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Optimization of Water Distribution in Pagerwojo District Tulungagung, Indonesia, using Linear Programming Model

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Abstract: Optimization approaches has been utilized in solving complex water service problems. This study attempts to determine the optimal distribution system for clean water pipelines by applying linear programming method which enables the determination of the optimal and most affordable solution under all constraints. The decision variable was the water quantity allocated to the system. The piping investment, operational and maintenance costs in present value with 4% interest were calculated to obtain the water unit price. The allocated water should meet the requirements within a dependable discharge. The study was conducted in Pagerwojo District, Tulungagung Regency, Indonesia, grouped into three transmission lines with 106 l/s demand. There are three sources of fresh water, namely Song River, Klantur River, and Gondang Spring. The analysis reveals that the minimum cost was Rp456,679,296/month. Linear programming method is proven useful for determining the allocation of clean water in the most cost-efficient manner.

Keywords: Linear programming; optimization; water distribution; water price.

Introduction

Providing adequate water supply for all users in a low-cost system is one of important issues in water resources management. To solve the complex water service problems, several optimization techniques have been implemented. The mathematical approach quantifies the ideal strategy for combining several water resources in achieving a particular goal. There have been numerous researchers in this field which considered the implementation of linear, non-linear, and dynamic programming methods in their studies [1-3]. Nonlinear optimization models can depict the complex system more accurately, but require higher computational demands [4]. Despite its efficiency, dynamic programming suffers from dimensionality problem where inaccuracy grows as the number of features increases [5]. Meanwhile, linear programming that identifies the optimal solution of inequalities using mathematical techniques in linear relationships is one of the most widely used techniques in tackling water allocation problems [6].

The rapid population growth in Pagerwojo District, Tulungagung Regency, Indonesia results in the limited access to adequate water for the community. However, there are several potential springs and rivers that can serve as municipal water sources. The district is located in the highest area of Tulungagung Regency and comprises of 11 villages with a total area of 88.22km^2. The elevation ranges from 250 to 1200 above mean sea level (AMSL). The peak of Mt. Wilis, which is in the same cluster with Mount Liman/Ngliman, is the highest point of this district. There are three potential water resources available in this region, i.e. Song River, Klantur River, and Gondang Spring, which will be able to fulfill the water demands for the 11 villages. For this purpose, the implementation of linear programming technique of water allocation is needed so that those limited water resources can be optimally distributed throughout the district. With current population of 30,680 and a growth rate of 1.15%, this region is challenged by safely managed water services.

A considerable amount of literature has been published on the use of linear programming to find the optimal water allocation solution [7-11]. In some recent studies, linear programming was used with some advancement in the method to solve various water problems. The variables considered in these studies are water quantity, energy reduction, and initial cost. However, there are still limited prior studies that added detailed water life-cycle costs including investment, operational, and maintenance costs as variables in the linear function.

This study examines the optimization formula using linear programming to obtain the minimum cost of clean water pipelines distribution system in Pagerwojo District, Tulungagung Regency, Indonesia. To plan the supply and distribution of water in a clean water project, in relation to the calculation of the unit price of water, several things must be considered, namely: (1) projections of future water demands in all villages; (2) technical feasibility of the available springs or rivers; and (3) proper transmission and distribution pipelines with adequate pressure.

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This is related to the water allocation, which is subject to water demands and available dependable discharges as the constraints. In this study, the output of the linear programming solution is the flow rate of allocated clean water in m^3/s. Meanwhile, the objective of the optimization is to minimize the total cost of water allocation. A mathematical linear formula was applied in this study to obtain the optimal solution. The results of this study can make an important contribution to the relevant authorities in designing cost-effective public water systems.

Methodology

Study Area

The study was conducted in Pagerwojo District, Tulungagung Regency, Indonesia, which spans between -7.884 to -8.048 S and 111.731 to 111.846 E. There are three potential water sources in this region, i.e. Song River, Klantur River, and Gondang Spring, with both Song River and Klantur River originating in Wilis Mountains. All of those three water sources are tributaries of Ngrowo River. Pagerwojo District itself comprises of 11 villages.

