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Reviews, challenges, and prospects of the application of Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) model in Indonesia

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Abstract

The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model can be applied to simulate hydrological processes. This model has been widely used in recent days because it is openly accessible to the public. The search result from this study identifies 180 cases discussing the model applications in Indonesian watersheds in peer-reviewed journal articles and conference papers. The model has been used in Indonesia since 2005, but the highest application is in 2020 with 42 articles. In the context of application distribution, Java Island ranks first place with 123 scientific publications. However, the HEC-HMS model is predominantly used to simulate the "Small" and "Very Small" watershed size categories. The availability of insufficient field data is huge obstacle for hydrological modeling in Indonesia. Furthermore, the model may be extended to address the issues in Indonesia's eastern watersheds. Moreover, the model also can be used to assess the impact of climate change on streamflow.

Keywords: Hydrologic engineering center-Hydrologic modeling system, Hydrological modelling, Review, Watershed

1. Introduction

Indonesia is one of the largest archipelagic countries, with more than 270 million population and an area of 1,904,569 km^2, consisting of 17,088 watersheds [1]. The watersheds require appropriate watershed management practices based on the recommendations of hydrological models. These practices will lead to the sustainability of ecosystems as well [2]. The principle is that any mass or energy entering the watershed will be modeled using a mathematical model. Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) model is classified as open source and has been widely used for more than 30 years since the release of its first version [3]. It is developed from various algorithmic combinations of Hydrologic Engineering Center (HEC-1), Hydrologic Engineering Center-Flood Hydrograph (HEC-1F), Precipitation Model (PRECIP), and Hydrologic Engineering Center-Interior Flood Hydrology (HEC-IFH) [3-6].

The HEC-HMS model at this time is well known in studies concerned with hydrological modeling. These modern versions reached this stage starting from the release of the HEC-1, which could only simulate rainfall and runoff processes [5]. In contrast, the current version of HEC-HMS has been designed with the assistance of more sophisticated and complex modern computer sciences. This re-engineered process has resulted in some changes in computing techniques. It can simulate the behavior of watersheds, channels, and water control facilities in a hydrological system [7].

The HEC-HMS model can also be used in watershed-related studies such as flooding, reservoir design, and erosion. Given its ability to assist various hydrology studies, this model is considered reliable for all related government agencies, stakeholders, and academic scholars throughout Indonesia. The higher the precision of a hydrological model, the more observed data from the field is required. The quality and quantity of data available for Indonesian hydrological conditions are still deficient. For instance, the observation stations that record meteorological and hydrological data for several regions are rarely found. Therefore, an alternative is to utilize a tool such as the HEC-HMS capable of simulating hydrological processes [7].

The HEC-HMS model is capable of simulating rainfall, evapotranspiration, runoff, infiltration, flow routing, baseflow, snow formation, and melting processes [8, 9]. It has three main components, including the basin model, meteorological model, and control specifications [10]. The control specification adjusts the time specification of the HEC-HMS model that can be run in daily or sub-daily time scales [11-13]. In HEC-HMS model, the water flow in the watersheds can be simulated in various methods that are already embedded in the model. Furthermore, it consists of four main component groups of infiltration losses, transforming precipitation into surface runoff, representing baseflow to subbasin outflow, and simulating flow in open channels. These groups can be stimulated by several alternative methods for the hydrologic process as outlined in the HEC-HMS user's manual [3].

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Different types of hydrological models, such as Soil & Water Assessment Tool (SWAT), Systeme Hydrologique Europeen (MIKE SHE), and Agricultural Non-Point Source Pollution Model (AGNPS), have emerged with several advantages and disadvantages. Similarly, the HEC-HMS model also has its advantages and disadvantages. This model is an open source software that can simulate runoff and rainfall processes for short and long simulation periods [14]. The disadvantage lies in the manual calibration process, which is time-consuming [15]. In addition, there are two aspects of simplification, including simplified model formulation and flow representation. A simplified model formulation speeds up the running process and provides accurate and precise results. Meanwhile, a simplified flow representation increases the efficiency of the running process [3]. All mathematical models utilized in the HEC-HMS model are deterministic [3, 16].

However, this model has numerous advantages in controlling and solving water resource problems at the watershed scale. In Indonesia, most watersheds still experience flooding, drought, erosion, sediment, and other similar problems [17]. The issues arise in very complex nature, therefore, the availability of a user-friendly hydrological model in this context is required to solve the problem. The selection of the hydrological models depends on the availability of field data. The HEC-HMS model has been used in different contexts to analyze the problem and find the proper solutions or approaches in terms of watershed management.

