Optimization of Water Distribution to Support the Balance of Water Usage: A Case Study of the Sempor Irrigation System, Central Java, Indonesia

Hanugerah Purwadi¹, Lily Montarcih Limantara¹, Ery Suhartanto¹, and Rispiningtati¹

¹Water Resources Engineering Department, Faculty of Engineering, Universitas Brawijaya, Malang 65145, Indonesia

E-mail: hanugrah1901@gmail.com

Abstract. The existence of irrigation in Indonesia is commonly quite influenced by environmental and social cultural characteristics, which the people have lived by and developed for a long time. Many factors cause changes in the pattern of water availability, which increases competition among stakeholders, as in the Sempor irrigation system area. It has four main dams, which are the Bojong Dam, Watubarut Dam, Rowokawuk Dam, and Sindut Dam; it provides approximately 5900 ha of services and receives supplies from the Great Sempor Dam (38 million m³). Currently there is a decline in the function of this dam due to sedimentation, making operational services less optimal, especially during the dry season. The methodology of this study is to perform water optimization for the balancing of water in the irrigation area. Meanwhile, the implementation of the water supply on the field considers the calculation of water availability, space, and time. In practice, the operation of water supply is held by a group system in the secondary blocks. In certain conditions, the water rotation in tertiary channels was performed by local cultural wisdom.

Keywords: Irrigation System, Water Optimization, Water Distribution

1. Introduction

In parallel with the paradigm changes of irrigation management in Indonesia from centralisation to decentralisation, Minister of Public Works Regulation Number 17/PRT/M/2015 [1] was issued. The minister regulation has consequences for the change in form of irrigation management institutions at both the central and regional levels. Irrigation scheduling depends on determining when to irrigate and how much water to apply to farmland; therefore, the successful application of irrigation depends on the understanding and utilizing of irrigation scheduling principles to develop a management plan [2]. Irrigation scheduling provides information that can be used to communicate to develop the plan of irrigation strategies for each farmed field. Irrigation scheduling methods are based on two approaches: a) soil measurements and b) crop monitoring [3]. According to a study [4], application of linear programming can aid small-scale farmers to efficiently adapt to a changing economic and technological environment in order to obtain farm planning.

As an agricultural country, Indonesia is very dependent on agricultural products to increase foreign trade; thus, water and land are the urgent factors for sustainable agricultural development of the nation [5][6][7]. However, water availability is sometimes at deficits or surpluses [8] and are quite influenced by seasons for some agricultural areas. The surplus water can be used for maximizing agricultural
yield productivity to produce maximum benefits. In some locations, water becomes a source of potential conflict as irrigation quality decreases due to degradation of irrigation network performance. The deterioration of the performance of irrigation networks is also caused by irrigation network designs that are not in accordance with existing conditions, or due to a decrease in the operation and maintenance of irrigation systems as well as a combination of both.

A study [9] was conducted on the influence of institutional framework changes of irrigation management in China, in which it is stated that the performance of irrigation is relatively closed with the institutional type, while performance of irrigation is affected by technical, economic, institutional, socio-cultural and political aspects. Therefore, the search for solutions of irrigation problems requires fundamental changes; effectively needing application of irrigation modernization [10]. On the pragmatic level, water is very urgent for increasing the productivity of available irrigation and must be realized in a tangible form [11]. For the case of Indonesia, a study [12] argued that overall improvement requires reform, both in the context of future development and the management system for the existing irrigation.

Sustaining increased agricultural production and realizing an acceptable return on the productive and hydrological impacts of internal irrigation processes has been crucial for obtaining satisfactory performance [13]. Understanding the importance of carrying out controlled irrigation management from the start of the planning process to the implementation and the willingness to carry out post-evaluations into a policy is very important. This policy emerged in line with the change in management paradigm from technical to managerial. In this study, the following are the research problems that can be identified:

1) There is a management disharmony between the way of thinking of the government and the way of thinking of farmers. The government tends to use an efficiency mind-set, while farmers use an effectiveness mind-set. In the condition of water resources that are becoming increasingly limited and the faced problems becoming increasingly complex, it is necessary to find an agreement by means of dialogue and sharing knowledge so that harmonization is achieved in the management of water resources.

