partly (25%) shaded by tree canopies. The tree canopies kept the local temperature low, and reduced incoming solar radiation to the SFR water surface, contributing to the lower evaporation. Evaporation in SFR2 (935 mm) was also lower than the potential evaporation. SFR2 was not covered by tree canopies, but was located near 3-meter tall teak plantation that functioned as a windbreak and a moisture blanket over the water surface via transpiration of trees (Helfer et al., 2009). SFR4 and SFR5 were located at open space, and evaporation was similar to the potential evaporation.

Overflow occurred when the water level exceeded the height of the spillway. Although SFRs were designed to harvest runoff from a single heavy rainfall event, overflow was inevitable in all SFRs during consecutive days of rainfall. As a result, 6.1-84.1% of the harvested water was lost as overflow (Table 3.1). The overflow volume of SFR1 was the greatest (445 m^3, 84.1% of total inflow; Table 3.1) because it was smaller than the reference volume (SFR ratio, 0.63; Table 2.1) and also was not used during CS2. On the other hands, the overflow volume of SFR5 was the smallest (44 m^3, 6.1% of total inflow; Table 3.1) because it was larger than the reference volume (SFR ratio, 1.7; Table 2.1) and was fully utilized for the largest irrigation area while the catchment area was relatively small (area ratio, 0.56; Table 2.1).

The critical period of rice growth is from 45 to 75 days after planting the seedlings when the water requirement (i.e., the crop coefficient) is the highest (Lee and Huang, 2014). The period was from the middle December to the early January in CS1, which contained a short drought (the latter December; Figure 3.1). SFRs successfully supported rice growth during the short drought by irrigation (Figure 3.1). CS2 had lower rainfall than CS-CS1 due to the dry season from May to June 2014 where the monthly rainfall was less than 100 mm (Figure 3.1). Rice cultivation schedules varied among SFRs. The farmers of SFR2 and SFR3 harvested rice earlier, respectively at May 20 (SFR2) and at May 29 (SFR3). Consequently, the critical periods were from end of March to the middle April for SFR2 and during April for SFR3, and the farmers could avoid the onset of the dry season. In contrast, the critical period contained the dry season for SFR4 (from the middle April to the early May) and SFR5 (from the late April to the middle May). SFR4 irrigated the paddy field successfully during the critical period and the subsequent period until harvesting in the dry season. On the other hand, SFR5 could not irrigate the paddy field without supplemental irrigation of 55.3 m^3 from groundwater.

3.2 The Optimization Principle of Storage Capacity of Small-Farm Reservoir for Rainfed Agriculture

The model simulations were conducted for each of two periods, CS1 and CS1-CS2, with each of two crop types, peanuts and rice. For rice cultivation, three daily percolation values were considered under flooding condition, 0, 2, and 4 mm. Figure 3.3 shows examples of the simulated time course where the SFR capacity was optimized for the

CS1-CS2 period. For peanut cultivation (Figure 3.3a), irrigation was necessary both in CS1 and CS2. A larger amount of irrigation water was required after the onset of the dry season in CS2, and the SFR was empty at the harvesting time. For rice cultivation with percolation 0 mm per day (Figure 3.3b), the paddy field was under flooding condition during CS1, and hence no irrigation was needed. In CS2, the paddy field was irrigated in May 2014 when dry season was occurred. For the daily percolation 2 mm (Figure 3.3c), the paddy field was under flooding condition almost all the time during CS1, except in four days in December was under field capacity but still in the range available soil moisture, and hence no irrigation was needed. In CS2, in contrast, the paddy field was dry from the onset of the dry season, and irrigation was necessary. Rice cultivation with percolation 4 mm per day was need irrigation in December 2013 when included into CS1 (Figure 3.3d). Besides that, in January and February 2014, irrigation also was needed. During CS2, irrigation from SFR was needed higher. The contrasting irrigation patterns between peanuts and rice (Figure 3.3) were because the paddy field functioned as a temporal storage of rainwater that can be utilized during the short drought periods in the rainy season.

