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Simulation of Multi Reservoir Operation Rules with Interconnected Tunnel and Water Transfer

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Keywords: multi-reservoir, interconnected tunnel, storage capacity, operation rule, simulation

Introduction
Managing Water Resources requires a comprehensive study indeed. Water resource management is carried out to overcome problems such as flooding, meeting domestic water demand, irrigation, and water quality (Iqbal et al., 2020b). Extensive management is required for unequal water supply. A reservoir retains water during the rainy season for later use (Lasdon et al., 1974). One of the solutions that are often used in managing water resources is by building dams. The practical application scenarios of reservoir operation are extremely complex and involve multiple time scales and multi-flow regimes, often accompanied by occasional emergencies (Zhang et al., 2018). In a river flow, the construction of multiple reservoirs is possible. This condition causes the release of water in the upstream reservoir to become water input to the downstream reservoir (Heydari et al., 2015), (Lund & Guzman, 1999), (Nandharata & Dasanto, 2011), (Pera, 2018).
Multi-reservoir operating policies are usually defined by rules that specify either individual reservoir desired (target) storage volumes or desired (target) releases based on the time of year and the existing total storage volume in all reservoirs (Oliviera & Loucks, 1997). The function of the reservoir largely determines Reservoir Operation. Besides that, the management pattern becomes a reference in decision-making in extreme conditions such as floods or droughts. Joint operating rules are also proposed based on a water diversion rule, a hedging rule based on an aggregated reservoir, and a storage allocation rule (Fang et al., 2014).
To obtain the appropriate operating rules, a new set of release rules for each reservoir is made to analyze the optimal conditions of water balance and reservoir value in each reservoir (Zeng et al., 2015). Water Transfers between Watersheds are usually considered one of the most effective facilities for balancing non-uniform temporal and spatial distributions between water resources and demand. This is done to divert water from excess areas to areas with fewer resources (Gao et al., 2017), (Iqbal et al., 2021). Several methods of operating reservoirs


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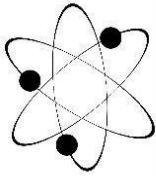
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Multi-reservoir operating policies are usually defined by rules that specify either individual reservoir desired (target) storage volumes or desired (target) releases based on the time of year and the existing total storage volume in all reservoirs (Oliveira & Loucks, 1997). The function of the reservoir largely determines Reservoir Operation. Besides that, the management pattern becomes a reference in decision-making in extreme conditions such as floods or droughts. Joint operating rules are also proposed based on a water diversion rule, a hedging rule based on an aggregated reservoir, and a storage allocation rule (Fang et al., 2014).

To obtain the appropriate operating rules, a new set of release rules for each reservoir is made to analyze the optimal conditions of water balance and reservoir value in each reservoir (Zeng et al., 2015). Water Transfers between Watersheds are usually considered one of the most effective facilities for balancing non-uniform temporal and spatial distributions between water resources and demand. This is done to divert water from excess areas to areas with fewer resources (Gu et al., 2017), (Iqbal et al., 2021). Several methods of operating reservoirs

with additional water from other watersheds have long been developed. A multi-reservoir operation pattern can be developed by transferring water and maximizing or minimizing the function of the reservoir operation. Objective functions that can be used as a reference include minimizing runoff and maximizing water availability patterns, minimizing the risk of water shortages, maximizing profits from agricultural products, and minimizing water transfer costs. (Guo et al., 2012), (Rani et al., 2014).

Kamal (2016) optimized the operation of the Rukoh Reservoir by utilizing additional supplies from Krueng Tiro. The amount of suppletion discharge is taken by comparing the area of irrigation to be served. The area to be served is 5,803 ha in DI Baro, which is an area that has not been irrigated under current conditions. The operating system of the Rukoh Reservoir with reservoir inflow depending on water supply from Krueng Tiro has the potential to cause a conflict of interest in the reservoir service area if the water supply is not sufficient to meet the water demand in the operation of the reservoir (Azmeri, Iwan K Hadihardaja, Nina Shaskia, 2017).

A water supply from the Kr River accompanies the Rukoh Reservoir's potential reservoir. Tiro is predicted to be able to meet the water demand of the Pidie Regency's Baro Irrigation Area. The simulation method prepares operating rules for constructing the Tiro and Rukoh reservoirs. This method uses inflow data, a synthetic discharge generated by rainfall generation, by using reservoirs for irrigation, raw water, river maintenance, and electricity generation. The assumption is that the two reservoirs are one unit. Hence, the sum of the two reservoirs is the inflow discharge, reservoir capacity, and outflow discharge. (Association of Sumatera Water Region I, 2015).

Utilizing the storage capacity of multi-reservoirs and connecting tunnels, the goal is to maximize water availability. Water loss in the analysis is only calculated as a result of evapotranspiration. The reservoir operation rules are adjusted the water availability during the dry, regular, and rainy seasons.

