

## THE APPLICATION AND RELEVANCY OF RAINFALL-RUNOFF-INUNDATION (RRI) MODEL IN INDONESIA

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**Abstract:** Indonesia has a very large number of watersheds and has a very diverse size. Damage to several watersheds in Indonesia has also occurred and often results in catastrophic floods and droughts that threaten people. The presence of the RRI Model with its capabilities will help contribute to watershed management in order to solve water resource problems. The RRI model is a two-dimensional (2D) model capable of simulating runoff, rainfall, and flood inundation simultaneously. The use of this model in Indonesia has reached 13 times which was compiled based on the number of publications on the application of the RRI model. All of these publications have passed peer-reviewed papers from both journals and conference papers. Applications have been made in several places including the Solo watershed, the Upper Citarum watershed, the Batanghari watershed, and the upstream Brantas watershed. Given the increasing number of problematic watersheds in Indonesia, the use of this model has the prospect and relevancy of being carried out in other watersheds. However, until now, researchers have had challenges in building hydrological models because of the constraints on the availability of climatological and hydrological data in the watershed. Therefore, in addition to improving the data measuring infrastructure in the field, remote sensing techniques are also needed in an effort to generate targeted watershed information. In fact, the effort to utilize remote sensing in generating unmeasurable data in the field has been successfully conducted in several studies.

**Keywords:** RRI Model; Hydrological Model; Rainfall; Runoff.

**Abstrak:** Indonesia memiliki jumlah DAS yang sangat banyak dan memiliki ukuran yang sangat beragam. Kerusakan beberapa DAS di Indonesia juga telah terjadi dan sering berakibat bencana banjir dan kekeringan yang mengancam penduduk setempat. Kehadiran Model RRI dengan kemampuannya akan membantu berkontribusi dalam memajemen DAS ataupun dalam usaha untuk menyelesaikan permasalahan sumberdaya air. Model RRI adalah suatu model dua dimensi (2D) yang memiliki kemampuan untuk mensimulasikan limpasan curah hujan dan genangan banjir secara simultan. Penggunaan model RRI ini di Indonesia telah mencapai 13 kali, yang tercatat berdasarkan jumlah publikasi yang terkait dengan aplikasi model RRI. Semua publikasi

tersebut telah melewati peer-review baik dari jurnal maupun dari konferensi. Aplikasi telah dilakukan di beberapa tempat termasuk DAS Solo, DAS Citarum, DAS Batanghari, dan DAS Brantas. Mengingat jumlah DAS yang bermasalah di Indonesia semakin meningkat, maka penggunaan model ini memiliki prospek untuk dilakukan di DAS lain. Namun sampai saat ini, para peneliti memiliki tantangan dalam membangun permodelan hidrologi karena terkendala pada ketersediaan data klimatologi dan hidrologi di dalam DAS. Oleh karena itu, selain peningkatan infrastruktur pengukur data dilapangan dan teknik penginderaan jauh juga diperlukan dalam usaha menyediakan informasi DAS yang ditargetkan. Usaha penggunaan teknik penginderaan jauh dalam menyediakan data yang tidak terukur dilapangan telah sukses dan terbukti dilakukan di beberapa studi.

**Kata Kunci:** RRI Model; Permodelan Hidrologi; Curah Hujan; Limpasan.

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## Introduction

Currently, the existence of water resources is threatened by several factors in Indonesia. Climate change factors have led to increased global temperatures and unstable rainfall patterns, resulting in more frequent periods of drought and higher flood intensities (M. Faisi Ikhwal & Pawattana, 2022; Pawattana et al., 2021). The rapid population growth and urbanization have also led to increased demand for water for domestic, industrial, and agricultural needs (Karunia & Ikhwal, 2021). Besides that, deforestation and forest degradation have caused the loss of forests' water retention functions, reduced the sustainability of river flows, and accelerated soil erosion. Water pollution from industrial, agricultural, and domestic waste also threatens water quality, making it unsuitable for consumption or sustainable use. All of these factors present significant challenges in preserving and managing water resources in Indonesia.