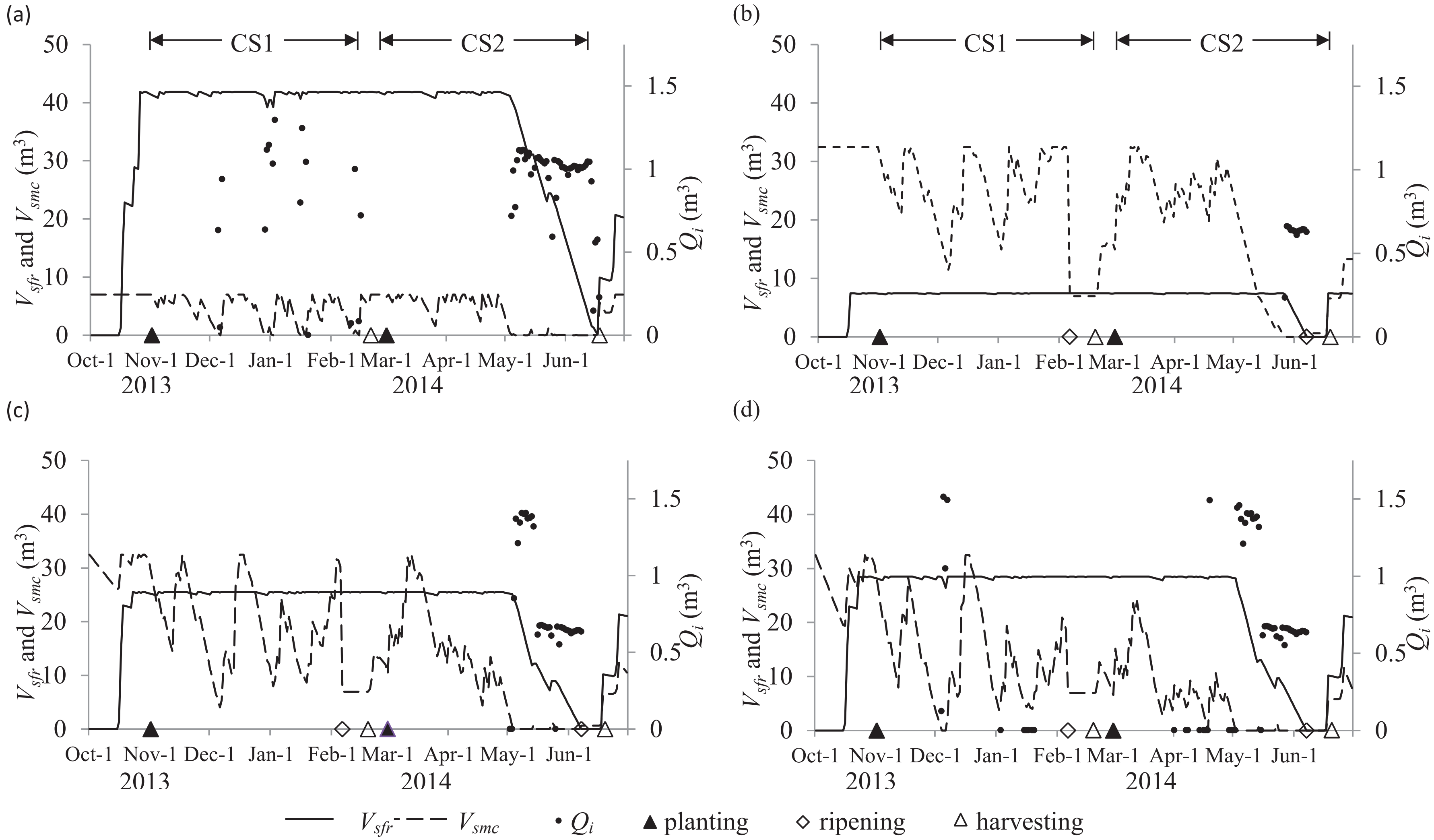


Figure 3.3 Examples of simulated volumes of an SFR (V_{sfr}), soil moisture content (V_{smc}), and irrigation water (Q_i) with WDI = 0.576 during two crop seasons, CS1 and CS2; (a) peanut cultivation; (b) rice cultivation with daily percolation 0 mm/day (c) rice cultivation with daily percolation 2 mm/day (d) rice cultivation with daily percolation 4 mm/day