Materials and Methods

Technical Data of Reservoir

The Rukoh and Tiro dams are in Pidie District, Aceh Province, Indonesia. Each dam aims to provide raw water and irrigation needs. The Baro Irrigation area is 11,950 ha, where the irrigation demand at Intake is 14.50 m³/s taken from the Baro River. The water demand of the Tiro Irrigation area (6,330 ha) is sourced from the Tiro River. The dependable discharge of Baro River is 2.52 m³/s, Tiro River is 1.89 m³/s, and Rukoh River is 0.77 m³/s. The condition of dependable discharge caused only 6417 hectares of Baro Irrigation land to be covered. Likewise, the area of Tiro irrigation can only be served 2463 hectares. The condition is decreasing in the dry season (Association of Sumatera Water Region I, 2015).

Table 1. Technical Data of Rukoh and Tiro Reservoir

Reservoir	:	Tiro	Rukoh
Catchment area (km ²)	:	174.24	19.63
Maximum of Normal Water Level (NWL) (m)	:	122.00	122.00
Gross Storage (With Sediment) (MCM)	:	41.4	128.65
Effective Storage (MCM)	:	37.66	124.4
Dead Reservoir +103,00 Elevation (MCM)	:	3.78	4.24
Tunnel (TWL) (m)	:	+112	+112

Reservoir technical data is used as a constraint parameter in the simulation process. Storage capacity constraint parameters are limited to tunnel elevation as minimum elevation and spillway elevation as maximum elevation.