2) With the decentralization of irrigation, many actors or institutions have become engaged in irrigation management at both the central and regional levels. At the central level, each ministry brings its own policies in accordance with their own targets. This condition has an impact on the number of irrigation development and management programs in each institution that run independently without coordination, which makes the implementation of irrigation management less coordinated and the results less than optimal. At the regional level, there is a limit on the number of Regional Work Units (SKPD) that cause the irrigation management authority to be unclear because the existing Technical Implementation Unit (UPT) as a management implementer is mixed with institutional stakeholders in other fields.

3) The existence of irrigation assets is currently experiencing many setbacks due to budget constraints for maintenance as well as the lack of concern that irrigation actors have for existing assets; the irrigation network and its supporting mechanisms have not been interpreted as principal capital assets that need to be maintained with a high capital value. Institutions and human resources are intangible assets that have not been optimally developed. There is much focus on the development of infrastructure as tangible assets that are indeed more able to provide results that are felt directly.

Departing from the real problems in the field mentioned above, it is necessary to perform a more comprehensive research on the aspects of water availability and from the institutional point of view in one single management. The reliability of each of the aspects that influence the performance of irrigation management is calculated through optimization methods. Generally, the model of optimization is a process of the best alternative options among a number of available solution alternatives [14] [15].
2. Materials and Methods

2.1. Study Location
Sempor Irrigation Area is an irrigation system that is a combination of four sub-irrigation systems located in Kebumen Regency, Province of Central Java, which are the Bojong irrigation system (2,599 Ha), Watubarut irrigation system (1,627 Ha), Rowokawuk irrigation system (916 Ha), and Sindut irrigation system (746 Ha) [16]. The water distribution operations become a single integrated management system; although the people receive irrigation water from their own weirs, at certain times and mostly in dry season, they obtain water supplies from the Sempor reservoir through Bojong Dam as a regulator dam. The total service area of the Sempor Irrigation System is 5,888 Ha. The map of Sempor Irrigation Area location and schemes are presented in the following figure.

![Figure 1. The map of Sempor Irrigation](source)

![Figure 2. Scheme of Sempor Irrigation](source)

2.2. Analysis Method
The method of analysis of this study is the linear programming model for optimizing water in the irrigation channel. To estimate water distribution, especially when conditions are limited while the needs for water increase, it is necessary to calculate how much water is available in the field. In this case, water requirements are calculated based on each cropping pattern that has been decided by the commission of irrigation. The output of this method is a number from the calculation results of the ratio between the volume of water requirements for plants in the irrigation area and the volume of water that can be provided by the irrigation network.

2.3. Water Demands
2.3.1. Water Demand for Paddy Fields
The amount of water needed by the plant in a paddy field terrace is represented by the equation

\[ NFR = ETc + P + WLR - Re \]  

(1)

Where:
- \( NFR \) = farm water demand (mm/day),
- \( ETc \) = plant water demand (mm/day),
- \( WLR \) = water layer replacement (mm/day),
- \( P \) = percolation (mm/day),
- \( Re \) = effective rainfall
2.3.2. Crop Water Demand

Crop water demand is the amount of water needed to replace the loss of water as a result of evapotranspiration. The amount of water plant demand (consumptive use) is calculated by the equation of

\[ ET_c = K_c \cdot ET_o \]  

Where:
\[ ET_c \] = plant evapotranspiration (mm/day),
\[ ET_o \] = reference plant evapotranspiration (mm/day),
\[ K_c \] = plant coefficient

Water demand during land preparation is calculated by the V.D Goor-Zijlstra equation below:

\[ IR = M \cdot e^k / (e^k - 1) \]  

Where:
\[ IR \] = irrigation water demand (mm/day),
\[ M \] = \( EO + P = (1,1 \cdot ET_o + P) \) (mm/day), water demand to replace the loss of the result
\[ k \] = \( MT/S \)
\[ T \] = the duration of land preparation (day),
\[ S \] = the water needed for saturation with an additional 50 mm

2.4. Water Availability

2.4.1. Dependable Flow (Q 80%)

\[ P = \frac{m}{n+1} \cdot 100\% \]  

Where:
\[ P \] = probability (%)
\[ m \] = data sequence number
\[ n \] = amount of data