Therefore, this study aims to (1) summarize and review the uses of HEC-HMS applications in Indonesia, (2) provide the geographical distribution of the model application, and (3) analyze the potential or prospects for utilizing this modeling in the future. Finally, the results can be used as the basis to manage and evaluate the management program of watersheds, particularly by using the HEC-HMS model.

2. Study area

Indonesia is in Southeast Asia, which is crossed by the equator between the mainland of Asia and Oceania and between the Pacific and the Indian Ocean. The geographical location is between 6°08’N to 11°08’S and 94°45’E to 141°45’E. Indonesia is an archipelagic country with many river basins of different sizes. Rivers flow hundreds or even thousands of kilometers, such as the Kapuas River (1143 km) in West Kalimantan, the Mahakam River (920 km) in East Kalimantan, the Barito River (909 km) in Central and South Kalimantan, and the Batanghari River (800 km) in West Sumatra and Jambi Province, Musi River (750 km) in South Sumatra, Eilanden River (674 Km) in Papua, Mamberamo River (670 km) in Papua Province, Martapura River (600 Km) in South Kalimantan, Bengawan River Solo (548 km) in Central and East Java, Digul River (525 km) in Papua, Indragiri River (500 km), and Seruyan River (350 km).

Based on data from the Indonesian Agency for Meteorological, Climatological, and Geophysics obtained from 91 observation stations [18], the average air temperature between 1981 and 2020 is 26.6°C. The average air temperature in 2020 was 27.3 °C, and the average rainfall ranges from 2000-3000 mm per year. Based on data from Statistics Indonesia [19], in 2020, the land cover were more dominated by forest than non-forest, with an area of 1,202,816 km^2 and 674,703 km^2 respectively.

The destruction of watersheds is worsened because of land use, climate changes, population growth, and the lack of public awareness. Therefore, the government prioritized the restoration of Citarum, Serayu, Ciliwung, Solo Lama, Brantas, Cisadane, Kapuas, Siak, Musi, Asahan Toba, Jeneberang, Saddang, Moyo, Way Sekampung, and the Limboto Bone Watersheds to maintain and manage the function of rivers and their ecosystems. This is stipulated in the Medium-Term National Development Plan (2015-2019) and Strategic Plan (2015-2019) documents of the Ministry of Environment and Forestry [2, 20]. Figure 1 shows the location of the watersheds.

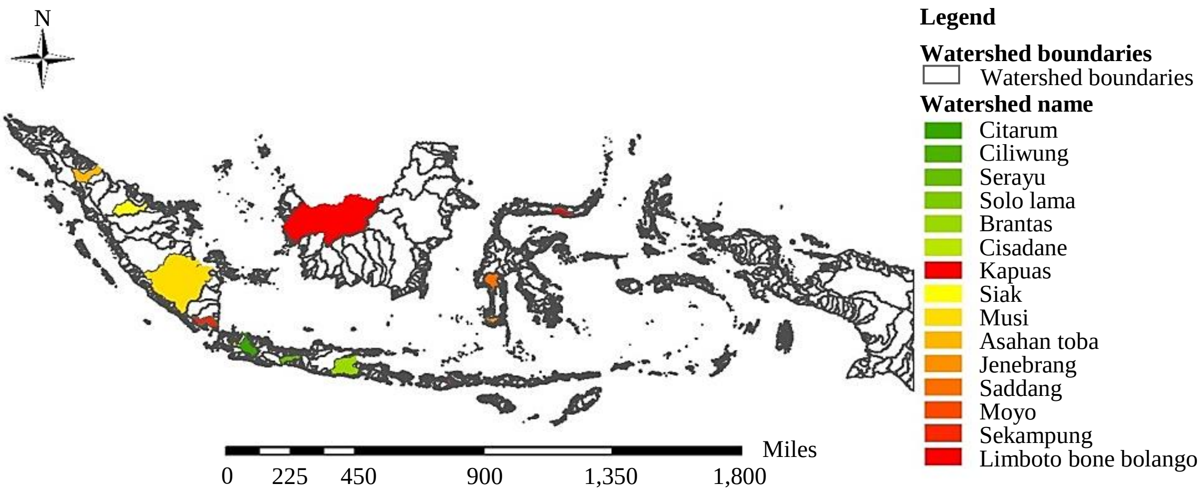


Figure 1 Prioritized watersheds for river ecosystem recovery in Indonesia.

