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

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Abstract: This study aims to develop a simulation model that provides the direction of how to design the capacity of a small-farm reservoir (SFR) for supplemental irrigation in rainfed agriculture. The model describes the water balance of an agricul-tural system that consists of an SFR, and the catchment and irrigation areas where peanuts or rice is cultivated. Simulations were conducted for two crop seasons during October 2013 and June 2014 with climate data in Gondangrejo, Central Java, Indonesia. The SFR capacity was either adequate, that is, the SFR supplied sufficient irrigation water throughout the crop seasons, or inadequate, the SFR failed to supply irrigation water. The optimum SFR capacity was defined as the minimum of the adequate capacity for given catchment and irrigation areas. Simulation results were compared with actual cases of five SFRs constructed in the simulation site. The results clarified the range of the adequate SFR capacity for peanut or rice cultivation in the first crop season during the rainy season and in the second crop season partly during the dry season. The model outputs can be utilized for evaluating and designing SFRs in rain-fed agricultural systems.

Keywords: Rainwater harvesting; Short drought; Simulation model; Water balance analysis

1 Introduction

Water shortage is one of the major problems in rainfed agriculture worldwide, and efficient rainwater harvesting is a key to the success (Arsyad, 2006; Komariah and Senge, 2013). Construction 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 seasons (Ariyanto et al., 2016).

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.

In this study, a simple model of rainwater harvesting and an irrigation scheme was developed, and a framework was proposed to determine the optimum capacity of an SFR. The model simulations were conducted for two crop seasons from November to February and from March to June of 2014 in Central Java, Indonesia. This study aims to propose the principle for estimating the optimum SFR capacity and the corresponding irrigation area in rainfed agriculture.

2 Materials and methods

2.1 Model description

The model consists of three submodels that collectively simulate the water budget of the rainfed agricultural system. Each submodel describes a daily runoff water volume from the catchment area (catchment area submodel), the daily increment of the SFR water volume (SFR submodel), and that of the soil moisture content of the irrigation area (irrigation area submodel), respectively (Figure 1). In the simulation, the daily increments are computed as a result of inputs and outputs that take place during the day. In the followings, the three submodels are described in detail.

2.1.1 Catchment area submodel

Two assumptions are made for the simplification. First, the runoff water volume from the catchment area is assumed to be linearly related to the total rainfall on the catchment area. The relationship can be replaced by a more detailed...
nonlinear function (Conservation Engineering Division, 1986; Ariyanto et al., 2016), 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 (Ariyanto et al., 2016).

With the above assumptions, the runoff water volume at day \(d\) (\(Q^{[d]}\), m\(^3\)) is expressed as a function of the total rainfall at the day \(d\) (\(R^{[d]}\), m):

\[
Q^{[d]} = H_r \cdot A_s \cdot R^{[d]}
\]

(1)

where \(H_r\) is the harvesting ratio and \(A_s\), 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; Ariyanto et al., 2016).

2.1.2 SFR submodel

The SFR water volume at day \(d\) (\(V^{[d]}_{sfr}\), 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 \(Q^{[d]}\), and direct rainfall, \(A_{sf} \cdot R^{[d]}\), where \(A_{sf}\) (m\(^2\)) is the area of the SFR. In the simulation, the depth of the SFR is set to 1.67 m and hence \(A_{sf} = V^{[d]}_{sfr} / 1.67\). The depth was determined through the agreement with farmers in order to prevent the risk of falling accidents. The outputs consist of irrigation water, \(Q^{[d]}\), evaporation loss, \(A_{sf} \cdot Ev^{[d]}\), where \(Ev^{[d]}\) (m) is the daily amount of evaporation from the SFR, and overflow from the SFR, \(Q^{[d]}\) (m\(^3\)). In this study, the SFR is assumed to be sealed at the bottom, and water leakage is ignored. This assumption was validated by the water balance analysis in Ariyanto et al. (2016), where plastic tarps were applied at the bottom of SFRs. In order to obtain \(V^{[d]}_{sfr}\), the following water balance equation is evaluated:

\[
V^{[d]}_{sfr} = V^{[d-1]}_{sfr} + Q^{[d]} - A_{sf} \cdot R^{[d]} - Q^{[d]} - A_{sf} \cdot Ev^{[d]}
\]