A simulation was either "adequate" or "inadequate" for a given pair of *WSI* and *WDI*, and climate conditions. The pairs of *WSI* and *WDI* were created according the simulation of variants size of catchment area, SFR volume, and irrigation area, included harvesting ratio (Table 3.2-3.9). Results were plotted on a *WSI*-*WDI* plane (Figure 3.4). The adequate cases are located at the left-hand side of a boundary line if it exists (e.g., Figure 3.4a). The boundary line intersects the origin with a positive slope until a critical *WDI* value where the line curves to an opposite direction. The critical *WDI* indicates the theoretical limit of the size of an irrigation area with supplemental irrigation by an SFR for a given catchment area. The boundary line was absent in the positive cone when rice was cultivated with the daily percolation 0 and 2 mm. (Figure 3.4c). These results indicate that the rainfed agriculture can be adequate without supplemental irrigation if rice is cultivated under flooding condition in the rainy season.

For a fixed WDI value, Figure 3.4 indicates the adequate range of the SFR capacity. The minimum of the adequate range is the optimum SFR capacity. It should be noted that the range has an upper bound if the boundary line exists, indicating that a larger SFR is not always better, or even inadequate. This is because the depth of SFRs are limited to some extent (here, 1.67 m due to the safety reason), and a larger SFR implies a greater evaporation loss due to the greater surface area. The range shrinks with increasing *WDI*, and diminishes at the critical *WDI* value. Figure 3.4 also shows the adequate range of the irrigation area for a fixed WSI value. The boundary line indicates the maximum adequate irrigation area that can be supported by a given SFR capacity.

Table 3.2 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1 for peanut cultivation

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
30	0.10	100	367.70	50.00	1.308	2.615
30	0.10	100	266.31	28.50	1.029	3.611
30	0.10	100	245.09	24.00	0.942	3.923
30	0.10	100	230.90	21.00	0.874	4.164
30	0.10	100	241.80	20.50	0.815	3.977
30	0.10	1,550	4,184.00	317.07	0.729	3.562
30	0.31	1,900	1,826.00	388.27	0.697	3.412
30	0.31	781	817.00	159.24	0.637	3.124
30	0.24	2,968	4068.00	604.51	0.612	3.002
30	0.30	600	1000.00	120.51	0.402	2.000
30	0.14	400	2877.00	76.91	0.191	0.993
30	0.31	260	1275.00	47.88	0.123	0.666
30	0.14	232	2877.00	41.83	0.104	0.576

Table 3.3 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1 for rice cultivation with percolation 0 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	100	83.61	50	1.960	3.922
140	0.31	100	12.31	4	1.065	26.629
140	0.31	100	48.18	3.3	0.225	6.805
140	0.31	3,250	1,826	106.21	0.190	5.836
140	0.10	1,550	4,184	50.01	0.115	3.562
140	0.31	781	817	25.17	0.100	3.124
140	0.24	2,968	4,068	95.64	0.097	3.002
140	0.30	600	1,000	19.32	0.064	2.000
140	0.14	400	2,877	12.88	0.032	0.993
140	0.31	260	1,275	8.37	0.021	0.666
140	0.14	232	2,877	7.47	0.019	0.576

Table 3.4 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1 for rice cultivation with percolation 2 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	100	103.92	50	1.577	3.155
140	0.31	100	51.23	16	1.024	6.400
140	0.31	3,250	1,826	487.19	0.875	5.836
140	0.31	100	57.43	15	0.856	5.709
140	0.10	1,550	4,184	229.73	0.528	3.562
140	0.31	781	817	115.28	0.461	3.124
140	0.24	2,968	4,068	437.5	0.443	3.002
140	0.30	600	1,000	86.89	0.290	2.000
140	0.14	400	2,877	54.82	0.136	0.993
140	0.31	260	1,275	33.73	0.086	0.666
140	0.14	232	2,877	25.51	0.063	0.576