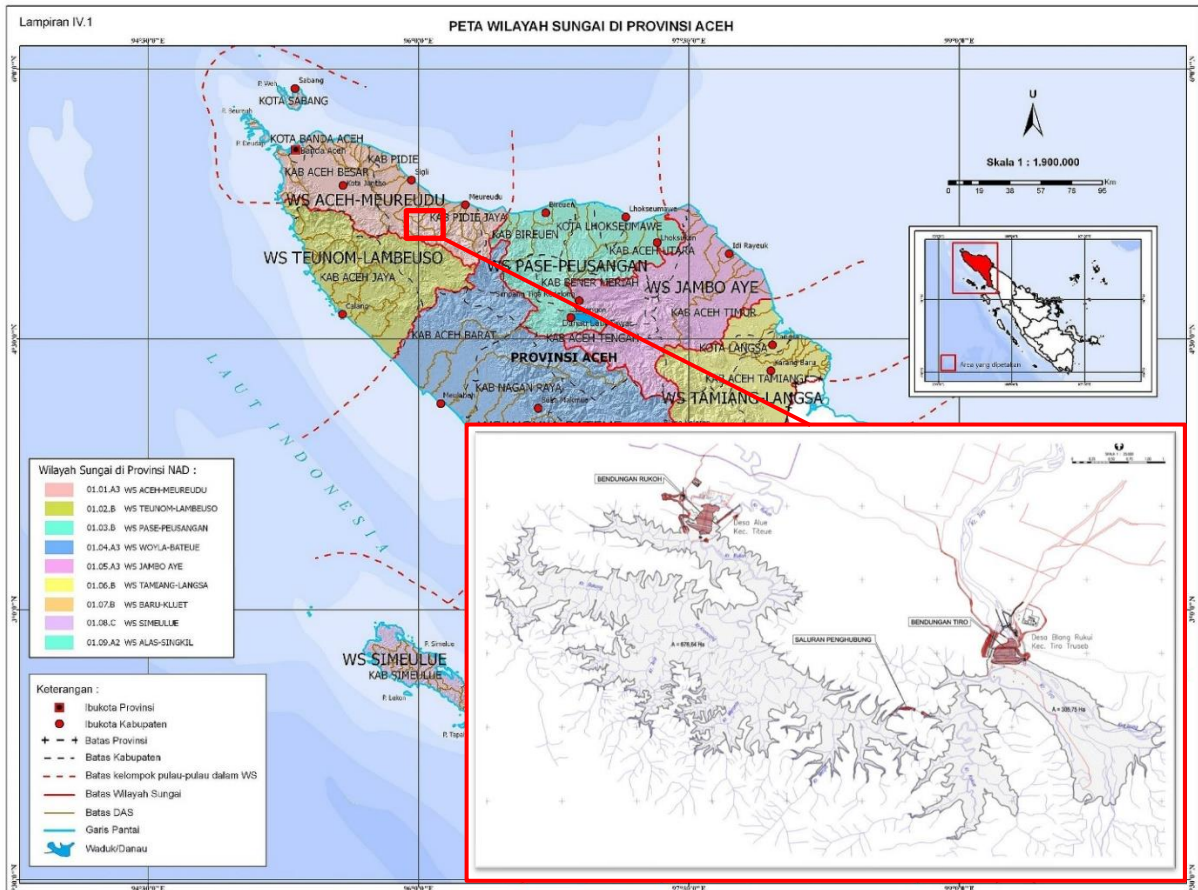


Figure 1. Location of Rukoh Tiro Reservoir

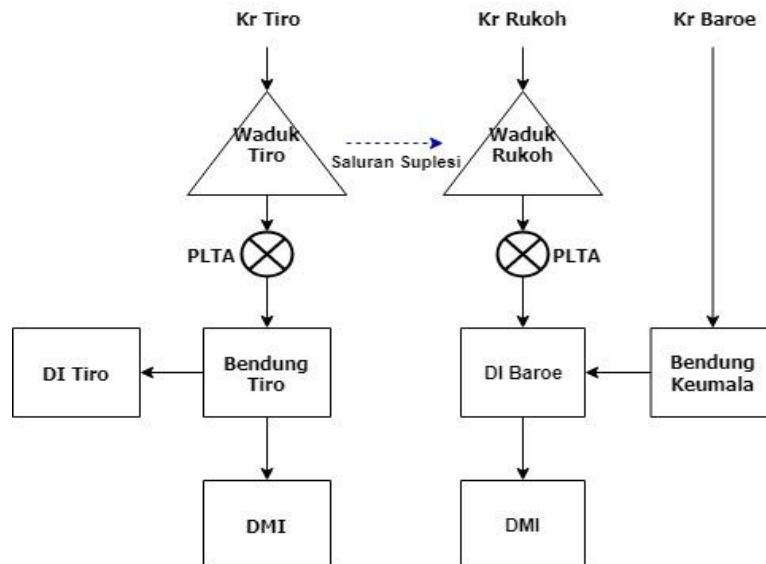


Figure 2. Rukoh Tiro Multi Reservoir with Interconnected Tunnel Scheme

An interconnecting tunnel between the reservoirs causes water transfer (suppletion) caused by fluctuations in the inflow and outflow of each reservoir. It was planned to be at an elevation of 112 m. With this scheme, only one unit of Intake and outflow is planned. So, the outflow of the reservoirs based on the needs of irrigation water, raw water, and maintenance will also be used to turn turbines for electricity generation.

Inflow Scenario

The use of reservoir inflow discharge follows a variety of possible water conditions, from excess to water shortage. The goal is to calculate the demand for supplied water based on a reliable inflow pattern scenario, Wet Seasons (20% probability), Normal Seasons (50% probability), and Dry Seasons (80% probability). Data was taken from Water Level Recorder of Gampong Jojo in Mutiara Sub-District. This location became a reference point of watershed area for calculating monthly average discharge based on the ratio of watershed area. Analysis of water availability was carried out using the FJ Mock method by generating rainfall data. The data is then calibrated using the existing AWLR recording data.

A reliable determination of the probability of discharge is carried out using the equation:

$$Pr = \frac{m}{n+1} \times 100 \% \tag{1}$$

Where: Pr = Probability (%); *m* = Sorted data; *n* = Number of data.

Water Demand

By the function of each reservoir, the water demand that must be provided includes the following:

River Maintenance Flow: river protection is also carried out for river maintenance flow to protect the river ecosystem. It is taken from the availability of reliable discharge of 95%.

Irrigation water demand, according to the irrigation area and the planned cropping pattern in both reservoirs. According to existing conditions and development plans, the area of irrigation to be served by the Tiro irrigation area is 6330 hectares, and the Baroe irrigation area is 11950 hectares. The cropping pattern used in the analysis is paddy-paddy-secondary crops.

The following equation can calculate the need for irrigation water at the intake gate:

$$Dr = \frac{NFR}{efx8,64} \tag{2}$$

$$ef = ef1 \times ef2 \times ef3 \tag{3}$$

where *Dr* = Requirement of irrigation water at intake point (m³/s), *NFR* = Requirement of irrigation water on agricultural land (lt/s/ha), *Eff* = Efficiency of irrigation (%), *ef1* = Main Channel Efficiency (90%), *ef2* = Secondary Channel Efficiency (90%), *ef3* = Tertiary Channel Efficiency (80%).

Urban water demand is calculated based on the total use of the population, industry, and livestock. In this case, water use for fisheries/ponds is not accounted for. According to data from the Central Statistics Agency for 2018, the population of Pidie Regency is 390,150 people in the medium city category. So, the water demand as a reference in this study is 105 l/people/day. The total population that will be served by the operation of the Rukoh and Tiro dams is 40% of the population of Pidie Regency.

Evaporation and Seepage

Evaporation is water loss, which reduces the volume of water stored in a reservoir. Therefore, the evaporation is a function of the surface area of the reservoir water inundation. Meanwhile, water loss due to seepage results from the potential analysis that may occur under the dam's condition. The evaporation value is calculated according to the operating rule analysis reference time, namely the one-month cumulative value. Furthermore, by adjusting the water surface area of the reservoir each month, the amount of evaporation volume that occurs during one month is obtained.