2.4.2. Effective Rainfall

The height of rainfall (mm) is utilized to determine the time of starting the first planting, to estimate the irrigation water needs in the field, and to calculate the amount of effective rainfall. Monthly rainfall data is often utilized. The effective rainfall constant/coefficient is calculated from the below equations:

(1). The equation of daily effective rainfall for rice paddies:

\[ Paddy = \text{coefficient of effective rainfall} \cdot \frac{R_{90}}{15} \]  

(2). The equation of daily effective rainfall for secondary crops (soybeans):

\[ \text{Sec. crops} = \text{coefficient of effective rainfall} \cdot \frac{R_{50}}{15} \]  

2.5. K-Factor

The K-factor is the comparison between water requirements and water availability. The guidelines for determining parameters refer to the Criteria for Public Works Plans (KP-01). Analysis of calculations utilize data such as rainfall, climatology (wind velocity, temperature, air humidity), water discharge availability, reports on plant conditions, and crop production.

\[ K = \frac{Q_t}{Q_b} \]
Where:
\[ Qt = \text{available outflow debit} \]
\[ Qb = \text{outflow debit needed} \]

2.6. Optimization
Optimization of the model consists of the preparation of a system that is accordance with the real situation, after which it could be converted into a mathematical model by separating the main elements; furthermore, a solution in accordance with the goals or objectives of decision can be achieved [17]. The mathematical model used to describe a linear programming problem utilizes the following equations [2]:

Purpose Function:
\[ Z = C1X1 + C2X2 + C3X3 + ... + CnXn \]

Constraint Function:
\[ 1) a11X1 + a12X2 + a13X3 + ... + a1nXn <b1 \]
\[ 2) a21X1 + a22X2 + a23X3 + ... + a2nXn <b2 \]
\[ m) am1X1 + am2X2 + am3X3 + ... + amnXn <bm \]
\[ X1 \in ^0, X2 \in ^0, ..., Xn \in ^0 \]

3. Results and Discussion

3.1. Rainfall Data
From the results of data analysis, 10-year influential daily rainfall data were obtained for the Sempor irrigation area. Effective rainfall for usage in hydrological calculations needs summarized available monthly data, which are obtained from the six rainfall stations within the Sempor Catchment Area, which are the Karanganyar, Adimulyo, Rowokawuk, Gombong, Kuwarasan, and Sempor Rainfall Stations, as presented in Figure 3 below. Based on the graph of rainfall fluctuation from Figure 3 below, it can be seen that in general in the Sempor Irrigation Area, the rainy season begins in June and finishes in September.

The rainfall characteristics can be divided into 2 patterns. During the wet season, the rainfall intensity is relatively constant, greater than approximately 130 mm/month, but sometimes up to 300 mm/month. Meanwhile, in the dry season, the rainfall intensity can be less than approximately 10 mm/month. Different conditions occur from July to August, when no rain occurs in the area. Sometimes the rainfall also occurs in early May with an average rainfall intensity of 50% of the normal rainfall that occurs in the rainy season. Using a cropping calendar and the crop intensity that applies and exists on the field, the graph of the optimization model showed and confirmed water shortages during the dry season.

3.2. River Discharge
The overall pattern of flow in relation to rainfall is realistic; the rainfall begins in early October while the discharge begins to flow in mid-October. This means that the rainfall will infiltrate into ground water at the first moment. The discharge recorder data from the Bojong, Watubarut, Rowokawuk, and Sindut Weirs are presented in Figure 4 below. The monthly mean discharge ranges from 1 m³/sec in July up to 5 m³/sec from March to May, with extremes of 5.5 m³/sec in December and zero from August to September. The graph of river discharge data showed and confirmed widespread water deficit during the dry season, which is from the end of July to early October. The overall reliability of irrigation water supply from
each weir is very low or there is absolutely no water in the river that indicatively run into water shortage.