Table 3.5 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1 for rice cultivation with percolation 4 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	100	123.93	50	1.323	2.646
140	0.31	100	85.19	25	0.962	3.849
140	0.31	100	86	19.26	0.734	3.812
140	0.31	100	89.99	19	0.692	3.643
140	0.10	2,000	1,826	378.48	0.680	3.591
140	0.31	1,550	4,184	292.59	0.672	3.562
140	0.24	781	817	141.08	0.564	3.124
140	0.30	2,968	4,068	528.92	0.535	3.002
140	0.14	600	1,000	101.56	0.339	2.000
140	0.31	400	2,877	64.57	0.160	0.993
140	0.14	260	1,275	40.06	0.103	0.666

Table 3.6 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1-CS2 for peanut cultivation

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
30	0.14	172.74	100	50	2.075	4.135
30	0.14	87.14	100	20	1.639	8.197
30	0.14	46.34	100	5	0.770	15.415
30	0.14	42.20	100	3	0.508	16.925
30	0.14	65.28	100	2.5	0.274	10.941
30	0.10	4,184	1,550	33.06	0.076	3.562
30	0.31	1,826	1,900	40.36	0.072	3.412
30	0.31	817	781	16.45	0.066	3.124
30	0.24	4,068	2,968	62.24	0.063	3.002
30	0.14	334.76	100	2	0.043	2.134
30	0.30	1,000	600	11.9	0.040	2.000
30	0.14	2,877	400	6.56	0.016	0.993
30	0.31	1,275	260	3.39	0.009	0.666

Table 3.7 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1-CS2 for rice cultivation with percolation 0 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	0	3,250	0	0	30.00
140	0.31	1,826	3,250	0	0	5.84
140	0.1	4,184	1,550	0	0	3.56
140	0.31	817	781	0	0	3.12
140	0.24	4,068	2,968	0	0	3.33
140	0.30	1,000	600	0	0	2.00
140	0.14	2,877	400	0	0	0.99
140	0.31	1,275	260	0	0	0.67
140	0.14	2,877	232	0	0	0.58

Table 3.8 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1-CS2 for rice cultivation with percolation 2 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	0	3,250	0	0	30.00
140	0.31	1,826	3,250	0	0	5.84
140	0.1	4,184	1,550	0	0	3.56
140	0.31	817	781	0	0	3.12
140	0.24	4,068	2,968	0	0	3.00
140	0.30	1,000	600	0	0	2.00
140	0.14	2,877	400	0	0	0.99
140	0.31	1,275	260	0	0	0.67
140	0.14	2,877	232	0	0	0.58

Table 3.9 The simulated volumes of SFR (V_{sfr}), catchment area (A_c), and irrigation area (A_i) during CS1-CS2 for rice cultivation with percolation 4 mm

Maximum SFR (SMC_{max})	Harvesting ratio (H_r)	Irrigation area (A_i)	Catchment area (A_c)	SFR volume (V_{sfr})	Water Storage Index (WSI)	Water Demand Index (WDI)
140	0.31	163.99	100	100	1.999	1.999
140	0.31	40.42	100	5	0.406	8.111
140	0.31	42.6	113.56	3.04	0.234	8.740
140	0.31	1,826	3,250	64.73	0.116	5.836
140	0.1	4,184	1,550	30.49	0.070	3.562
140	0.31	817	781	15.29	0.061	3.124
140	0.24	4,068	2,968	58.02	0.059	3.002
140	0.30	1,000	600	11.5	0.038	2.000
140	0.14	2,877	400	7.21	0.018	0.993
140	0.31	1,275	260	4.39	0.011	0.666
140	0.14	2,877	232	3.79	0.009	0.576

The adequate range increases with the increasing *WSI* value until the boundary line reaches the curvature at the critical *WDI* value, and shrinks thereafter due to the greater evaporation loss. This indicates that an SFR should be designed to be smaller than the value at the curvature.

Data of actual five SFRs (Table 2.2) are also plotted on Figure 3.4. All data are located in the adequate region for peanuts cultivation during CS1 (Figure 3.4a), and the irrigation area can be extended further (Table 3.10 and Table 3.11). In contrast, peanuts cultivation during CS1-CS2 was adequate only in the case of SFR1, and was inadequate in other cases (Figure 3.4b). In such cases, farmers may consider to irrigate smaller area as given by the boundary line. Rice cultivation in CS1 was adequate even with 4 mm daily percolation (Figure 3.4c). It was adequate in CS1-CS2 if the daily percolation was as small as 0 mm (Figure 3.4d). The results correspond well with the actual decision of farmers in CS2. Except for the case of SFR1 where the farmer stopped cultivation in CS2 due to the labour shortage, all farmers successfully cultivated rice in CS2 where cultivation of annual crops was difficult for the SFR capacity and the irrigation area (Figure 3.4b). This also indicates the daily percolation under flooding condition was in the range of 0-2 mm (Figure 3.4d).