3. Previous HEC-HMS application in Indonesia

Data of HEC-HMS model applications were collected through publicly available peer-reviewed articles. The reports are filtered to include only journal articles and conference proceedings published either in Indonesian or English that experts have evaluated. The number of HEC-HMS application reports found were 180 publications spread across several regions including Java, Sumatra, Sulawesi, Kalimantan, Maluku, and Nusa Tenggara. The 180 publications were processed, and one publication did not mention where this model was applied. Data collection was conducted from December 2, 2021, to February 3, 2022. Search results from all publications or reports regarding HEC-HMS are tabulated in Table 1, with the highest application in Java Island. This coincides with the severity of damage to watersheds on the island, as measured by the critical threshold [21]. In addition, the erosion rate in Java Island is potentially high, caused by various factors, such as land changes that led to the increased sediment flux to coastal areas over the past 150 years [22]. These premises increase hydrological modeling to manage and solve watershed problems on Java Island.

Table 1 HEC-HMS Applications in Indonesia

Region / Island	Count	References
Java	123	[23-145]
Sumatra	29	[146-174]
Sulawesi	13	[175-187]
Kalimantan (Borneo)	7	[188-194]
Maluku	4	[195-198]
Nusa tenggara	3	[199-201]
Not reported area	1	[202]

4. Application trend

The model's first reported application was in 2005 as shown in Figure 2 for the Upper Ciliwung Watershed to determine land-use scenarios and apply engineering perspectives in flood analysis of the watershed. The Upper Ciliwung Watershed is located in West Java Province, and the calibration of the hydrological model was carried out based on recorded discharge data at Katulampa Station. After 2005, the model users increased in other islands in Indonesia. The increase has seen a very drastic number starting from 2015 to 2021. Overall, the highest utilization from 2005 to 2021 is found in Java Island, with 123 publications. The number of users has increased significantly, and it will contribute to establishing a platform that offers better perception sharing regarding water issues. The platform can be useful in management negotiation and finding suitable policy [203]. This model was primarily used in 2020, with 42 publications for diverse reasons. The significant purposes among those are land-use change impact studies. The most frequently used HEC-HMS models are in West, Central, and East Java Province, with 41, 36, and 28 publications.

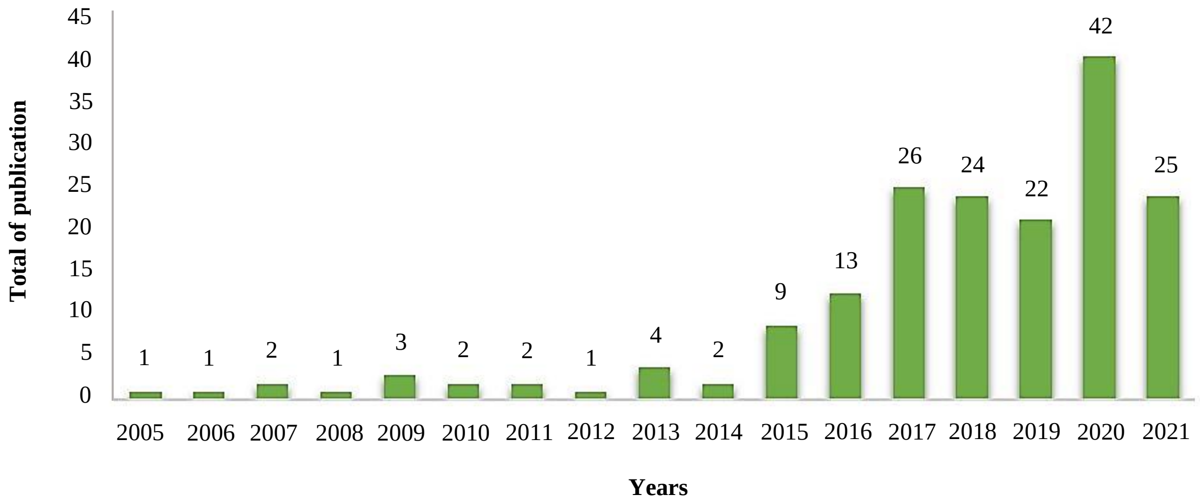


Figure 2 Application trend of HEC-HMS in Indonesia

5. Distribution of HEC-HMS applications in Indonesia

West, Central, and East Java are provinces located on Java Island, with the highest density population in Indonesia [19]. The island of Java's rapid expansion and economic prosperity entice locals to relocate to cities. Urbanization often changes the function of other land use in settlement areas, particularly in the Java Island, which causes the watershed degradation. The resettlement areas are often converted from forest covers and other land use with inappropriate soil capacity [17]. In addition, most of the urban in Indonesia is located near or on small river basins, which often causes several serious problems such as flood [204].