Hydrological modeling is one of the tools in water resource management and also to solve or avoid watershed problems (M Faisi Ikhwal, Ibrahim, et al., 2022; Safriani et al., 2023). Hydrological Modeling in its simplest sense is a form of simplifying the hydrological cycle on a certain scale. The ability of hydrological modeling to imitate hydrological processes is highly dependent on the level and type of hydrological modeling. The best model is the model that gives results that are close to reality with the least use of parameters and model complexity (Devia et al., 2015). This model can help researchers and practitioners in investigating alternative water management (Dai et al., 2016).

Hydrological modeling has various uses including flood prediction, water resources planning, evaluation of climate change impacts, river basin management, project evaluation and decision-making in water management. By utilizing hydrological models, it can predict floods, effectively manage water resources,

anticipate the impacts of climate change on the hydrological cycle, understand interactions within river basins, and evaluate the impacts and make decisions related to projects and sustainable water management.

Nowadays, various levels or categories of hydrological modeling have emerged. Models can be categorized based on the structure and spatial processing of the algorithm into empirical, conceptual, physical, lumped, semi-distributed, and distributed models (Sittersona et al., 2018). This paper discusses specifically the Rainfall-Runoff-Inundation (RRI) Model. This model belongs to the physical-based distributed hydrological modeling (Pakoksung & Takagi, 2016). The RRI model is a two-dimensional (2D) model capable of simulating runoff, rainfall, and flood inundation simultaneously. The 2D diffusive wave model is applied to various areas ranging from mountainous areas to low-lying areas (T. Sayama et al., 2017).

The RRI Model is used to model the catchment's reaction to climatological data. The RRI model is used to simulate the watershed's reaction to climatological data that characterizes the water cycle process in the grid-based catchment region. (Hapsari, Syarifuddin, Putri, & Novianto, 2021). The RRI model is a stand-alone product and its outputs, i.e., discharge, water level, and inundation can be easily displayed (Tam et al., 2019). In this model, the movement of water both on the slopes and the river channel is calculated by the mass balance equation and the momentum equation. The RRI model takes into account water interactions between slopes and channels, as well as percolation and groundwater movement (Yoshimoto & Amarnath, 2018). The RRI model, despite its advantages, has a few notable disadvantages. The RRI model relies heavily on accurate and extensive input data, including precipitation data, topographic information, soil characteristics, land use data, and hydraulic parameters. Acquiring such comprehensive and precise data can be challenging, particularly in regions with limited monitoring infrastructure or data availability.

Furthermore, the RRI model has the capability of doing computations for numerous basins in circumstances when the downstream floodplain is influenced by many rivers; and it is available for free, making it more accessible to developing countries (Yoshimot & Amarnath, 2017). Easily accessible hydrological models mean more economical models (Azraie et al., 2022). Therefore, Indonesia as a developing country which has approximately 17 thousand watersheds of various sizes will be the right choice in using the RRI model in simulating the water cycle in the watershed. The choice of the right model to use in a particular simulation project should lead to better results (Ghonchepour et al., 2021). This paper will review the extent of the use of the RRI Model throughout Indonesia and will discuss the challenges and prospects of using this model in the future.

### Model Structure and Theoretical Basis of RRI Model

The main objective of the RRI model was developed to simulate a flood inundation model on a catchment basis. In considering the hydrological cycle, RRI is more capable because it can simulate rainfall, runoff and inundation (Azraie et al., 2022). The model treats river slopes and channels independently in the grid cell where the river channel is located, and it is assumed that the slope and river are in the same grid cell. The channel is discretized as a line from the slope grid cells above it along its center line. A 2D diffusive wave model is used to calculate the flow in the slope grid cells, while a 1D diffusive wave model is used to compute the flow in the channel.

A "storage cell-based inundation model" is a method for determining lateral flow in slope grid cells. The mass balance equation (1) and momentum equation (2) for a gradually changing variable flow are used to construct the model equation (Takahiro Sayama et al., 2014).