For efficiency reasons, the distribution network of clean water supply is generally considered to consist of transmission and distribution pipelines in most practical cases. In this study, 11 villages of Pagerwojo District were then grouped into three transmission systems, hereinafter referred to as the West Sector, Central Sector, and East Sector, according to the geographical location of the three water sources. The highest elevation is located in the North, making it easier to assign three vertical transmission lines. The first allocation point in the West Sector was Gondanggunung Village, followed by Kradinan Village and Sidomulyo Village. Meanwhile, the Central Sector began in Pagerwojo Village towards Samar Village, Mulyosari Village, Wonorejo Village, Kedungcangkring Village. Gambiran Village, Penjor Village, and Segawe Village were the areas served in the East Sector. Figure 1 shows the geographical location of Pagerwojo District, as well as its topographical map, water sources and their major tributaries, and the meteorological station.

Pipeline Design

The placement of the intakes in the three water sources and the arrangement of the three groupings of transmission system were designed mainly based on the topography of the region. Figure 2 presents the framework of the linear model of water allocation. Water was supplied from three sources *(S_i)* and allocated to three demand sectors *(D_j)* in certain quantity *(X_{ij})*, where *i* and *j* indicate the supply and demand points, respectively. The layout of the pipeline was designed by applying the principles of gravity flow water system. Then, the head loss was calculated using the Hazen-Williams formula [12]. The pressure at the points was analyzed by the Bernoulli equation [12] to ensure sufficient flow pressure to supply water under the permissible velocity. Furthermore, pipe and facility specifications were examined based on projections of future domestic, non-domestic, and fire protection water demands as well as water losses in 20 years.

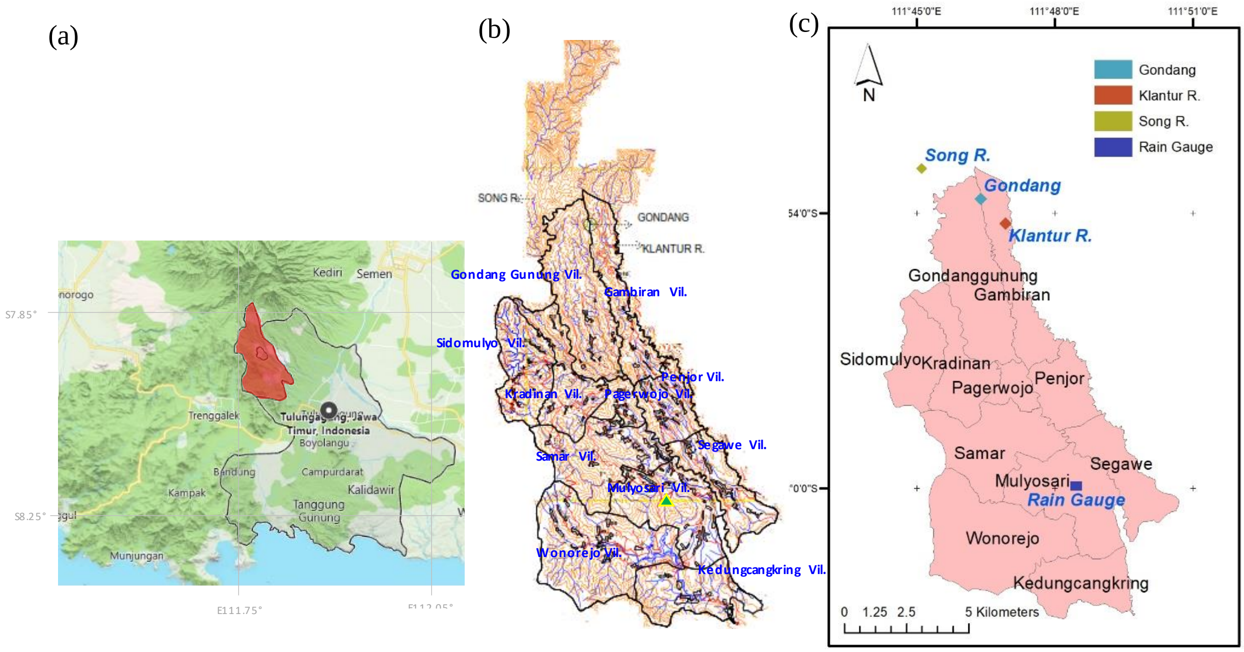

Figure 1. (a) A Map of Tulungagung Regency, with Pagerwojo District Marked in Red; (b) Topography of Pagerwojo District; and (c) Village Boundaries, Rain Gauge, and Water Sources