Table 2. Distribution of City Status and Domestic Water Demand

Category	Number of Population	Water Use (L/people/day)
Metropolitan city	> 1,000,000	150
Big city	500,000 – 1,000,000	135
Medium city	100,000 – 500,000	120
Small City	20,000 – 100,000	105
Village/Rustic	< 20,000	82.5

Source: *National Standardization Agency (2015)*

The amount of evapotranspiration depends on climatological factors such as air temperature, air humidity, wind speed, and solar radiation. Evapotranspiration was calculated using the modified Penmann method.

$$ET_0 = c [W.R_n + (1-W) f(u) (e_a - e_d)] \tag{4}$$

$$R_n = (1-a) R_s - R_{n1} \tag{5}$$

$$R_s = R_a (0,25 + 0,50 n/N) \tag{6}$$

$$R_{n1} = f(T) \cdot f(e_d) \cdot f(n/N) \tag{7}$$

$$f(u) = 0,27 (1 + U/100) \tag{8}$$

$$e_d = e_a \times RH/100 \tag{9}$$

Where: ET_0 = evapotranspiration. potential (mm/day); c = adjustment factor, influenced by weather conditions day and night; W = factor affected by temperature and altitude; R_n = net radiation (mm/day); $f(u)$ = average wind speed measured at a height of 2 m (km/day); e_a = air vapor pressure (mbar); e_d : saturated vapor pressure (mbar); a = the number of reflected solar radiation for albedo reference plants, taken $a = 0.25$; R_s = solar radiation (mm/day); R_{n1} = net longwave radiation (mm/day); R_a = solar radiation based on latitude (mm/day); $f(T)$: temperature-dependent factor; $f(e_d)$ = factor that depends on saturated steam; $f(n/N)$ = factors that are influenced by the length of sunlight; U = wind speed measured at a height of 2 m (km/day); and RH = relative humidity (%).

Simulation Operation Rules Model

The primary function of the reservoir is to provide storage, so the physical characteristics considered very important are storage capacity. The form of the storage equation that is often used for reservoir operations is the continuity equation, which provides a relationship between input, output, and changes in storage, which is called behavior analysis (simulation model) as in the following flowchart:

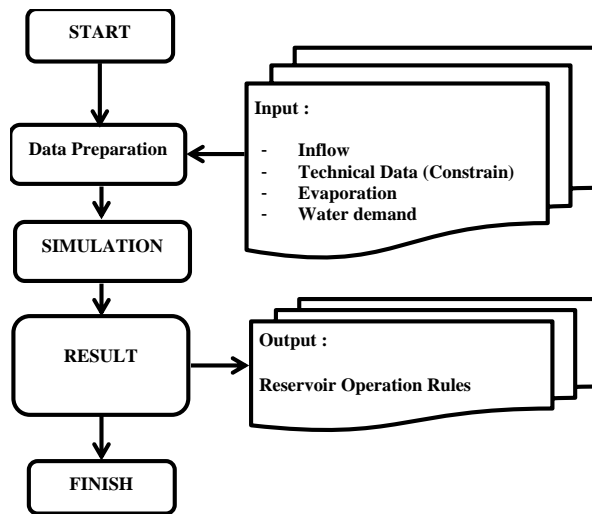


Figure 3. Simulation Process

The data input in the simulation is reliable debits for various seasons, evaporation, and water demand. At the same time, the output is in the form of a graph of the reservoir and water level elevation of the reservoir in one period of the operating season.

The reservoir operation modeling for conservation purposes is based on the water balance for the time interval (Limantara, 2010).

$$V_t = V_{t-1} + Total\ Inflow - Total\ Outflow \tag{10}$$

$$STr_t = STr_{t-1} + ITr_t - LTr_t - DivTr_t(x) - \sum DTr_t(y) - SpillTr_t(x, y) \tag{11}$$

$$SRk_t = SRk_{t-1} + IRk_t - LRk_t + DivTr_t(x) - \sum DRk_t(y) - SpillRk_t(x, y) \tag{12}$$

Where V_{t-1} = Reservoir volume in periode t-1 (m³), V_t = Reservoir volume in periode t (m³), IR = irrigation water requirement, S_t = initial storage in periode t (m³), S_{t-1} = storage in the end of periode t (m³), I_t = Inflow periode t (m³), L_t = water loses in periode t (m³), $D_{i,t}$ = volume of water transfer in periode t (m³), D_t = water demand in periode t (m³), $S_{p,t}$ = Volume of Spillway in periode t (m³), T_r = Tiro and R_k = Rukoh.

Water Transfer

The management of water resource distribution between the receiving watershed and the donor watershed is the main concept of water transfer. Physical relationships between watersheds can be an element in facilitating the joint water management benefit of both watersheds (Bekchanov et al., 2016). Water transfer has three dimensions. First, water can be transferred from one user (donor) to another (recipient). It is shown in the potential discharge of the donor river. Second, the temporal dimension in which alternative forms of water storage (groundwater recharge, natural or manmade reservoir) increase water availability in the dry seasons by storing the excess water received during the rainy seasons. Third is the spatial dimension involving water transfer from one location to another using groundwater pathways, natural waterways, canals, and/or pipelines (Gichuki & McCornick, 2008). The main objective of water transfer is to reduce water scarcity for domestic and agriculture, hydropower generation, navigation, and improving water quality (Misra et al., 2007).