It should be recognized that there are restrictions to reservoir construction in the study site. First, each catchment area is occupied by a single group of farmers, and the cost of constructing a larger reservoir is not affordable. Second, the depth is restricted to 1.67 m to avoid accidents. Under these restrictions, this study showed that a larger SFR is not always better because of the evaporation loss from the surface (Figure 3.4). Although such SFRs cannot supply irrigation water during the whole dry season, they are shown to be effective during short droughts.

Table 3.10 The maximum adequate irrigation area (m^2) estimated by the model simulations during the CS1 or during CS1-CS2 for five actual SFRs in Gondangrejo, Central Java, Indonesia; "Peanuts" indicates peanut cultivation; "Rice-0", "Rice-2", and "Rice-4" indicate rice cultivation with daily percolation 0 mm, 2 mm, and 4 mm, respectively

	SFR1	SFR2	SFR3	SFR4	SFR5
CS1					
Peanuts	2,756	1343	5,277	7,537	4,650
Rice-0	∞	∞	∞	∞	∞
Rice-2	∞	∞	∞	∞	∞
Rice-4	3,298	1,565	3,206	9,106	4,284
CS1-CS2					
Peanuts	348	169	668	952	588
Rice-0	2,034	962	4,080	5,624	3,499
Rice-2	474	230	912	1,297	801
Rice-4	408	198	787	1,118	691

Table 3.11 Optimum SFR capacity (m^3) estimated by the model simulations during the CS1 or during CS1-CS2 for actual irrigation areas of five SFRs; notations follow Table 3.10

	SFR1	SFR2	SFR3	SFR4	SFR5
CS1					
Peanuts	6	18	44	72	80
Rice-0	0	0	0	0	0
Rice-2	0	0	0	0	0
Rice-4	5	16	72	60	87
CS1-CS2					
Peanuts	44	144	344	569	632
Rice-0	8	25	56	96	106
Rice-2	32	106	252	418	464
Rice-4	38	123	292	485	538