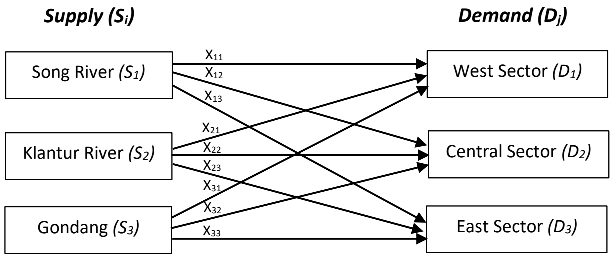

Figure 2. Framework of the Linear Model of Water Allocation

Dependable Discharge

One of the constraints in this optimization was the dependable discharge in the three sources. There was insufficient recording data of water level in the spring and the upstream part of the rivers. Therefore, the low-flow analysis method, namely the F.J. Mock method [13] was applied to calculate the discharge at the sources with 95% reliability. This method estimates the amount of discharge in a watershed based on the concept of a water balance. The followings are the steps of the analysis. First, rainfall data from Pagerwojo Station was analyzed to obtain monthly dependable rainfall using Basic Year method [14]. According to the Indonesian National Standard for river dependable discharge calculation [15], the availability of raw water should be calculated using the minimum reliability of 90%, hence leading to the application of the 95% reliability in this study. Second, the Blaney-Criddle method [16] was utilized to obtain the monthly evapotranspiration ET_0 using the following formula according to the vegetation cover in the catchment area:

$$ET_0 = p(0.457t + 8.128) \quad (1)$$

Where p is the mean daily percentage of annual daytime hours and t is the average temperature (°C). Third, the parameters to calculate the dependable discharge were determined, i.e., the infiltration coefficient, groundwater recession factor, initial groundwater storage, and soil moisture, whose values were 0.2, 0.4, 50 mm, and 100 mm, respectively. Fourth, the dependable discharge as surface runoff was calculated through several equations. Initially, the actual evapotranspiration was calculated by Equation (1). Furthermore, the subsurface water parameters consisting of soil storage and groundwater storage were calculated using Equations (2) to (4). By applying Equations (5) and (6), the water surplus that will contribute to surface runoff can be analyzed. Then, Equations (7) and (8) were used to calculate the infiltration rate and groundwater content. Base flow, or the portion of the stream flow that is continuously sustained in the river, is the difference between infiltration rate and groundwater content measured by Equation (9). Direct runoff can be obtained by subtracting water surplus with infiltration as in Equation (10). Finally, the discharge was obtained from base flow plus direct runoff as shown in Equation (11).

$$E_t = ET_0 - ET_0 \times \frac{m}{20}(18 - n) \quad (2)$$

$$s = P - E_t \quad (3)$$

$$GS = 50 \; for \; initial \; condition \; or = s \; if \; s < 0 \quad (4)$$

$$SMC = s + 50 \; if \; GS < 0 \; or = 50 \; if \; GS > 0 \quad (5)$$

$$WS = 0 \; if \; s + GS < 0 \; or = s + GS \; if \; S + GS > 0 \quad (6)$$

$$I = WS \times i \quad (7)$$

$$V = k \times (V_n - 1) + 0.5 \times (1 + k) \times I \quad (8)$$

$$BF = I - V \quad (9)$$

$$DR = WS - I \quad (10)$$

$$Q = BF + DR \quad (11)$$

Where E_t is actual evaporation, m is vegetation factor, n is rainy days, s is soil storage, P is precipitation with 95% dependable rainfall, GS is groundwater storage, SMC is soil moisture capacity, WS is water surplus volume, I is infiltration, i is infiltration coefficient, V is groundwater content, k is groundwater flow recession factor, BF is baseflow, DR is direct runoff, and Q is surface runoff.

Life Cycle Cost

In the life cycle cost analysis, cost comparisons for all alternatives were made over a 20-year economic lifetime while taking into consideration all important economic factors, in terms of costs, benefits, and interest rates. The life cycle cost comprises of initial costs of pipeline construction, system operation, replacement, and repair. From the Net Present Value (NPV) of the annual cost, the unit price of water per cubic meter within a specific period can be calculated for each water distribution route. Once the unit price of water is obtained, the value is introduced into the linear programming function.