The potential discharge that can be diverted from the Tiro River is large. The reservoir capacity and inflow of the two rivers are the rules of the joint operation. The Rukoh and Tiro interconnecting tunnel is 120 meters in length and 4 meters in diameter. The largest volume of water can be utilized between July and November. In the dry season, the total volume of water from the Tiro River reaches 147.31 MCM. In the regular season, the water volume is 176.61 MCM. Meanwhile, for the rainy season, water volume reached 221.17 MCM (Iqbal et al., 2020a).

Results

The operating rules follow the inflow discharge scenario described previously. The operation rules start from January with the surface in complete condition at an elevation of +121.57, and the elevation at the end of the year is the same as the elevation at the beginning of the year.

Dry Seasons Operation Rules

In the dry season operating rules, the tunnel has an open flow. This condition occurs from June - August. However, the water level is still above the ground level of the tunnel at +112 m.

Table 3. Rukoh-Tiro Simulation (Dry Seasons)

Description	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Inflow (MCM)	36,80	21,08	30,12	33,72	22,13	8,24	8,04	11,37	15,10	27,94	43,12	45,76
Total Demand (MCM)	20,93	27,86	56,87	40,48	31,86	9,82	8,67	16,98	5,35	48,47	31,18	40,39
Water Volume (MCM)	165,86	159,08	132,33	125,57	115,84	114,26	113,62	108,01	117,76	145,32	157,26	165,86
Water Elevation (m)	121,57	120,87	117,99	117,17	116,00	115,80	115,71	114,98	116,24	119,43	120,69	121,57
Spillout (MCM)	0,00	0,00	0,00	12,65	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

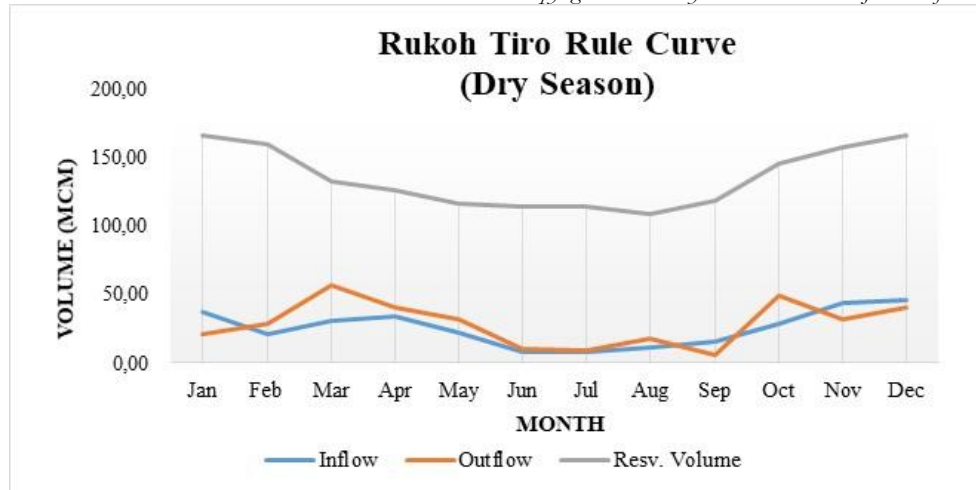


Figure 4. Rukoh-Tiro Operation Rule Simulation (Dry Season)

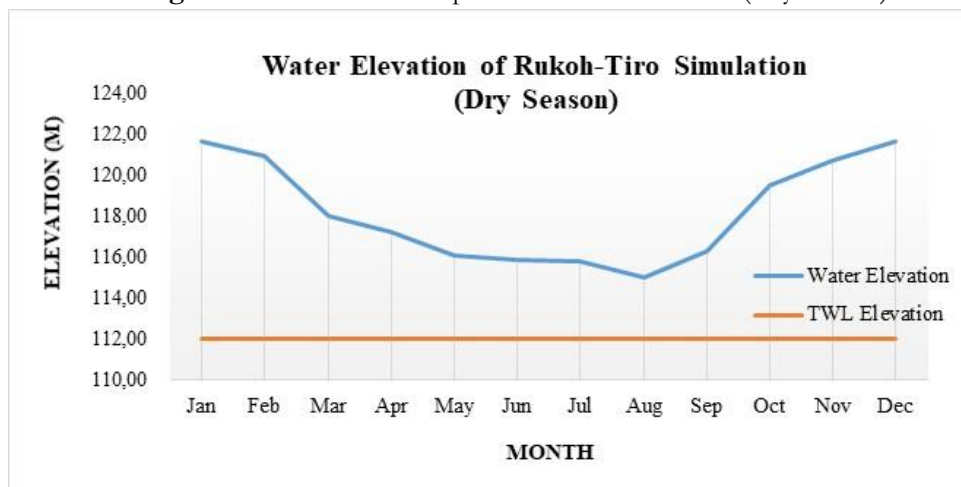


Figure 5. Water Elevation of Rukoh-Tiro Operation Rule Simulation (Dry Season)

The peak elevation of the spillway is planned to be at + 121.57 m, and the base elevation of the supply channel is at + 112.00 m. The maximum storage capacity of both reservoirs is 165.68 MCM, which is as high as the top of the spillway. This value is the basis for limiting the simulations carried out apart from the inflow and outflow discharge amount as needed.

