Rainfall-Runoff Simulation for Water Availability Estimation in Small Island Using Distributed Hydrological Model wflow

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Abstract. Hydrological data in Indonesia, especially in the small islands, is minimal, including spatial distribution and temporal completeness. It will affect the accuracy of water availability estimation for water resources management interest. One of the solutions that can be undertaken is applying rainfall-runoff modeling to obtain the discharge value at a specific location. This study aims to determine surface water availability in each sub-catchment of the small island by implementing the hydrological model. The wflow model is applying to perform the model. This model uses input data including Digital Elevation Model (DEM), landuse, soil, Leaf Area Index (LAI), rainfall, evapotranspiration, and observation of river discharge for the calibration process. As a result, this island consists of 30 catchments with some potential catchments, namely Cao, Sakita, and Tatamo, that have a 90% dependable flow of 4213.3 L/s, 3803.6 L/s, 8117 L/s, respectively. The result of water availability in Morotai Island is highly expected to be the reference for water resources management, especially for tourism and urban development.

Keywords: distributed hydrological model, small island, water availability, wflow

1. Introduction

Water resources management can be carried out optimally with supporting of complete and adequate data. In order to determine surface water potential, it requires long and continuous data. The discharge data used to calculate the dependable flow has to meet the minimum criteria of data length for ten years to get the probability of success less than or equal to 0.9. While in order to get the probability greater than 0.9, a minimum discharge data available for 20 years is required [21]. However, the data is minimal in terms of the discharge gauges distribution in Indonesia, especially in the eastern and small islands. The quality of hydrological data in Indonesia is generally still inadequate [13]. The data availability is mainly concentrated in Java, Sumatera, and Sulawesi, while other regions are almost ungauged. A term of the ungauged basin can be used for an area with inadequate records of hydrological observations, both quantity and quality at the spatial and temporal scales, and the acceptable accuracy for practical applications [26].

Rainfall-runoff modeling is an important issue that has been widely used for generating discharge data for operational hydrology and water management purposes during the past decades [11, 22, 14]. The implementation in the data-scarce region will be a unique challenge [1]. The hydrological model can be categorized as a lumped model, semi-distributed model, and fully distributed model. The various hydrological models have been designed with different hydrological processes represented by
mathematical equations [20, 5, 18, 8]. Hydrological models were developed at least 50 years ago to study hydrological behavior or to manage them [30, 23, 4, 24, 7, 6]. Some examples of hydrological models have been widely used for rainfall–runoff simulation, including: SWMM, MIKE-SHE, HSPF, PSRM, HEC-1, TOPMODEL, SWAT, etc [6, 12]. There is even a kind of model built specifically for a small nonurban watershed, namely SWMHMS which was developed in 1972. That model generally has good accuracy except on watersheds with snowfall accumulation [3] and has been implemented in Indonesia to analyze river discharge in Coba Rondo Hulu watershed, Malang [15]. However, the other problems arise when the availability of rainfall data is limited both spatially and temporally. Therefore, satellite data plays an essential role in replacing rainfall observation data. Satellite-derived precipitation products are a promising approach to reflect rainfall's spatial pattern and temporal variability [17].

Morotai island is one of Indonesia's small islands with enormous natural resources potential. It starts from agriculture, forestry, fisheries and marine, mining, and historical tourism potential, especially the historical sites from World War II. This island has been selected as one of the strategic areas for national tourism in Indonesia. According to the Development Planning Agency of Morotai Island District [10], an urban development based on spatial planning is for forestry, settlement, industry, and sea tourism. Urban development certainly requires various optimal carrying capacities. One of them is the water resources sector. Morotai island is located in the northern part of Maluku Island which is bordered on the north by the Pacific Ocean, on the west by the Sulawesi Sea, on the east by Halmahera Sea, and on the south by Morotai Strait (Figure 1). This island is categorized as a small island since it only has an area of 2314.9 km².
Morotai Island should have substantial water resources related to the hydrological condition. The rainfall pattern is unique, with two rainfall peaks per year. The rainfall pattern of Morotai Island causes it to be monsoonal pattern affected by local factors [2, 29]. The rainfall intensity in this region is about 1500 – 2000 mm/year. Morotai island is included in the North Halmahera River Basin that has identified seven potential rivers. This river namely are Tiley, Sabatai Tua, Sangowo, Tawakali, Pangeo, Sambiki, and Tutuhu [19]. The strategic issues in the North Halmahera River Basin include clean water services that are still centralized in the capital city with a service coverage of only 60%.