West, Central, and East Java have watershed that has applied the HEC-HMS model the most (Figure 3). For example, the watersheds of West Java are parts of the Ciliwung, Cisadane, and Citarum Watersheds. In contrast to West Java, the distribution of model use in Central and East Java tends not to be concentrated in just a few watersheds.

The second highest use of applications is in Sumatra Island, with 29 publications. West Sumatra Province used this application six times with distribution in Air Dingin, Batang Kuranji, and Batang Mahat Watersheds. In addition, Riau and South Sumatra Provinces have applied the model five times, respectively. However, Riau Province has already experienced this application where the use is spread in the Rokan, Kampar Kiri, and Sipatak Sub-watershed. In South Sumatra Province, this application is in several areas such as Buah, Lematang weir, Weir, Sekanak Watersheds, and an area in Palembang Raya Metropolitan. Meanwhile, using HEC-HMS hydrological modeling application for planning and managing watersheds is still insignificant on other islands.

In Sumatra Island, the only watershed that has not been managed and studied using this application is the Batanghari Watershed in Jambi Province. This is one of Indonesia's largest watersheds, with a drainage of approximately 44,590 km^2. The Batanghari Watershed has an area of 5.3 million ha, but from 1990 to 2013, the land conversion was estimated at around 1 million ha of original forest areas (including primary and secondary forests) into other types of land use [205]. This situation leads to further problems in the watershed, particularly floods caused by the increases in the water level of the Tembesi river in the last two decades [206]. To provide early and proper management of the watershed, HEC-HMS applications can be utilized.

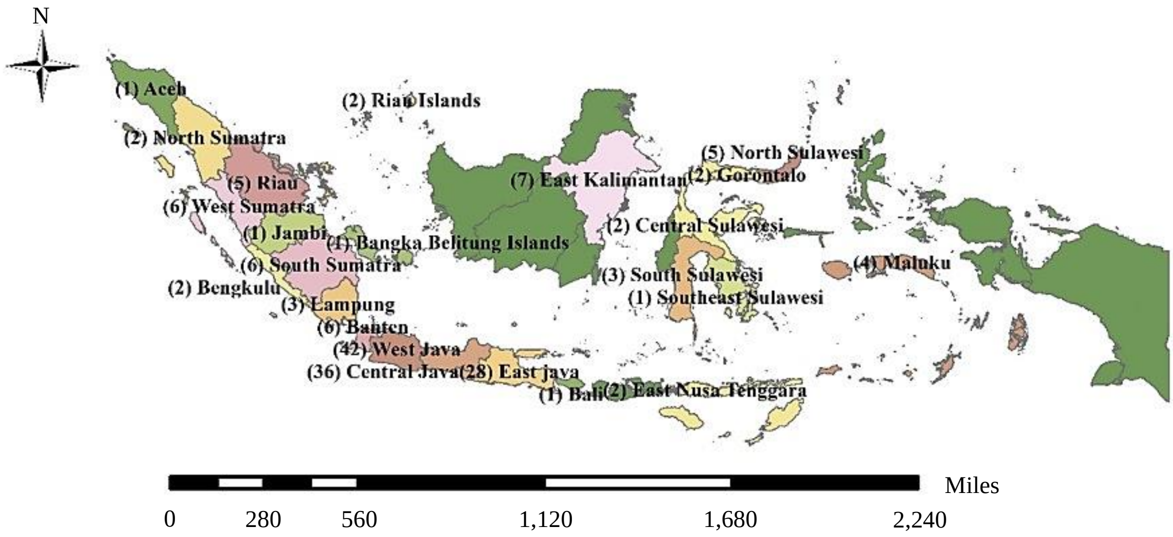


Figure 3 Distribution of HEC-HMS application in Indonesia

According to Figure 3, only East Kalimantan Province has been developed for this hydrological model on Kalimantan Island. This is a positive trend considering the plan of the Indonesian government to move the capital to East Kalimantan Province. Watersheds and sub-watersheds in East Kalimantan have applied hydrological modeling, including Posindo Sub-watershed, Kelay, Bontang Karangmusmus, and Separi Watershed. The relocation of the new state capital will change the environmental conditions or ecosystems in the watersheds in East Kalimantan. Based on statistics data issued in 2020 [1], land use is dominated by a land cover of forests and non-forests at 63% and 37% respectively. Deforestation has continuously occurred in East Kalimantan [207], and this condition will continue to occur when it is not appropriately managed. This will increase the consequence of watershed damage in the East Kalimantan Province. Nevertheless, good and proper management with the help of hydrological modeling is expected to maintain the conditions of remaining in their natural condition.