Linear Programming Method

In the application of linear programming to this case, the decision variables are the allocated clean water supply (l/s) from each source to each sector. The objective function is to minimize the onsite water price (Rp) by multiplying the water tariff (Rp/l) with the allocated discharge (l/s). The constraints include water demands (l/s) in all sectors and available dependable discharge (l/s) in all sources. The problem formulations, including the minimization function and the constraints, are given in Equations 12 and 13, respectively.

$$Min \; Z = aX_{11} + bX_{12} + cX_{13} + dX_{21} + eX_{22} + fX_{23} + gX_{31} + hX_{32} + iX_{33} \quad (12)$$

Subject to constraints:

$$aX_{11} + dX_{21} + gX_{31} \geq D_1 \quad (13)$$

$$bX_{12} + eX_{22} + hX_{32} \geq D_2 \quad (14)$$

$$cX_{13} + fX_{23} + iX_{33} \geq D_3 \quad (15)$$

$$aX_{11} + dX_{12} + gX_{13} \leq S_1 \quad (16)$$

$$bX_{21} + eX_{22} + hX_{23} \leq S_2 \quad (17)$$

$$cX_{31} + fX_{32} + iX_{33} \leq S_3 \quad (18)$$

$$S_1 + S_2 + S_3 = Q_1 + Q_2 + Q_3 \quad (19)$$

$$X_{ij} \geq 0 \quad (20)$$

X_{ij} in Equation 20 is the decision variable, which is the volume of water distributed from the sources to the relevant sectors. The constants of a, b, c, d, e, f, g, h, i in the equations above are the water price (Rp/m^3). Meanwhile, S is the water demand in each sector (m^3/s) and Q is the dependable discharge for each source (m^3/s). After obtaining the constants, the objective function (Equation 12) is set to be minimized. The linear formulation is solved by utilizing NCSS 2021 statistical software that applies the Mixed Integer Programming Algorithm using the branch and bound algorithm [17].

Results and Discussions

Piping System and Water Demand Constraints

To obtain the initial cost of the piping system, the pipe layout is first designed. Figure 3 shows the pipeline system from Song River, Klantur River, and Gondang Spring to the West, Central, and East Sectors. The elevation and distance of Klantur River at the potential intake location to the nearest residential area are about 1050 AMSL and 2300m, respectively. Meanwhile, the watershed area is approximately 5,394 km^2. As for Song River, the distance to the nearest village is about 14,500 m, the catchment area of this river to the designed intake point is 38.264 km^2, and its elevation is 1150 AMSL. Gondang is a natural spring with a catchment area of 2.69 km^2, with the intake being at about 1000 AMSL. Meanwhile, the distance from Gondang Spring to the closest distribution point is about 3000 m.

To obtain the total water demand in all villages, the population is projected up to 2038 using the Arithmetic method. The water requirement is calculated by referring to the Indonesian National Standard for Water Balance of Spatial Water Resources no. 19-6728.1-2002 [18]. According to the standard, the water requirement for a village is 100 l/capita/day. Non-domestic water demand is assumed to be 20% of domestic water demand and the amount of water allocated for fire protection is 5% of domestic water demand. Meanwhile, the amount of water losses is 20% of the total consumption. The results of population and water demand calculations are presented in Figure 4, with the highest water demands being that of Samar Village and Mulyosari Village. The amount of water demand will be treated as a constraint for the linear formulation. The results of the calculations found the total water demand for the West, Central, and East Sectors being 19 l/s, 26 l/s, and 61 l/s, respectively.