(2)

The obtained \(V^{[d]}_{sfr}\) from Eq.(2) is employed if it is within the range of 0 and \(V_{max}\) (m\(^3\), the SFR storage capacity). If the value is negative, then the SFR is empty, that is,

\[
V^{[d]}_{sfr} = V^{[d-1]}_{sfr} + Q^{[d]} - A_{sf} \cdot R^{[d]} - Q^{[d]} - A_{sf} \cdot Ev^{[d]} < 0,
\]

then \(V^{[d]}_{sfr} = 0\)

(3)

If the value exceeds \(V_{max}\), then the SFR is full and water overflows, that is,

\[
V^{[d]}_{sfr} = V_{max}\] and \(Q^{[d]}_{out} = V^{[d-1]}_{sfr} + Q^{[d]} - A_{sf} \cdot R^{[d]} - Q^{[d]} - A_{sf} \cdot Ev^{[d]} - V_{max}.
\]

(4)

\(Q^{[d]}\) is determined by the irrigation area submodel described below.

2.1.3 Irrigation area submodel

The submodel describes the change in the total volume of \(SMC^{[d]}\) (m) in the irrigation area at day \(d\). In this study, \(SMC^{[d]}\) is defined as available soil moisture (Ayu et al., 2010) for plants in the root zone at the day \(d\), and ranges from 0 (the wilting point) to the maximum \(SMC_{max}\) (m). With the irrigation area \(A_i\) (m\(^2\)), the total volume of \(SMC^{[d]}\) \((V^{[d]}_{smc})\), m\(^3\)) is expressed by:

\[
V^{[d]}_{smc} = A_i \cdot SMC^{[d]}.
\]

(5)

\(V^{[d]}_{smc}\) changes as a result of inputs and outputs. The inputs consist of irrigation water \(Q^{[d]}\), and direct rainfall \(A_{i} \cdot R^{[d]}\). The outputs consist of evapotranspiration \(A_i \cdot ETc^{[d]}\), and percolation \(A_i \cdot P_i^{[d]}\), and overflow \(Q^{[d]}\), m\(^3\)). In this study, the SFR is assumed to be sealed at the bottom, and water leakage is ignored. This assumption was validated by the water balance analysis in Ariyanto et al. (2016), where plastic tarps were applied at the bottom of SFRs. In order to obtain \(V^{[d]}_{smc}\), the following soil moisture balance equation is evaluated:

\[
V^{[d]}_{smc} = V^{[d-1]}_{smc} + A_i \cdot R^{[d]} - A_i \cdot ETc^{[d]} - A_i \cdot P_i^{[d]}
\]

(6)

The obtained \(V^{[d]}_{smc}\) from Eq. (6) 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:

\[
V^{[d]}_{smc} = V^{[d-1]}_{smc} + A_i \cdot R^{[d]} - A_i \cdot ETc^{[d]} - A_i \cdot P_i^{[d]} < 0,
\]

then

\[
V^{[d]}_{smc} = 0.
\]

(7)

2.2 Model simulations

2.2.1 Simulation site

The simulations consider rainfed agricultural systems located in Gondangrejo, Karanganyar, Central Java, Indonesia, where five experimental SFRs were constructed in 2013 (Ariyanto et al., 2016). Table 1 summarizes the dimensions of the five SFRs. The climate is classified to tropical mon-
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, the SFR field is set to 30 mm. This value corresponds to the field capacity measured at the simulation site (31.5-33.9 mm, Ariyanto et al., unpublished data). In simulations where rice is cultivated, the Paddy field is set to 140 mm, and the SFR field stores 100 mm of water above the soil surface. During two weeks before harvesting when rice is at the ripening stage, the paddy field is drained and SMCmax is set to 30 mm.