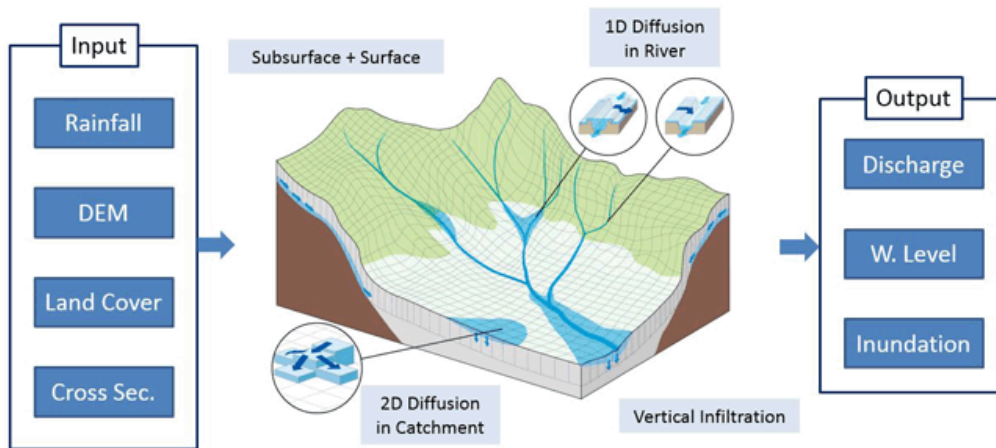
$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f \dots\dots\dots(1)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial u q_x}{\partial x} + \frac{\partial v q_x}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho_w} \dots\dots\dots(2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial u q_y}{\partial x} + \frac{\partial v q_y}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{\tau_y}{\rho_w} \dots\dots\dots(3)$$

Where  $h$  is the height of water from the local surface,  $q_x$  and  $q_y$  are the unit width discharges in  $x$  and  $y$  directions,  $u$  and  $v$  are the flow velocities in  $x$  and  $y$  directions,  $r$  is the rainfall intensity,  $f$  is the infiltration rate,  $H$  is the height of water from the datum,  $w$  is the water density,  $g$  is the gravitational acceleration, Shear stresses in  $x$  and  $y$  directions are denoted by  $\tau_x$  &  $\tau_y$ .

The RRI model additionally models lateral subsurface flow, vertical infiltration flow, and surface runoff to provide a more accurate picture of the rainfall-runoff-inundation process. Lateral subsurface flow, which is typically more relevant in hilly environments, is addressed in a discharge-hydraulic gradient relationship that incorporates both subsurface flow and saturated surface runoff. The Green-Ampt model, on the other hand, was used to predict the vertical infiltration flow. Flow interactions between the river channel and the slope are evaluated using various overflow formulae dependent on water level and embankment height.

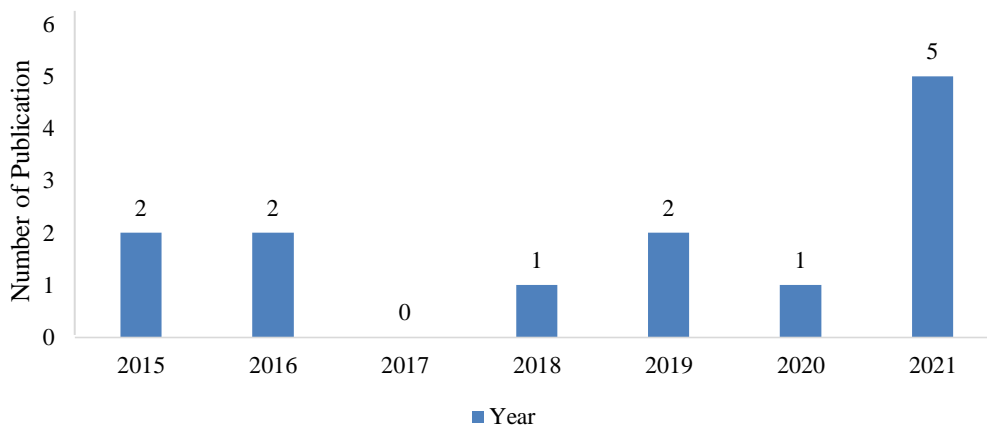


**Figure 1.** Rainfall-Runoff-Inundation (RRI) schematic diagram

Figure 1 is a schematic diagram of the running RRI model which is divided into three groups of working stages. The first stage is the input of data or information from the target watershed. The second stage is the simulation stage along with what methods or formulas are used in the process of simulating water flow in the watershed. The last stage is the stage of extracting the output data from the simulation results process such as discharge data, water level and inundation area.