The simulation is carried out by releasing water for irrigation, raw water, and river maintenance. The simulation limits the volume of water or the elevation of the reservoir's water level at the beginning and end of the season. Table 3 shows that the most significant inflow volume during the dry season occurred in December, which was 45.76 MCM, and the smallest inflow volume occurred in July, which was 8.04 MCM. Meanwhile, the maximum water demand for this season occurs in October, which is 48.47 MCM, and the minimum water demand occurs in September, which is 5.35 MCM. There are water transfer processes during this seasonal period. This can be seen from the elevation of the water level, which is still above the base elevation of the supply channel.

The simulation results in the dry season show that the operation of the two reservoirs simultaneously can meet irrigation needs with a cropping intensity of up to 100% in both the first growing season (MT I) and the second growing season (MT-II). The release of water for river maintenance is the basis for analyzing the resulting energy production. It can be seen in Table 3 that there was a runoff in April of 12.65 MCM. The large volume of this runoff becomes an additional discharge to produce energy.

Normal Seasons Operation Rules

In the normal season operation rule with 50% percent water availability, river maintenance requirements discharge follows the amount of availability.

Table 4. Rukoh-Tiro Simulation (Normal Seasons)

Description	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Inflow (MCM)	43,07	37,72	37,05	42,23	22,78	9,78	9,67	14,62	16,20	35,61	47,00	53,03
Total Demand (MCM)	21,22	28,61	57,21	40,90	31,96	9,96	8,83	17,21	5,48	48,82	31,38	40,74
Water Volume (MCM)	165,86	165,86	145,70	147,03	137,84	137,66	138,50	135,91	146,63	152,64	165,86	165,86
Water Elevation (m)	121,57	121,57	119,47	119,61	118,60	118,58	118,67	118,38	119,57	120,22	121,57	121,57
Spillout (MCM)	0,00	2,41	12,29	21,85	9,12	0,00	0,00	0,00	0,00	0,00	0,00	0,00

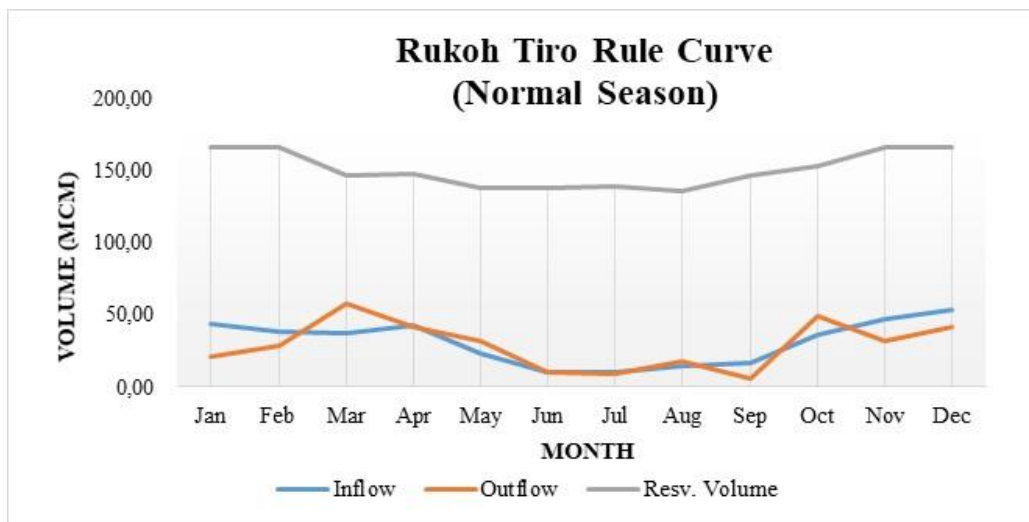


Figure 6. Rukoh-Tiro Operation Rule Simulation (Normal Season)