Based on the problems mentioned above, this study aims to determine surface water potential in Morotai Island by implementing wflow hydrological model. The expected product is the dependable flow in each catchment as water availability information that can be utilized as raw water supply. The study results can be an essential reference for the stakeholders in determining strategic policy for Morotai Island development.

2. Material and Methods
The basic philosophy of the hydrological model is to simplify the complex reality in the hydrological system by constructing a conceptual model. Modeling conception in hydrology involving the relationships between water, climate, soil, and landuse [16]. The wflow hydrological model framework was developed by Deltareas. This model can simulate the processes in the hydrological cycle. This model is open source and has been setting up worldwide and implementing raster-based GIS packages suitable for dynamic computations [9]. Wflow is categorized as a fully distributed hydrological model since the data input, calculation, and output are grid-based. This model consists of python-based programs that can be run on the command line and perform hydrological simulations.

The hydrological concept of wflow implemented in this study is the SBM concept, which is more suitable for tropical conditions. The SBM hydrological concept comprises some sub-models describing the water balance calculation of each raster cells [27]. The wflow_sbm model is derived from the topog_sbm model [28] that has been applied in various countries, most notably in Central America. This model consists of 3 main modules as follows [25].

1. The rainfall Interception module is based on an analytical approach by Gash in 1979. The amount of water needed to saturate the canopy completely is defined as:

\[ P = \frac{-R S}{E_w} \left[ n \left( 1 - \frac{E_w}{R} (1 - p - p_t)^{-1} \right) \right] \]  

where:
\[ R = \text{average precipitation intensity on saturated canopy} \]
\[ E_w = \text{average evaporation from the wet canopy and with the vegetation parameters} S \]
\[ p \text{ and } p_t \text{ are defined previously.} \]

2. In the soil module that is calculated, the water balances of the unsaturated and saturated zones are computed by the TOPOG_SBM model, including lateral groundwater flow of the phreatic aquifer. Actual infiltration happens when there is storage in free surface water and remaining capacity in an unsaturated zone. The infiltration capacity is set in the input parameter to describe the rate of infiltration. The soil is considered as a bucket with a certain depth \( z_i \), divided into a saturated store \( S \) and an unsaturated store \( U \) that is expressed in units of depth. The top of the S store forms a pseudo-water table at depth \( z_i \) such that the value of \( S \) at any time is given by:

\[ S = (z_i - z_r)(\theta_s - \theta_r) \]  

Where \( \theta_s \) and \( \theta_r \) are the saturated and residual soil water contents, respectively.

The unsaturated store \( U \) is subdivided into storage \( U_s \) and deficit \( U_d \) which are expressed in units of depth as follows.

\[ U_d = (\theta_s - \theta_r)z_t - U \]  
\[ U_s = U - U_d \]  

The saturation deficit \( S_d \) for the soil profile as a whole is defined as:

\[ S_d = (\theta_s - \theta_r)z_t - S \]
All infiltrating rainfall enters the U store first. The transfer of water from the unsaturated to the saturated store \((st)\) is controlled by the saturated hydraulic conductivity and calculated below.

\[
st = K_{\text{sat}} \frac{u_s}{s_d}
\]

where:

- \(K_{\text{sat}}\) = hydraulic conductivity in saturated condition \((\text{m}^2/\text{day})\)
- \(u_s\) = unsaturation storage
- \(s_d\) = saturation deficit

When the value of \(st\) is negative, the water will flow from the saturated zone to the unsaturated zone. However, the horizontal water exchange also takes place between the hydrological units.

3. Kinematic wave module is used to route water over the surface and through streams and rivers. For the calculation, this module is implemented the Manning equation. For this purpose, a Stahler order is determined for every grid cell. The typically cells larger than five are considered rivers.