### **RRI History and Its Application Trend in Indonesia**

The Rainfall-Runoff-Inundation (RRI) model was developed by the International Center for Water Hazard and Risk Management (ICHARM) under the auspices of UNESCO. The RRI model is one of the key technologies of ICHARM developed by Dr. Takahiro Sayama during his tenure at ICHARM. The Japan Society of Civil Engineers honored the RRI model with an excellence award in 2014. In 2013, the ICHARM researcher who developed the model earned the Ministry of Education, Culture, Sports, Science, and Technology's 2013 Young Scientist Award, as well as the Ministry of Land, Infrastructure, Transport, and Tourism's 15<sup>th</sup> Infrastructure Technology Development Award (Takahiro Sayama et al., 2014).



**Figure 2.** Trends in the use of RRI models in Indonesia

In Indonesia, the RRI model was first used through two publications in 2015, each of which was used in the Solo River Basin and Upper Citarum Watershed (Shun Kudo et al., 2015; Nastiti et al., 2015). Figure 2 shows the trend of using RRI applications in Indonesia. This data was collected through reports of the uses or applications of the RRI model in Indonesia in the form of journal articles and conference papers. This trend is based on the number of publications in the last 7 years. The highest usage trend is in 2021 with 5 publications. However, in 2017 there were no publications regarding the use of RRI in Indonesia. From 2015 to 2021, there were 13 publications on RRI models in Indonesia.

### **RRI Application in Indonesia**

Since 2015, researchers have published various studies regarding the RRI model. When viewed from the size of the watershed, the use of this model in Indonesia is indeed in watersheds with relatively large sizes such as The Solo River Basin (15,752 km<sup>2</sup>) six times, The upper Brantas River Basin (112.54 km<sup>2</sup>) two times, Upper Citarum Basin 1,800 km<sup>2</sup> for two times, and The Batanghari River Basin (42,960 km<sup>2</sup>) for three times. The research objectives are also varied, some only focus on the application of the RRI model and also in an effort to assess the impact on flood events. So far, the use of the RRI model in Indonesia has been dominated by flood studies. Furthermore, the RRI model was also used to evaluate the impacts of climate change on water resources conditions and agricultural conditions. There are six publications whose focus is on flood studies with details of 5 publications with the research location in The Solo River Basin and a location in The Batanghari River Basin.

The Solo River is the longest river on the Indonesian island of Java, stretching over 600 kilometers and covering a watershed area of 15,752 km<sup>2</sup>. It stretches along the provinces of Central and East Java and flows northeast to the coast of the Java Sea, northwest of the city of Surabaya (Hendrawan & Komori, 2021). Agriculture, especially rice cultivation, is one of the most important land use categories in this watershed. This land use condition is very vulnerable to

climate change. Based on the results of a study conducted by Shrestha *et al.* (Badri Bhakta Shrestha *et al.*, 2019) with the help of the RRI Model, shows that there will be an increase in inundation area and agricultural damage with changes in flood intensity from 50 to 100 years of flooding in the case of a relatively higher climate in the Solo River Basin watershed. Similar results are also shown by Kudo Shun *et al.* (Shun Kudo *et al.*, 2015) that peak discharge and maximum inundation volume will increase in the future period (2075-2099), especially low flood events with a frequency of more than 10 years return period. Expansion of the inundation area will also occur around the Solo River flow in the future. Then in another study, the results of the frequency analysis show that the differences in terms of rainfall and peak discharge are not too large in the short return period whereas they show large differences especially the return period of more than 10 years (S. Kudo *et al.*, 2016). Additional research in this watershed studies the presentation of alternative approaches to obtain the relationship between flood yields using remote sensing and hydrodynamic models (Hendrawan, 2020).