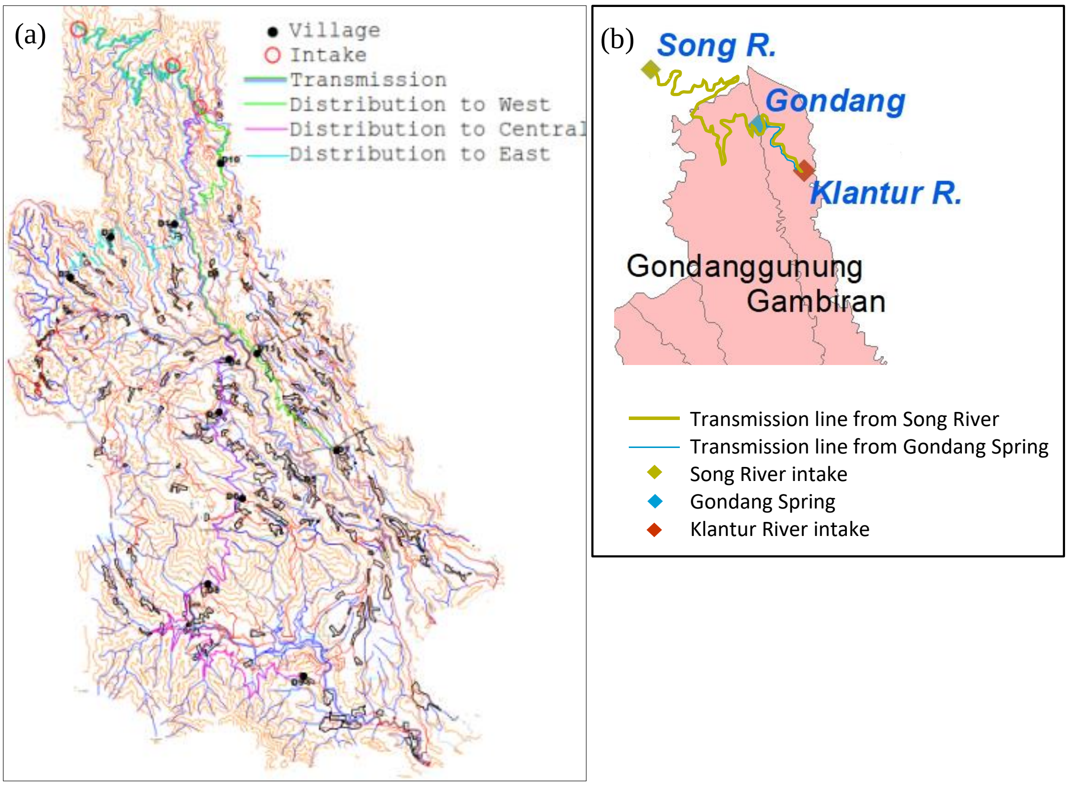

Figure 3. Layout of the Pipeline Showing the Distribution to All Villages (a) and Transmission from the Three Sources (b)