Additionally, there are some supplementary modules like snow and glacier melt module, simple reservoir, lake module, and crop growth modules as well. Figure 2 shows the schematization and processes that are calculated in wflow model.

![Figure 2](source.jpg)

**Figure 2.** The schematization of wflow rainfall-runoff modeling

This model has been successfully connected to other models such as SOBEK for the hydraulic model, Delwaq for water quality, RIBASIM for water allocation, and MODFLOW for groundwater modeling [9]. Some implementation of this model includes flood forecasting in Rhine River, landuse and climate change assessment in Colombia, flood early warning system in Pakistan, calculation of inflow to the reservoir combined with RIBASIM model in Gangga River, North India, as well as the water resources framework di Indonesia.

In this study, we implemented the wflow model builder concept by utilizing google earth engine and hydro engine. This simplifies the model building process, provides easy access to global data and reduces the time to construct models. Data requirement to construct the model is as follows.
1. Static data
   a. Digital Elevation Model (DEM)
   b. Landuse map
   c. Soil map
   d. River and catchment map
2. Dynamic data
   a. Precipitation
   b. Potential evapotranspiration
   c. Discharge observation
3. Model parameters based on landuse map, soil map, and Leaf Area Index (LAI).

3. Result and Discussion

3.1. Model input
As mentioned before, the input data required in wflow can be separated into dynamic data represented by the meteorological forcing or the model and static data considering the land surface description.

![Figure 3. Static Map](image-url)
3.1.1. Static data.
The Digital Elevation Model (DEM) map is used based on SRTM v4 with the pixel size 30 x 30 m. Land use and soil map are derived from the Ministry of Marine and Fisheries Indonesia. The three kinds of maps can be seen in Figure 3. Another static piece of data necessary for this model is the river and catchment map derived from the Ministry of Public Works and Housing. The static maps are transformed into PCRaster maps format with a pixel size of 0.001 x 0.001° or 111 x 111 meters.

The original landuse map consists of 13 types, as can be seen in Figure 3. In order to simplify the parameterization, these specific types are reclassified into seven classes (Table 1). The land area of Morotai Island is dominated by natural forest 48%, dense forest 15%, as well as shrubs and field 11%, respectively. Related to the soil type, this island is generally dominated by clay loam in the center part of the area. Sandy and silty clay is found in West, South, and East of the coastal area.

### Table 1. Landuse Reclassification

| No | Landuse Type       | Reclassification |
|----|--------------------|------------------|
| 1  | Lake               | Water body       |
| 2  | Dense forest       | Forest           |
| 3  | Natural forest     | Forest           |
| 4  | Mixed forest       | Plantation       |
| 5  | Certain forest     | Plantation       |
| 6  | Field              | Crops            |
| 7  | Mangrove           | Waterbody        |
| 8  | Sparse settlement  | Paved            |
| 9  | Dense settlement   | Paved            |
| 10 | Dense village      | Paved            |
| 11 | Swamp              | Waterbody        |
| 12 | Shrubs             | Shrubbland       |
| 13 | Open ground        | Grassland        |

3.1.2. Dynamic data.
The rainfall pattern and intensity in Morotai Island were examined by historical data from 2 rainfall stations, namely Daruba Station and Leo Watimena Station, with 4 and 10 years, respectively. The monthly average rainfall pattern for each station can be seen in Figure 4. The graph shown in Figure 4 illustrates the monsoonal rainfall pattern, which is affected by local factors. It can be seen by the two peaks of rainy seasons, in December-January and May-June.

However, the available rainfall data in Morotai Island is not representative. Both in spatially and temporally data to perform in hydrological simulation using wflow model. Therefore daily rainfall data from the Tropical Measuring Mission (TRMM) satellite is utilized to substitute the absence of this data. TRMM products used in this study are corrected TRMM 3B42RT. This data has been available since February 2002 with 0.25 degrees spatial resolution.

Rainfall data validation was performed to check the reliability of satellite data compared to rain gauge data. The validation is essential to know the quality of satellite data that will be used for the simulation. TRMM and rain gauge data from Leo Watimena Station have a correlation value of 0.6. According to [20], the rainfall correlation of TRMM and observation data in the equatorial region with two peaks of rainy seasons is >0.6. As mentioned before that the rainfall pattern in Morotai Island also has two peaks of rainy seasons. Therefore the correlation value is considered to be acceptable.