The Upper Citarum watershed is located in West Java, which often floods every year. The RRI Model has also been applied by Nastiti K, *et al.* (Nastiti *et al.*, 2015). The RRI model simulates the inundation area with good results, however, the simulated discharge shows some differences due to the uncertainty involved in the observed discharge and the deficit of input data for the simulation. Then in the next attempt, Nastiti K, *et al.* (Nastiti *et al.*, 2018) used the Monte Carlo method for the model calibration process in the Upper Citarum Watershed. The results of this study indicate that the RRI model identifies inundation areas in large-scale river basins more effectively when using multiple satellite-derived data sets than the observed inundation maps obtained from JICA in 2010 and Landsat 7 images.

Future climate change is also projected to have a significant impact on the Batanghari River basin watershed, increasing the level of danger in terms of flood frequency, extent and depth and the risk of flooding in the Batanghari River basin (Ikhzan *et al.*, 2021). The Batanghari watershed is the largest watershed on the island of Sumatra, which is located in Jambi Province. The prediction regarding land use changes in this watershed indicates that significant changes will occur. By 2040, the area of residential land and agricultural land is predicted to increase to 158,950 hectares and 2,853,200 hectares, respectively. On the other hand, the predicted decrease in forest area, shrubland, and open land is projected to be 1,221,800 hectares, 19,900 hectares, and 106,650 hectares, respectively (Utami *et al.*, 2018). Based on the other results of the study with the help of the RRI model, flooding will increase in this area; for example, the volume of flood inundation corresponding to a 20-year return period will increase by 3.3 times (Takahiro Sayama *et al.*, 2019; Yamamoto *et al.*, 2021).

In another study, the use of the RRI model not only revolves around predicting the level of potential future flooding but it has also been carried out with other objectives in the upper Brantas River basin. In the upper Brantas River

basin, a watershed has been applied for the need to compare the runoff model of distributed rainfall (RRI Model) and lumped (Tank Model) for soil moisture estimation. The objective of this study is to obtain soil moisture indicators from the physically-based distributed hydrological model and the lumped model (Hapsari, Syarifuddin, Putri, & Novianto, 2021). Regarding the quantitative amount of soil moisture content, the RRI model can make reasonable simulations even though the temporal variations are not sufficiently reproducible. Another type of research in this watershed is to simulate soil moisture using the RRI hydrological model in landslide-prone sub-watersheds and to use runoff simulation as a proxy to reduce satellite soil moisture (Hapsari, Syarifuddin, Putri, Sasongko, et al., 2021).

**Table 1.** References of RRI Model Application in Indonesia

| Reference   | Watershed                     | Objective   |
|---|-------------------------------|---|
| (Shun Kudo et al., 2015)                              | The Solo River Basin          | To assess the effects of climate change on flood discharge and inundation   |
| (Nastiti et al., 2015)                                | Upper Citarum Basin           | To construct the optimized RRI Model with limited data  |
| (S. Kudo et al., 2016)                                | The Solo River Basin          | To analyze the effects of climate change on flood discharge and inundation  |
| (B B Shrestha et al., 2016)                           | The Solo River Basin          | To assess agricultural flood damage   |
| (Nastiti et al., 2018)                                | Upper Citarum Basin           | To apply the RRI model  |
| (Badri Bhakta Shrestha et al., 2019)                  | The Solo River Basin          | To assess flood damage for future floods under the impact of climate change   |
| (Takahiro Sayama et al., 2019)                        | The Batanghari River Basin    | To conduct field investigations and modeling to simulate rainfall-runoff and flood inundation processes   |
| (Hendrawan, 2020)                                     | The Solo River Basin          | To study crop yield response to the flood hazard using remote sensing data and a hydrodynamic model   |
| (Hapsari, Syarifuddin, Putri, & Novianto, 2021)       | The upper Brantas river basin | To obtain the soil moisture value from two hydrological models, namely the RRI Model and the Tank Model   |
| (Hapsari, Syarifuddin, Putri, Sasongko, et al., 2021) | The upper Brantas River basin | To simulate the soil moisture using the hydrological model in a landslide-prone sub-catchment and to use the simulated runoff as a proxy for downscaling the satellite soil moisture. |



| Reference                  | Watershed                  | Objective  |
|----------------------------|----------------------------|--|
| (Hendrawan & Komori, 2021) | The Solo River Basin       | To study flood vulnerability curves for rice crops using crop yield loss estimated by crop statistics and remote-sensing modeling as a loss indicator. |
| (Yamamoto et al., 2021)    | The Batanghari River Basin | To assess the impact of climate change on flood inundation   |
| (Ikhzan et al., 2021)      | The Batanghari River Basin | To quantify the spatial information of flood hazards with high spatial resolution.   |