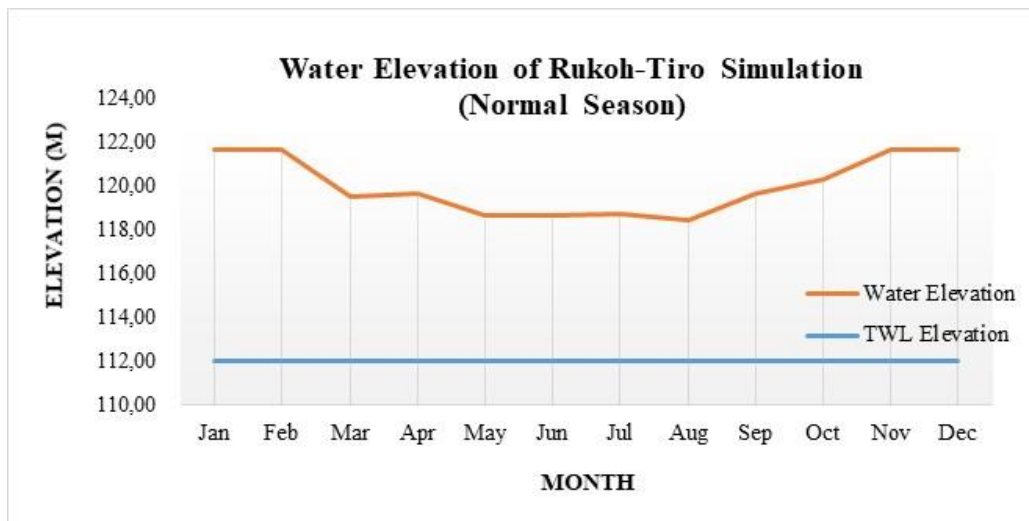


Figure 7. Water Elevation of Rukoh-Tiro Operation Rule Simulation (Normal Season)

Table 4 shows that the largest inflow volume during the dry season occurred in December, 53,03 MCM, and the smallest inflow volume occurred in July, 9,67 MCM. Meanwhile, the maximum water demand for this season occurs in March, which is 57,21 MCM, and the minimum water demand occurs in September, which is 5.48

MCM. There are water transfer processes during this seasonal period. This can be seen from the elevation of the water level, which is still above the base elevation of the supply channel.

The reservoir's water level is at a maximum position of + 121.57 m, occurring in January, February, November, and December. while the lowest reservoir water level occurs in August, at an elevation of +118.38 m. The simulation results show that the water level during the normal season period is still above the base elevation of the connecting channel, namely + 112.00 m, so the water transfer process occurs throughout the year.

Wet Seasons Operation Rules

The reservoir operation rules in the wet season follow the water availability discharge of 80%. The amount of water demand is the same for all seasons except for river maintenance discharge. Following are the operating rules analysis result for the wet seasons.

Table 5. Rukoh-Tiro Simulation (Wet Seasons)

Description	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Inflow (MCM)	53,33	42,81	42,24	48,87	23,17	10,98	11,02	17,46	17,40	38,46	53,73	58,27
Total Demand (MCM)	21,68	28,84	57,44	41,22	32,02	10,06	8,93	17,39	5,59	48,95	31,69	40,98
Water Volume (MCM)	165,86	165,86	150,65	158,31	149,46	150,38	152,47	152,54	164,35	155,37	165,86	165,86
Water Elevation (m)	121,57	121,57	120,01	120,80	119,88	119,99	120,20	120,21	121,41	120,50	121,57	121,57
Spillover (MCM)	0,00	11,55	17,29	31,65	13,97	0,00	0,00	0,00	0,00	0,00	0,00	0,00

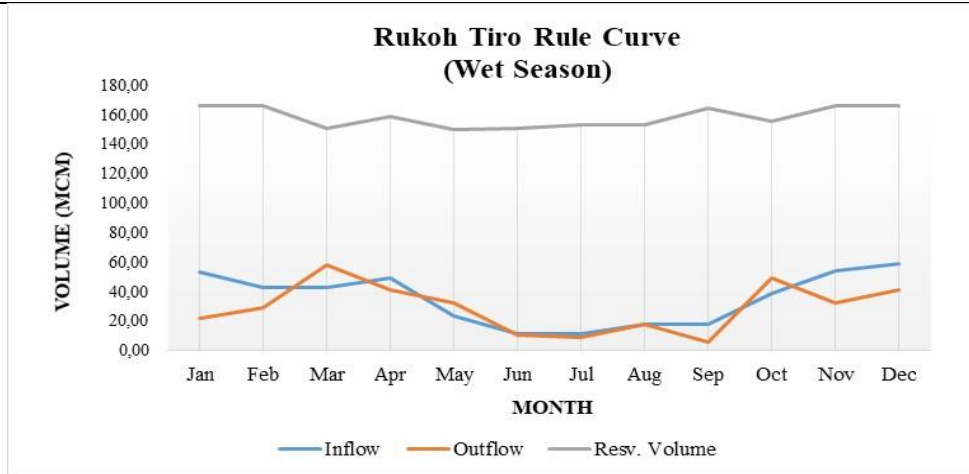


Figure 8. Rukoh-Tiro Operation Rule Simulation (Wet Season)