**Figure 3.** Monthly Rainfall in the Sempor Catchment Area

**Figure 4.** River Discharge in the Sempor Catchment Area
3.3. Water Optimization

The results of the optimization calculation with linear programming showed that the Sempor irrigation area is divided into 3 groups in each planting season. This allocation is intended to accommodate the different planting schedules in each irrigation distribution system, which will reduce the peak water demand in the irrigation area if the farmers plant at the same time. The pattern of water distribution uses a mixed system (vertical or horizontal system) to accommodate the availability of water and the position of the paddy fields of each agricultural irrigation area. These are the results of the calculation of water optimization in the Sempor Irrigation System:

1. Simulation using K-factor = 0.5 (Figure 5) indicated that from August to October, according to the water demand balanced with the water supply, the distribution of water irrigation is divided into 2 classifications with 3 sub-irrigation areas (Bojong, Watubarut, and Rowokawuk) allocated in distribution system 1 and 1 sub-irrigation area (Sindut) allocated in distribution system 2. The irrigated area reaches a total area of 5,888 ha of the Sempor Irrigation System, as in Table 1 below.

2. Simulation using K-factor = 0.7 (Figure 6) show similar results with the prior simulation, but the distribution of irrigation water is relatively unequal. There are 2 sub-irrigation areas (Bojong and Watubarut) that can be irrigated according to area targets, which reaches 5,475 ha as in Table 2 below.

3. Simulation using K-factor = 1.0 (Figure 7) showed that only 2 sub-irrigation systems (Watubarut and Rowokawuk) can be irrigated according to the area targets, but the other areas such as the Sindut sub-irrigation area cannot obtain water and water to the Bojong sub-irrigation area must be reduced (Table 3).

3.3.1. Water optimization with K-Factor = 0.50

![Figure 5. Water Balance with K-Factor = 0.50](image-url)
Table 1. Distribution of irrigation water with the Distribution Systems (K-Factor = 0.5) in Sempor Irrigation Area

| Sub-Irrigation Area | Total Area | Distribution Systems | Irrigated Area | Volume of Water Requirement | Volume of Water Availability |
|---------------------|------------|----------------------|----------------|----------------------------|----------------------------|
|                     | ha         | 1 2 3               | ha            | m³                         | m³                         |
| Bojong              | 2,599      | 2,599 0 0          | 2,599         | 20,562,428                 | 27,792,509                 |
| Watubarut           | 1,627      | 1,627 0 0          | 1,627         | 12,872,285                 | 12,525,496                 |
| Sindut              | 916        | 0 916 0            | 916           | 7,651,394                  | 9,458,173                  |
| Rowokawuk           | 746        | 746 0 0            | 746           | 5,902,105                  | 4,721,637                  |
| Total               | 5,888      |                     | 5888          | 46,988,212                 | 54,497,815                 |

3.3.2. Water optimization with K-Factor = 0.70

Table 2. Distribution of water irrigation with the Distribution Systems (K-Factor = 0.7) in Sempor Irrigation Area

| Sub Irrigation Area | Total Area | Distribution Systems | Irrigated Area | Volume of Water Requirement | Volume of Water Availability |
|---------------------|------------|----------------------|----------------|----------------------------|----------------------------|
|                     | ha         | 1 2 3               | ha            | m³                         | m³                         |
| Bojong              | 2,599      | 2,599 0 0          | 2,599         | 26,028,389                 | 28,483,926                 |
| Watubarut           | 1,627      | 1,627 0 0          | 1,627         | 16,294,032                 | 12,837,103                 |
| Sindut              | 916        | 686 0 230          | 916           | 9,571,816                  | 8,718,745                  |
| Rowokawuk           | 746        | 333 0 0            | 333           | 3,332,296                  | 2,620,889                  |
| Total               | 5,888      |                     | 5475          | 55,226,534                 | 52,660,664                 |
3.3.3. Water optimization with $K$-Factor = 1.00

![Figure 7. Water Balance with K-Factor = 1.0](image)

**Table 3.** Distribution of water irrigation with the Distribution Systems (K-Factor = 1.0) in Sempor Irrigation Area

| Sub Irrigation Area | Total area | Distribution Systems | Irrigated Area | Volume of Water Requirement | Volume of Water Availability |
|---------------------|------------|-----------------------|----------------|----------------------------|------------------------------|
|                      | ha         | 1 2 3                 | ha            | m$^3$                      | m$^3$                        |
| Bojong              | 2,599      | 0 1,983               | 0 1,983       | 20,962,049                 | 15,989,807                   |
| Watubarut           | 1,627      | 285 815              | 527 1,627     | 17,662,521                 | 17,662,521                   |
| Sindut              | 916        | 0 0 0                | 0             | 0                          | 0                            |
| Rowokawuk           | 746        | 0 746                 | 0 746         | 7,887,817                  | 7,887,817                    |
| **Total**           | **5,888**  |                       | **4356**      | **46,512,387**             | **41,540,144**               |