SMCmax 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, SMCMAX is set to 30 mm. This value corresponds to the field capacity measured at the simulation site (31.5-33.9 mm, Ariyanto et al., unpublished data). In simulations where rice is cultivated, the Paddy field is set to 140 mm, and the SFR field stores 100 mm of water above the soil surface. During two weeks before harvesting when rice is at the ripening stage, the Paddy field is drained and SMCmax is set to 30 mm.

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

In this study, ET[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 computed from the Penman-Monteith equation for climate conditions provided by the automatic weather station, and was multiplied by the crop coefficient (Allen et al., 1998; Ariyanto et al., 2016). The obtained daily crop water requirements are shown in Figure 2 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).

### Table 1: Dimensions of five SFRs constructed in Gondangrejo, Central Java, Indonesia

| SFR | SFR1 | SFR2 | SFR3 | SFR4 | SFR5 |
|-----|------|------|------|------|------|
| 1. Catchment area (Ac) [m²] | 2,877 | 817 | 4,184 | 4,068 | 1,826 |
| 2. SFR volume (Vsfr) [m³] | 66.0 | 31.2 | 132.5 | 182.6 | 113.6 |
| 3. Irrigation area (Ai) [m²] | 232 | 781 | 1,733 | 2,968 | 3,270 |
| 4. Harvesting ratio (Hr) | 0.14 | 0.30 | 0.10 | 0.24 | 0.31 |
| 5. Water storage index (WSI): [(2)/(4)-(1)] [m] | 0.16 | 0.13 | 0.32 | 0.19 | 0.20 |
| 6. Water demand index (WDI): [(3)/(4)-(1)] | 0.58 | 3.19 | 4.14 | 3.00 | 5.87 |

Figure 2: Evapotranspiration of peanuts and rice during the simulation period from Oct. 2013 to Jun. 2014
tion 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 the SFR storage capacity per a catchment area weighted by the harvesting ratio, and expresses the amount of rainfall stored by the SFR (Eq.(9)).

$$\text{WSI} = \frac{V_{\text{max}}}{H_c \cdot A_c}$$

A water demand index WDI (dimensionless) is a relative extent of an irrigation area to a catchment area weighted by the harvesting ratio (Eq.(10)).

$$\text{WDI} = \frac{A_i}{H_c \cdot A_c}$$

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 1 shows the two indexes of five SFRs constructed in the simulation site. WSI values ranged from 0.13 to 0.32 m, and 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.

3 Results and discussion

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 flooded condition, 0, 2, and 4 mm. Figure 3 shows examples of the simulated time course where the SFR capacity was optimized for the CS1-CS2 period. For peanut cultivation (Figure 3(a)), irrigation was necessary both in CS1 and CS2. A larger amount of irrigation water was required after the onset of the dry season (the beginning of May) in CS2, and the SFR was empty at the harvesting time. For rice cultivation with the daily percolation 2 mm (Figure 3(b)), the paddy field was under flooded condition almost all the time during CS1 (except in four days in December), 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. The contrasting irrigation patterns between peanuts and rice (Figure 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 (Ariyanto et al., 2016).

A simulation was either "adequate" or "inadequate" for a given pair of WSI and WDI, and climate conditions. Results were plotted on WSI-WDI plane (Figure 4). The adequate cases are located at the left-hand side of a boundary line if it exists (e.g., Figure 4(a)). 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 supported by an SFR for a given catchment area. The boundary line was absent in the positive domain (i.e., WSI > 0 and WDI > 0) when rice was cultivated with the daily percolation 0 and 2 mm (Figure 4(c)). These results indicate that the rainfed agriculture can be adequate without supplemental irrigation if rice is cultivated under flooded condition in the rainy season.

For a fixed WDI value, Figure 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 from the greater surface area. The range shrinks with the increasing WDI, and diminishes at the critical WDI value.