The other areas of the island of Kalimantan, precisely in the Kapuas Watershed (Figure 1), are prioritized to restore ecosystems and water resources. There is the longest river in Indonesia in the Kapuas Watershed, at 1143 km. The Kapuas River is located in West Kalimantan Province through Kapuas Hulu, Sintang, Sanggau, Sekadau Regencies, and Pontianak City. However, the Kapuas River has recently been polluted by mercury from illegal gold mining activities [208]. Regardless of being polluted by mercury, the Kapuas River is still a place supporting the livelihood of the Dayak and Malay tribes around the river.

Looking at the eastern part of Indonesia, specifically, Papua, as shown in Figure 3, it is discovered that no study on the HEC-HMS model has been conducted. Meanwhile, large watersheds, such as the Membramo Watershed, are also beginning to experience problems with both quality and ecosystems in the watersheds [209]. The Mamberamo River has 670 km in length and a catchment area of 138.877 km² covering 9 regencies. Therefore, it is crucial to provide policies for the area to strengthen the local communities' efforts of protecting the ecosystem [210]. The management should also look at other watersheds in Papua Province, such as the Eilanden, Digul, and other watersheds. Having reviewed the use of the HEC-HMS model, it can be seen that the application is mostly still limited to the damaged watersheds. The application should focus not only on watersheds that are already experiencing problems but also on improving the management to mitigate the damage in the future.

6. HEC-HMS Application based on classification of watershed

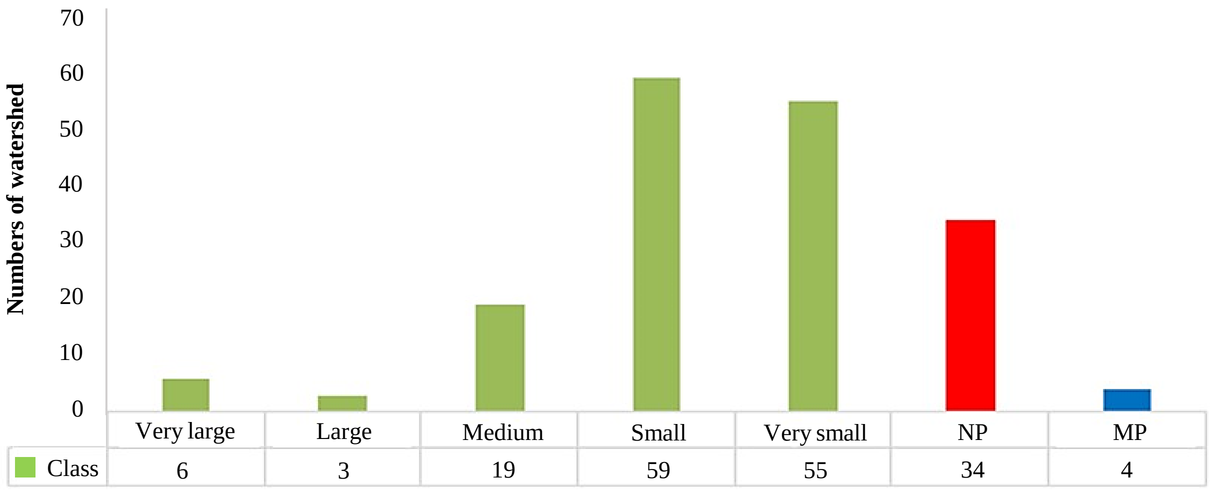
According to the Regulation of the Director-General of Watershed Management and Social Forestry, the watershed area can be classified into 5 size groups consisting of Very Large (1,500,000 ha and above), Large (500,000 ≤ 1,500,000 ha), Medium (100,000 ≤ 500,000 ha), Small (10,000 ≤ 100,000 ha) and Very Small Watersheds (Less than 10,000 ha) [211]. Therefore, the size might affect a hydrological model's calibration process [212]. The larger the watershed area, the longer time is consumed for the calibration and validation process [213]. Consequently, the classification of watersheds (as shown in Figure 4) is essential to indicate that the application of this model in Indonesia is still limited to very small and small sizes of watershed.