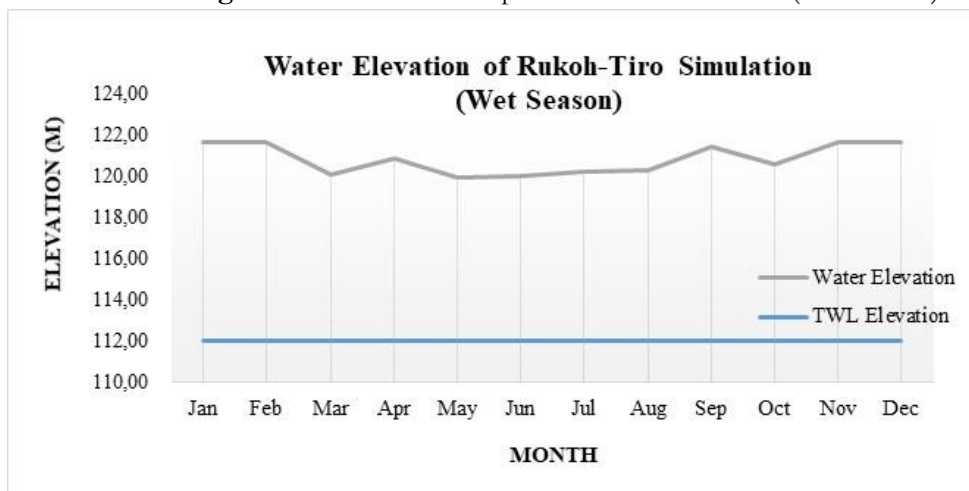


Figure 9. Water Elevation of Rukoh-Tiro Operation Rule Simulation (Wet Season)

The volume of reservoir inflow in the lowest wet conditions was in June, amounting to 10.98 MCM. The lowest water demand was 5.59 MCM in September. Meanwhile, the maximum water demand for this season occurs in March, which is 57,44 MCM, and the minimum water demand occurs in September, which is 8.93 MCM. The reservoir volume is packed during the four months of the seasons, while the other eight months vary according to the monthly water demands. The minimum water volume in May amounted to 149.46 MCM at +119.88 m elevation.

From the operating rule in the three seasons, water transfer always occurs. Only in the dry seasons does an open flow in the tunnel happen. The rest is a fully developed flow. Tables should be typed and included as part of the manuscript. They should not be submitted as graphic elements. Supply succinct and clear captions for all tables, figures, and plates. Ensure that any superscripts or asterisks are shown next to the relevant items and have corresponding explanations displayed as footnotes to the table, figure, or plate. An example of the figure in the text is shown in Figure 9.

Discussion

The annual reservoir operation pattern is prepared by considering that the water level at the beginning of the operation is the same as at the end of the operation time. Reservoir water release is a decision based on the volume of water availability in the reservoir and water demand at that time (Iqbal et al., 2020b). The release of water in various seasonal reviews adjusts to the inflow and storage volume in the reservoir so that the function of irrigation services also follows these conditions (Oliveira & Loucks, 1997), (Mujumdar & Ramesh, 1997). The resulting review of the water level elevation in the operational pattern of the Rukoh Tiro reservoir is still at the limit, which is between the practical reservoir elevations (Zeng et al., 2015), (Wei et al., 2021).

Simulations were carried out to produce operational patterns for the Rukoh and Tiro reservoirs managed simultaneously. The technical condition of the two reservoirs is one system under review. Inflow in dry, standard, and wet years is the reference for water release, while the demand for irrigation and raw water is constant. Water demand for river maintenance conservation follows the discharge value used in the analysis. More significant discharge means a greater requirement for river conservation and maintenance.

The most extreme conditions during the dry season cause the water level to reach its maximum condition only at the beginning and end of the operating period. In the regular and wet seasons, the maximum storage is reached in January, February, November, and December. At the same time, the minimum water level occurs in August but is still above the tunnel elevation, so the resulting operating rule is still in the form of one system.

The simulation results of the Rukoh Tiro reservoir, operated simultaneously in all three seasons, show that the level of fulfillment of irrigation water demand can reach 100% as needed. At the same time, the water transfer process through connecting channels occurs throughout the year. This can be seen from the reservoir's water level, which is always above the base elevation of the connecting channel at + 112.00 m.

Conclusion

The Rukoh Tiro operation rules are arranged according to the function of the reservoir development. Considering the potential storage capacity of the Rukoh Reservoir with a small inflow and the potential discharge on the Tiro River, water transfer is carried out by utilizing a connecting tunnel. The function of each reservoir can be fulfilled with the proper operating rule. Based on the operation rule curve, you can see a high success rate from the water level in one operation period. The planting area and water transfer arrangements must only be adjusted in the dry season. In addition, each reservoir's water demand can be met by utilizing the existing inflow. Joint operation of both the Rukoh and Tiro reservoirs can still be developed. By considering the inflow discharge and requirement of each watershed in simulation, the maximum objective function can be used as a reference for increasing the function of these two reservoir management.

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