Figure 3: Examples of simulated volumes of an SFR ($V_{\text{sfr}}$), soil moisture content ($V_{\text{smc}}$), and irrigation water ($Q_i$) with WDI = 0.576 during crop seasons, CS1 and CS2; (a) peanut cultivation; (b) rice cultivation with the daily percolation 2 mm
Figure 4: Simulation results and actual cases of five SFRs plotted on WSI-WDI plane divided by a boundary line into adequate (the simulated SFR can supply sufficient irrigation water) and inadequate (the simulated SFR fails to supply irrigation water) cases; adequate cases are located on the left-hand side of the boundary line; (a) peanuts cultivation during CS1; (b) peanuts cultivation during CS1-CS2; (c) rice cultivation during CS1; (d) rice cultivation during CS1-CS2

Figure 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. 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 1) are also plotted on Figure 4. All data are located in the adequate region for peanuts cultivation during CS1 (Figure 4(a)), and the irrigation area can be extended further until the maximum adequate irrigation area (Table 2). In contrast, peanuts cultivation during CS1-CS2 was adequate only in the case of SFR1, and was inadequate in other cases (Figure 4(b)). In such cases, farmers may consider to irrigate smaller area as given by the maximum adequate irrigation area. Rice cultivation in CS1 was adequate even with 4 mm daily percolation (Figure 4(c)). It was adequate in CS1-CS2 if the daily percolation was as small as 0 mm (Figure 4(d)). 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 labor shortage, all farmers successfully cultivated rice in CS2 where cultivation of annual crops was difficult for the SFR capacity and the irrigation area (Figure 4(b)). This also indicates the daily percolation under flooded condition was in the range of 0-2 mm (Figure 4(d)).

|                | SFR1 | SFR2 | SFR3 | SFR4 | SFR5 |
|----------------|------|------|------|------|------|
| **CS1**        |      |      |      |      |      |
| Peanuts        | 2,756| 1,343| 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 2: The maximum adequate irrigation area (m²) estimated by the model simulations during 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 the daily percolation 0 mm, 2 mm, and 4 mm, respectively.
Table 3: Optimum SFR capacity (m³) estimated by the model simulations during CS1 or during CS1-CS2 for actual irrigation areas of five SFRs; notations follow Table 2

|          | SFR1 | SFR2 | SFR3 | SFR4 | SFR5 |
|----------|------|------|------|------|------|
| Peanuts  | 6    | 17   | 44   | 72   | 80   |
| Rice-0   | 0    | 0    | 0    | 0    | 0    |
| Rice-2   | 0    | 0    | 0    | 0    | 0    |
| Rice-4   | 5    | 17   | 72   | 60   | 87   |

CS1-CS2

|          | Peanuts | SFR1 | SFR2 | SFR3 | SFR4 | SFR5 |
|----------|---------|------|------|------|------|------|
| 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  |

In the irrigation scheme of the simulation model, the irrigation water volume is given as an exact amount that keeps the available soil moisture non-negative. Moreover, the calculation also requires knowledge of rainfall, evapotranspiration, percolation, and the soil moisture content in the subsequent day (Eq.(7)). Therefore, the obtained optimum SFR capacity and the maximum adequate irrigation area are their theoretical limit in an ideal situation. In this sense, these results should be considered with some margins. Yet, such theoretical practice gives an important baseline for evaluating the existing SFRs, and for designing SFRs in rainfed agricultural systems.

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 4). Although such SFRs cannot supply irrigation water during the whole dry season, they are shown to be effective during short droughts (Ariyanto et al., 2016).

4 Conclusions

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 (Table 3) and the irrigation maximum adequate irrigation area (Table 2) 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 with 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.

Acknowledgments

We thank Arief Rahmadiyanto, Kengo Ito, and Takeo Onishi for their help with the field experiment. This work was supported by JSPS Program Japan and Directorate General of Higher Education (DGHE) Republic of Indonesia.

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Discussion open until June 30, 2017