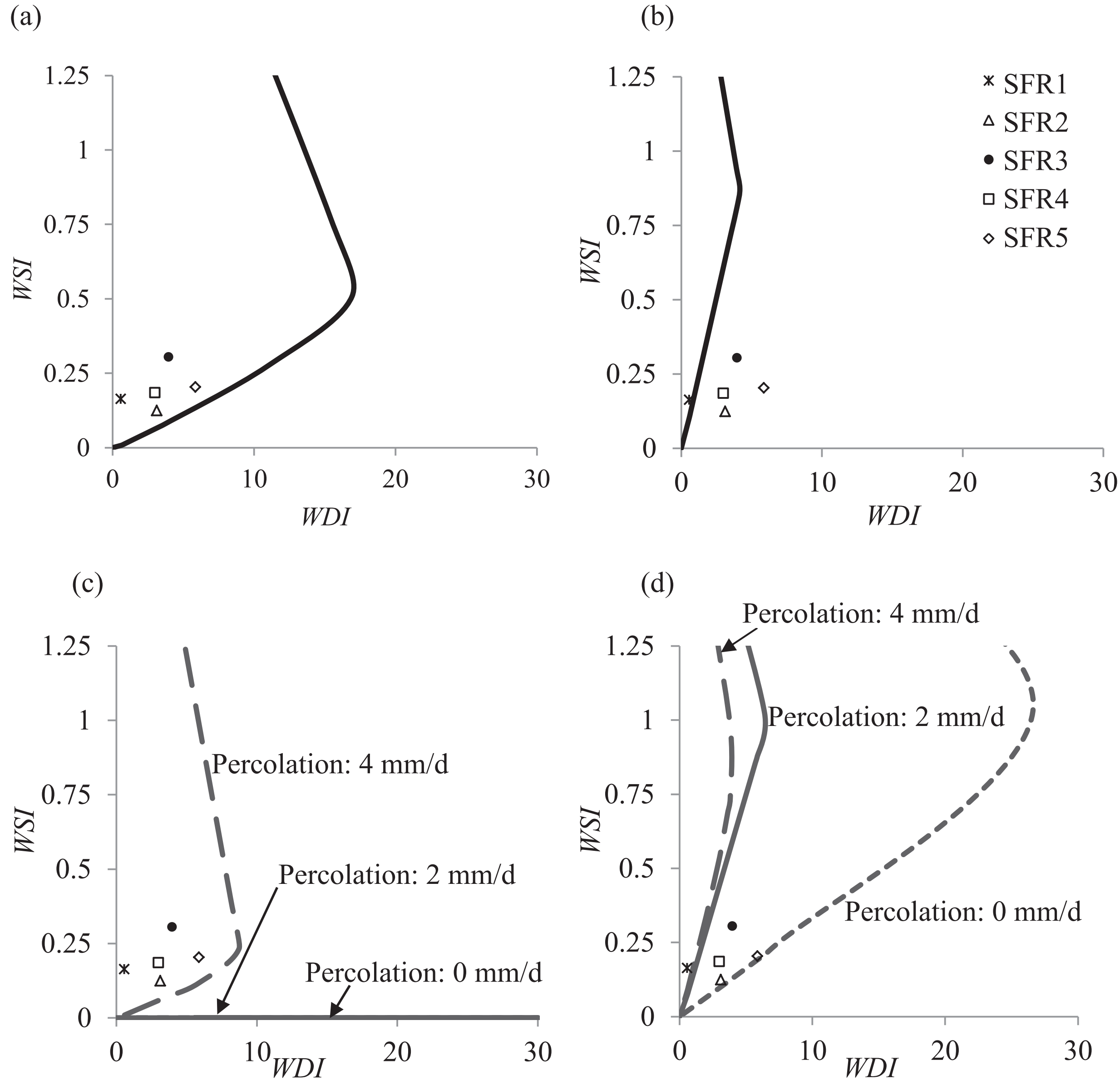


Figure 3.4 Simulation results and actual cases of SFRs plotted on *WSI*-*WDI* plane divided by a boundary line into adequate (the simulated SFR can supply enough irrigation water) and inadequate (the simulated SFR fails to supply irrigation water) cases by a boundary line; adequate cases are located on the left-hand side of the boundary line; (a) peanuts cultivation during CS1; (b) peanuts cultivation in CS1-CS2; (c) rice cultivation in CS1; (d) rice cultivation in CS1-CS2

IV. CONCLUSIONS

The results showed that an SFR was capable of irrigating a paddy field during short droughts in the rainy season and during the early dry season even in the critical period of rice cultivation. SFRs were advantageous because they enabled farmers to cultivate rice in CS2. Nevertheless, it was also indicated that a proper design of the SFR volume and the size of the irrigation area was important in order to get the most out of an SFR. For example, the size of SFR1 was smaller than the reference volume for the catchment area, and a large fraction of the harvested water was lost as outflow. The irrigation area of SFR5 was too large for the catchment area to be irrigated by the SFR alone. In order to design an SFR and the irrigation area for a given catchment area, it is crucial to consider the characteristics of the catchment area (i.e., the size and slope), the local rainfall pattern, and the type of the crop field.

Farmers cannot control climate and the catchment area. The simulation results provide directions of how to design a rainfed agricultural system. The optimum SFR capacity and the irrigation area are obtained from the model simulation. Because the aim of this study was the model development, the simulations were conducted only with the climate data in 2013-2014. The design of the rainfed irrigation system should be based on more extensive simulations based on multi-year climate data. In particular, the results would be greatly affected if the simulation period includes monsoon droughts (D'Arrigo et al., 2006). Further simulation and experimental studies are needed in order to verify the model framework presented in this study.

The advantages of SFR are the farmers could cultivate rice twice in a year which was previously difficult. Besides that, the farmer can decide to cultivate early after SFR filled water during the uncertainly rainfall as impact of climate change so that water scarcity during short drought and critical period of rice in dry season can be avoided.

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