Potential evapotranspiration was derived from the Consultative Group on International Agricultural Research (CGIAR) climatology data. The dataset is calculated using the Hargreaves method,
considering average monthly temperature data, average monthly temperature range, and the radiation on top of the atmosphere. Those data are taken from the WorldClim Global Climate Data. It is a monthly pattern repeated yearly from 1950 – 2000 with a grid cell resolution of approximately 1 km. It is disaggregated to a daily basis assuming equal distribution over the month.

![Monthly Rainfall Pattern](image)

**Figure 4.** Rainfall pattern

3.1.3. Discharge observation.

Field measurement and gauges installation are essential due to the absence of adequate discharge data in Morotai Island. The measurement and installation are carried out in Sabatai Tua and Mira River, as shown in Figure 5. The water level condition is monitored and recorded three times a day by local people manually. Instantaneous discharge measurement was performed in order to get the equation that can be utilized to convert water level to discharge data. This data will be used for the calibration process.
3.2. Model set up
This step was performed by using a tool, namely wflow-model builder. The tool aims to build the model using local and global input data (if the local data is unavailable). The model builder uses 1 set of tools called hydro-engine that constructed under Google Earth Engine. The model will be automatically connected to the FEWS system as an interface and pre- and post-processing data of the wflow model. In this case, the model that has been constructed has a cell size of 0.001 degrees or 111 km. The model is run on each grid cell, and the water flows from one grid cell to another through the kinematic wave routine and lateral flow.

The other steps in the model setup include entering observation for model calibration purposes. The parameters involved in wflow model related to soil type and landuse condition as presented in Table 2, Parameters Infiltcapsoil, Ksatver, M, Theta R, Theta S, InfilcapPath, Maxleakage, Capscale, RunoffGeneratingGWPer, Cf_soil, Cfmax, MaxPercolation are varied over soil classes. In contrast, parameters Pathfrac, ETreftopot, N, N_river, Rootdistpar, Rootingdepth, Rootingdepth, LCToBranchTrunkStorage, LCToExtinctionCoefficient, LCToSpecificLeafStorage, and EoverR are varied over landuse classes. In the calibration process, adjusting these parameters settings will be part of the continuous process of model improvement.

### Table 2. Model parameters

| No | Parameter                  | Type     | Range Value & Dimension | Model Value |
|----|----------------------------|----------|-------------------------|-------------|
| 1  | Infiltcapsoil              | Soil     | 25 - 750 mm/day         | 600         |
| 2  | Ksatver                    | Soil     | 0 - 10000 mm/day        | 100-8000    |
| 3  | M                          | Soil     | 20 - 2000               | 200-2000    |
| 4  | Theta R                    | Soil     | 0.056 - 0.109           | 0.09-0.02   |
| 5  | Theta S                    | Soil     | 0.2 - 0.6               | 0.3-0.45    |
| 6  | InfilcapPath               | Soil     | 5 - 10 mm/day           | 10          |
| 7  | Maxleakage                 | Soil     | 0.1                     | 0.1         |
| 8  | Capscale                   | Soil     |                         | 100         |
| 9  | RunoffGeneratingGWPer      | Soil     | 0.1                     | 0.1         |
| 10 | Cf_soil                    | Soil     |                         | 0.038       |
| 11 | Cfmax                      | Soil     |                         | 3.75653     |
| 12 | MaxPercolation             | Soil     |                         | 0           |
| 13 | Pathfrac                   | Landuse  | 0 - 1                   | 0.05-0.8    |
| 14 | ETreftopot                 | Landuse  |                         | 0-0.88      |
| 15 | N                          | Landuse  | 0.01 - 0.4              | 0.1         |
| 16 | N_river                    | Landuse  | 0.02 - 0.15             | 0.045       |
| 17 | Rootdistpar                | Landuse  |                         | 0-500       |
| 18 | Rootingdepth               | Landuse  | 0 - 5000 mm             | 0-5000      |
| 19 | LCToBranchTrunkStorage     | Landuse  |                         | 0-0.5       |
| 20 | LCToExtinctionCoefficient  | Landuse  |                         | 0-0.8       |
| 21 | LCToSpecificLeafStorage    | Landuse  |                         | 0-0.13      |
| 22 | EoverR                     | Landuse  | 0 - 1                   | 0.1-0.3     |