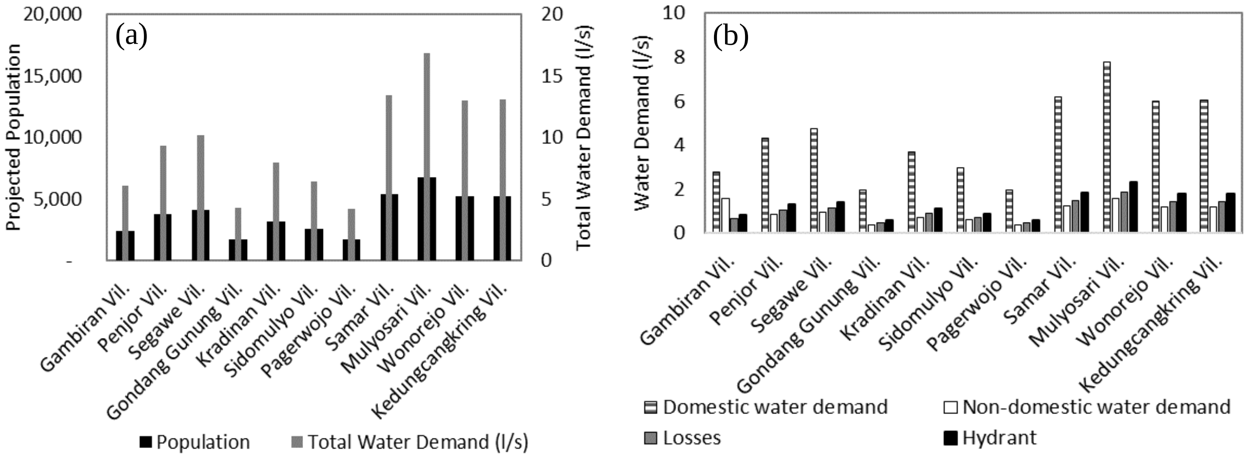

Figure 4. Population and Water Demand of All Villages

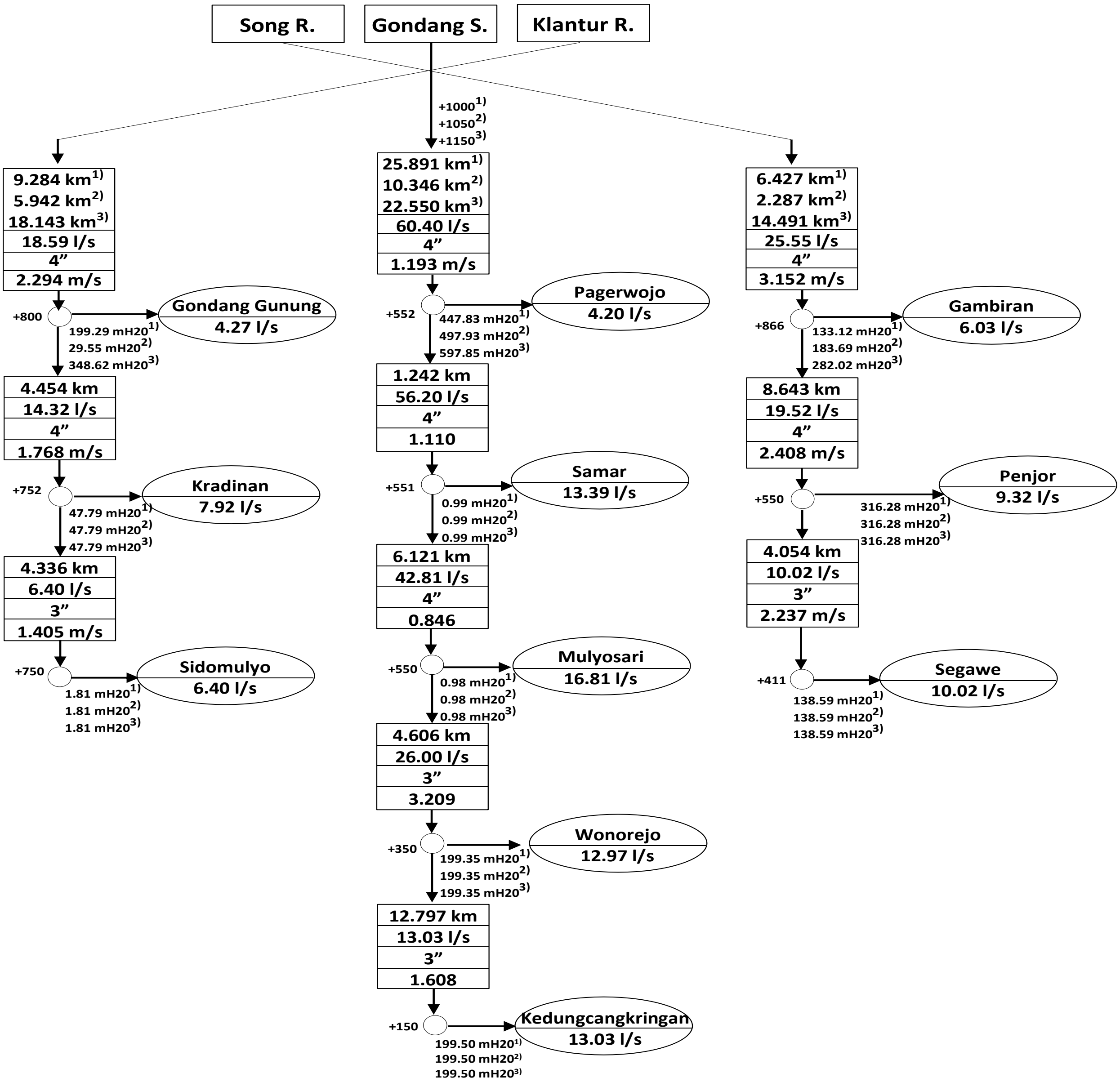

Figure 5. Pipeline Design. Superscript Numbers 1, 2, and 3 Refer to the Calculation Results for Gondang Spring, Klantur River, and Song River.