4. Conclusion

During the dry season, the pattern of operations for weirs is quite necessary for the purposes of water distribution system mostly when the water shortages. The pattern of water distribution with $K$-factor = 0.5 is better than $K$-Factor = 0.7 and $K$-Factor = 1.0 as the indication of the total area of irrigated land that can be reached. The allocation with the distribution systems has a considerable advantage in reducing the peak water requirements, since it demands a relatively low water management capacity due to continued flow and anticipating the knowledge of the cropping pattern calendar.

5. References

[1] Minister of Public Works Regulation No. 17/PRT/M/2015. (2015). Komisi Irigasi. Jakarta.

[2] Erdem, T., Erdem, Y., Orta, H., & Okursoy, H. (2006). *Water-Yield Relationships of Potato under Different Irrigation Methods and Regimens*. Journal of Science and Agriculture, 226-231.

[3] Hoffman, G.F., G., Howell T.A., T., & Solomon, K. (1990). *Management of Farm Irrigation System*. ASCE.
[4] Peter B. R. Hazell and Roger D. Norton. *Mathematical Programming for Economic Analysis in Agriculture*. Macmillan Publishing Company, 1986.

[5] S. Osama, M. Elkholy, and R.M. Kansoh, “Optimization of the cropping pattern in Egypt”, Alexandria Engineering Journal, 2017: 3-8, www.sciencedirect.com

[6] L.M. Limantara, M. Bisri, and F. Risq, “Optimization of water usage at irrigation area of Pakis-Malang regency-Indonesia by using linear programming”, International Journal of Engineering & Technology, 7(4), 2018, pp. 6432-6436

[7] P.T. Juwono, L.M. Limantara, and F. Rosiadi, “Optimization of irrigation cropping pattern by using linear programming: Case study on irrigation area of Parsanga, Madura Island, Indonesia”, Journal of Water and Land Development. No. 39, 2018, p. 51–60. DOI: 10.2478/jwld-2018-0058.

[8] L.M. Limantara, Suhardjono, Rispiningtati, S.F. Jadfan, and N. Secillia, “Water economic value of fresh water system in the Tanggunggunung village Indonesia”, International Journal of Geomat, Vol. 15, Issue 50, 2018, pp. 113-120

[9] Huang et al. (2010). *Irrigation water demand and implications for water pricing policy in rural China*. Environ. Develop. Econ, 15, 293–319.

[10] Oi, S. (1997). *Introduction to Modernization of Irrigation Schemes*. In: Modernization of Irrigation Schemes: Past Experience and Future Options. , F. , Rome: Food and Agriculture Organization

[11] Molden , D., Lautze, J., Shah , T., & Giordano, M. (2010). Governing to grow enough food without enough water. International . *Journal of Water Resource Development*, 26(2) 249-263.

[12] Pasandaran, E. (2005). *Reformasi Irigasi Dalam Kerangka Pengelolaan Terpadu Sumberdaya Air* [Irrigation Reforms in the Framework of Integrated Management of Water Resources]. Jakarta: Badan Penelitian dan Pengembangan Pertanian.

[13] Perry, C., & Allen, R. (2009). *Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities*. Journal of Agriculture Water Management, 96: 1517-1524

[14] B. Pavoni, A. Voinov. and N. Zhavora, “Basin (Watershed) approach as a methodological basis for regional decision making and management in the EX USSR”, Published on line in http://helios.unive.it/%7Eintas/gaboart.htm1. March 12, 2001.

[15] W. Soetopo, “Model-Model simulasi stokastik untuk sistem sumber daya sir (Stochastic simulation model for water resources)”, CV Citra Malang, 2012.

[16] Balai Besar Wilayah Sungai Serayu Opak, “Sempor Irrigation Study”,2016

[17] Montarcih, L., & Soetopo, W. (2009). *Pengantar Menejemen Teknik Sumber Daya Air* [Introduction to the Management of Water Resources Engineering]. Malang: CV. Citra.