3.3. Sensitivity Analysis and Calibration
Before the calibration process, it is necessary to conduct a sensitivity analysis of all parameters in the wflow model. It aims to determine the most sensitive parameters in changing the pattern of simulation discharge. The wflow parameters consist of 10 parameters related to landuse and 12 parameters related to soil type. Table 2 shows the range of parameter values allowed in the model as a boundary in adjusting parameters and the parameter values used in the model.

From the 22 parameters involved, only the four most sensitive parameters are Ksatver, Pathfrac, M, and Theta S & Theta R. However, only Ksatver dan Pathfrac is more effective in adjusted parameters for the calibration process. Pathfrac is a parameter related to landuse that can describe the percentage of impermeable areas in 1 grid cell. At the same time, Ksatver is a parameter related to the soil which can describe the soil's ability to transmit the water. The simulation result shows that the discharge value at the low flow condition is too high, while the peak condition is too low. Consequently, the adjusting
parameters were carried out by reducing Pathfrac to release more water enter the soil and reducing Ksatver to make the water longer to stay in the soil so that the baseflow is expected to be increased in the dry season significantly as in the observation data.

Meanwhile, during the calibration process, it was discovered that the streamflow observed in Sabatai Tua and Mira River had been affected by tides since the gauges were installed too downstream. Therefore, the discharge observation data is corrected using online tidal data from the Indonesian Geospatial Information Agency. The calibration result at two stations, Mira and Sabatai Tua, is presented in Figure 6 with RMSE values 2.2 and 2.35, respectively. The calibration result seems not too perfect, especially for the peak discharge. It is because of the tidal effect that it still cannot be adequately described.

Figure 6. Calibration result
3.4. Model result
After passing the calibration process, the model runs for 14 years daily from 2003 – 2017 according to the availability of input data. The simulation length is expected to meet the criteria in calculating the dependable flow for each catchment. The discharge series resulting from the simulation was then used to calculate the Q90 dependable flow, as presented in Figure 7. Water availability in Morotai Island is quite potential, with the average value of each watershed is 1500 L/s. The most potential catchment is Tatamo, with the Q90 discharge value of 8117 L/s. In comparison, the less potential catchment is Kocago, with a value of only 125 L/s. One of the fundamental reasons is Kocago has a tiny area that is only 10 km$^2$. In comparison, the area of Tatamo is massive, with an area of 323 km$^2$.

4. Conclusion
It can be concluded that the wflow model has been successfully implemented in a small island in Indonesia to obtain the surface water availability of each catchment. Based on the land condition, Morotai Island is dominated by natural forest for landuse and sand for the lithology that will be the main factors for the excellent potential of the water resources. It is also supported by the climate condition represented by rainfall patterns with two peaks. Some sensitive parameters to be adjusted in the calibration process are Ksatver, M, Theta S, Theta R, and Pathfrac. The calibration process shows a good result with RMSE values 2.2 and 2.35 at Sabatai Tua and Mira Station, respectively. As a result, this island consists of 30 catchments with some potential catchments, namely Cao, Sakita, and Tatamo that have a 90% dependable flow of 4213.3 L/s, 3803.6 L/s, and 8117 L/s, respectively. The result of water availability in Morotai Island is highly expected to be the reference for water resources management, especially for tourism and urban development.

This research still has many limitations, especially in the availability of observation data for the calibration process. Therefore, further research development needs more comprehensive observation data. Other than that, the placement of gauges must be far from the influence of backwater from the sea. Hopefully, this research can be used as a reference in applying the distributed hydrological model on small islands or catchments.

Acknowledgment
The authors are grateful for the opportunity given by the Research Center for Water Resources, Ministry of Public Works and Housing to carry out research relating to water availability in Morotai Island in 2018.

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