Table 1. Dependable Rainfall with 95% Dependability (P), Average Monthly Temperature (t), Evapotranspiration (ET_0), and dependable discharge with 95% dependability (Q)

	P95% (mm/month)	T (°C)	ET_0 (mm/day)	Q95% (l/s) Klantur R.	Q95% (l/s) Gondang S.	Q95% (l/s) Song R.
Jan	171	25.72	5.87	60.42	30.14	193.56
Feb	183	25.88	5.87	75.45	37.64	114.11
Mar	210	26.09	5.90	66.89	33.37	124.44
Apr	117	26.28	5.75	11.11	5.54	16.72
May	97	25.90	5.55	4.30	2.15	6.47
Jun	0	25.51	5.44	1.78	0.89	2.67
Jul	0	24.46	5.14	0.69	0.34	1.04
Aug	0	24.44	5.21	0.28	0.14	0.41
Sep	0	25.60	5.55	0.11	0.06	0.17
Oct	0	26.43	6.07	0.04	0.02	0.07
Nov	168	25.74	5.80	4.03	2.01	8.45
Dec	254	26.22	6.03	133.39	66.53	280.06

Figure 5 displays the results of the analysis of obtained hydraulics parameter and pipe specifications, namely: discharge, velocity, pressure, elevation, pipe length, and pipe diameter. The results indicated that all flows from the three sources to the three sectors meet the required flow velocity and flow pressure.

Discharge Constraint

The calculation of the dependable discharge using the F. J. Mock method was performed in monthly period. The results obtained from the dependable rainfall, evapotranspiration, and dependable discharge analyses are presented in Table 1. The parameters used in the analyses are infiltration coefficient of 0.2, groundwater recession factor of 0.4, initial groundwater storage of 50 mm, soil moisture capacity of 100 mm, and vegetation factor of 40%. The average dependable discharge is defined as a constraint for the linear formulation, which is 30 l/s, 15 l/s, and 63 l/s for Klantur River, Gondang Spring, and Song River, respectively.

Water Supply Cost

The initial costs of pipeline construction are calculated based on the designed pipeline including tax. After obtaining the construction costs, the operational and maintenance costs are then calculated, which are assumed to be 0.9% and 1.3% from the investment cost according to the Regulation of the Minister of Public Works and Housing no. 18/PRT/M/2015 [19]. Table 2 shows the total project construction costs as well as the annual operational and maintenance costs. The water price to compensate the life cycle cost of the project calculated in NPV with predetermined discount interest rates is presented in Figure 6. The results show that the pipeline construction from Song River to Central Region has the highest investment cost since it is the longest route. Meanwhile, the lowest investment cost is for the pipeline construction from Klantur River to West Region, because the distance is also the shortest.

Table 2. Construction, Operational, and Maintenance Costs

	Initial Cost (Rp)	Operational Cost (Rp/year)	Maintenance Cost (Rp/year)
Klantur to East	7,369,460,922	66,325,148	95,802,992
Klantur to West	7,143,479,387	64,291,314	92,865,232
Klantur to Central	36,521,319,530	328,691,876	474,777,154
Song to East	14,340,397,423	129,063,577	186,425,167
Song to West	14,307,492,431	128,767,432	185,997,402
Song to Central	56,629,855,525	509,668,700	736,188,122
Gondang to East	9,658,570,063	86,927,131	125,561,411
Gondang to West	9,181,721,749	82,635,496	119,362,383
Gondang to Central	59,745,552,770	537,709,975	776,692,186

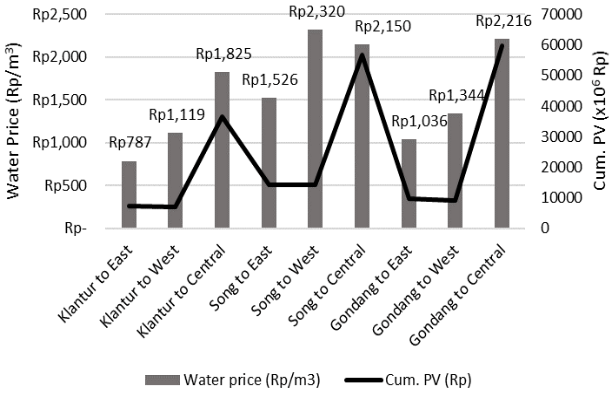

Figure 6. Present Value of Life Cycle Cost (line) and the Water Price (bar). The Price Remarks are the Water Prices in IDR

In terms of the unit price of water, the allocation from Song River to West Sector resulted in the highest cost, which was Rp2320/m^3, while the allocation from Klantur River to East Sector had the lowest cost, i.e. Rp787/m^3. These results are in line with those reported in the Standard Cost of Drinking Water Usage for Customers in Tulungagung Regency, which ranges from Rp2562 to Rp6005 per m^3. The differences in those costs are explainable by the inclusion of profits in the official water tariff from the state-owned water utility company. In the final stage of the analysis, the dependable discharge, water demand, and water tariff are introduced to the linear formulation for optimization analysis.