### Challenges and Prospects of the RRI Model Application

Hydrological modeling always has challenges in applying in a country or in a particular watershed. The type or form of the challenge is highly dependent on each country. The RRI model has recently become known in Indonesia in line with increasing watershed problems. One of the main causes of these issues is climate change. Climate change has threatened various sectors and increased the potential for disasters in Indonesia (M F Ikhwal et al., 2022; M Faisi Ikhwal et al., 2023). However, the application of hydrological modeling has a major challenge if the information and data quality of the watershed is not available properly (Livneh et al., 2017).

In general, building a hydrological model must go through four main steps, namely preparation and input data, running the model, calibration, validation, and reading the output. These stages also apply to the RRI model. As in Figure 1, the required input data in RRI models such as Rainfall, Digital Elevation Model (DEM), Landuse, and River Cross-section. The biggest challenge in Indonesia in developing this RRI model is the availability of observation data in the watershed. For example, the availability of DEM data with large resolution is still scarce and generally will result in poor flow simulation and represent less accurate watershed boundaries (Yang et al., 2014). Infrastructure for measuring rainfall in Indonesia's watersheds is not yet adequately available. Likewise, the availability of land use data with good resolution that can be free access is still rare.

During the calibration and model validation stages, observational data such as discharge data or river water level data are also needed. This data is very important as a basis for determining how well the RRI model is being built in a watershed. The lack of water discharge data in the catchment also contributes to the poor relationship between observed and simulated daily river flows (Aduah et al., 2017). The availability of discharge and water level data in the watersheds is also still lacking and cannot be easily accessed by researchers. The process of calibrating and validating hydrological models has long been a challenge for the professional hydrological community (Marshall et al., 2005). If in the future this challenge can be solved by the relevant parties, it is possible for us to increase the number of publications on RRI hydrological modeling. The model that has been

built and published will be the basis for taking steps for watershed management or water resource management. As we know models such as the RRI model with its capabilities can help in making the best decisions in an effort to manage large-scale watersheds.

Data scarcity is a major challenge for hydrological modeling in Indonesia (M Faisi Ikhwal, Pawattana, et al., 2022). The government continues to increase the number of infrastructures for measuring climatological and hydrological data to deal with this problem. In addition, remote sensing techniques will be an alternative solution for generating the data needed in hydrological modeling. Remote sensing techniques can be utilized to improve model performance in unmeasured or poorly measured catchments (Milzow et al., 2011). The increasing availability of data encourages the use of new calibration techniques that can take advantage of additional information about the watershed (Manfreda et al., 2018).

### **Conclusion**

From the results of collecting reports on the use of the RRI model in Indonesia, until 2021 this application has been used 13 times with the location distribution of The Solo River Basin 6 times, The Upper Brantas river basin 2 times, The Upper Citarum Basin for 2 times, and The Batanghari River Basin for 3 times. All reports are in the form of scientific articles that have gone through a peer-reviewed process, both in journals and conferences. The highest usage is in 2021 with 5 scientific articles. When viewed from the purpose of its use, the use to analyze flood conditions is the most dominant use with 6 publications. Indonesia has a large number of watersheds to apply this modeling, but in terms of developing this model, it has challenges in the scarcity of climatological and hydrological data. Mostly application of RRI Model was applied in relatively large watersheds. If the availability of data or information from watersheds can be improved, Indonesia's watersheds of various sizes (especially large-size watersheds) and characteristics are very prospective to apply this model for watershed management needs, water resources and also for disaster mitigation needs such as floods. Several studies have achieved successful implementation in utilizing remote sensing to generate data (hydrological data and meteorological data) that cannot be directly measured in the field.

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