Water Allocation

The objective functions, constraints, and decision variables including the supply and demand in l/s are summarized in Table 3. A linear programming solver was applied to find the optimal solution. Table 3 displays the results of water volume distributed from the three water sources to the three sectors that will minimize the total distribution costs while meeting the water demand of each sector and remaining within the amount that can be supplied from each water source.

Table 3. The Values of Constraint (l/s) and Decision Variables (Rp/l), as Well as the Optimal Solution Shown in the Parentheses

	Song River	Klantur River	Gondang Spring	Demand (l/s)
West Sector	2.320	1.119 **(4)**	1.344 **(15)**	19
East Sector	1.526	0.787 **(26)**	1.036	26
Central Sector	2.150 **(61)**	1.825	2.216	61
Supply (l/s)	63	30	15	

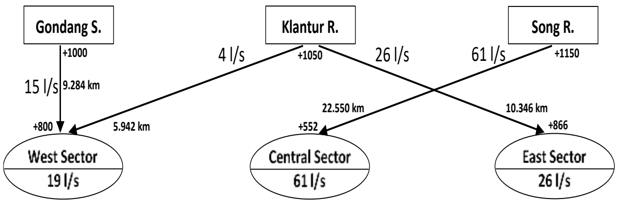

Figure 7. The Optimal Water Allocation Scenario

Gondang Spring with an availability of 15 l/s will supply water to the West Sector. However, since the water demand of the West Sector is not fulfilled, Klantur River will contribute 4 l/s to this sector. The remaining water available in Klantur River will be transmitted to the East Sector. As for the Central Sector, the water demand of 61 l/s will be fulfilled entirely by Song River. There is a remaining of 2 l/s in the discharge of Song River. Results as seen in Table 3 were then used to calculate the total cost of water allocation, which was Rp176.19/s or Rp456,679,296/month. Figure 7 presents the detailed water supply scenario at a minimum cost.

In this study, it should be noted that the water sources were assumed to be used only as public water supply, while other downstream utilizations such as irrigation, flood control, and stream maintenance were neglected. Therefore, future studies on the inclusion of these water utilizations in a linear function are highly recommended. In addition, due to practical constraints, the optimization discussed in this study disregarded the changes in piping costs due to the shared water allocation. In regard to the water allocation problem discussed in this study, this study has important implications to find out the best scenario where the available water sources must be combined in a cost-minimizing manner.

Conclusions

The aim of the current study is to determine the optimal distribution system of clean water pipelines using linear programming in Pagerwojo District Tulungagung Regency, Indonesia. In this district, three fresh water sources, namely Klantur River, Song River, and Gondang Spring, are distributed to three sectors. The calculations of domestic, non-domestic, and fire protection water demands as well as water losses indicated the corresponding water requirement for each sector of 19 l/s, 26 l/s, and 61 l/s. Dependable discharge analysis using F.J. Mock method showed the water availability of 63 l/s, 30 l/s, and 15 l/s for Song River, Klantur River, and Gondang Spring, respectively. The results of the life cycle cost analysis showed that the unit price of water ranged from Rp787 to Rp2320 per m^3. The optimization algorithm projected that the West Sector will be supplied by Gondang Spring at 15 l/s and by Klantur River at 4 l/s. Meanwhile, the East Sector will be fully supplied by Klantur River. As for the Central Sector, the water demand of 61 l/s will be fulfilled by Song River. The analysis revealed that the minimum cost of water distribution is Rp456,679,296/month. The implication is that it is possible to apply the results of this study in determining the best clean water allocation scenario for Pagerwojo District efficiently. Furthermore, it is advisable for future studies to include the constraints of other water demands in the linear formulation using multi-criteria decision support systems. In addition, further analysis on the redesign of the water infrastructure corresponding to the optimal solution that will affect the total life cycle cost will help to make decisions with a greater degree of accuracy.

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