From the 180 HEC-HMS applications found, 34 articles do not report the watershed size. Therefore, the use of the "Small" category became the most widely applied and reported in the form of publications. However, in Figure 4, the HEC-HMS model still revolves around watersheds classified as "Very Small" and "Small," which are 59 and 55 times, respectively.

In addition, four publications use the HEC-HMS model in several location and size of watershed in a publication, such as research undertaken by Sharaswati et al. [114], Cahyono and Adidarma [116], Adidarma [117], and Natakusumah et al. [113]. For example, Sharaswati et al. [114] used the HEC-HMS model to analyze the effectiveness of two methods (the SCS Unit Hydrograph and Kinematic Wave) by comparing two hydrographs in Urban and Rural Watersheds. Meanwhile, Cahyono and Adidarma [116], Adidarma [117], and Natakusumah et al. [113] used this model to analyze the occurrence of floods.

7. Challenges and prospects

After exploring the distribution of the uses of this hydrological model in Indonesia from the results of the data in Figure 3, the HEC-HMS is not evenly distributed either by province or watershed size. Even though, the problems of floods, droughts, landslides, and water crises have recently increased in almost all regions. Erosion is another significant worldwide concern and a global challenge that gravely jeopardizes water and soil resources [214]. This shows that watershed management in Indonesia has not promoted sustainable development effectively [215]. Accurate problem estimation in a watershed is crucial for water resources management [216]. In the future, the solution to watershed problems should utilize hydrological modeling that can help effectively and precisely. The role of the model should be considered in this regard [217]. Hydrological modeling uses computerized models and has become an important tool in understanding the effects of human activities on river ecosystems and designing ecologically sustainable water management approaches [218]. The challenge faced in solving the problem is the ineffectiveness of finding solutions related to management. The government should assist and support the improvement of management capabilities related to the environment, institutional framework, and management instruments to contribute to efficient problem solving [219].



*NP: Not reporting size of the watershed, MP: multiple size watershed application

Figure 4 HEC-HMS Model application based on classification of watershed area

Another challenge in using and developing hydrological models is that the availability of meteorological and hydrological recording data is still severely lacking and not evenly distributed. The performance of a hydrological model heavily depends on the accuracy and the amount of observed data [220]. This data limitation will make the modeler challenge the model to calibrate. The conditions will produce a hydrological model with a high level of uncertainty in predicting and will also reduce the level of reliability of the model [221]. Therefore, the HEC-HMS can model processes in a watershed where the hydrological or meteorological observation data is rarely available [222]. It can predict the reliable transformation of rainfall into the runoff for areas with no observation tools available [223].

The government should provide data recordings of hydrology, meteorology, water quality, and others and easily accessible by users in tabular and spatial formats [224]. Indonesia may be able to use hydrological modeling in previously unmodeled regions or islands when data is readily available and dispersed uniformly. The island of Borneo will be one of the targets of researchers or modelers in model development. Moreover, East Kalimantan Province has been planned as the new capital city of the Republic of Indonesia. Instead, the area of East Kalimantan and its surroundings will undergo large-scale land changes or conversions in the future. Several studies have examined the impact of land change within watershed conditions, such as those conducted among others by Kadaryanti et al. [188] in East Kalimantan, Tisnasuci et al. [90] in Central Java, Mujibadi and Lasminto [73] in East Java, and Dwi Indriastuti [57] in West Java Province. These studies will be references for future advanced research, provided sufficient recording data is available.

Another most-discussed issue recently emerged that can affect ecosystems in the watershed is climate change. Climate change influences several vital sectors such as agriculture, marine, and fisheries [225, 226]. Indonesia is often called an agrarian country because most people are engaged in agriculture [227]. In the future, this will be an interesting topic or prospect topic related to hydrological modeling. Hydrological modeling will be a tool to calculate the impact of climate change on the agriculture sectors. Several regions have conducted climate change combined with land use change studies using the HEC-HMS model. For example, those conducted by Sarminingsih et al. [93] in Dengkeng Watershed (Central Java), Mishra et al. [86] in Ciliwung River Basin (West Java), Al Dianty et al. [47] in the Tenggang River (Central Java), and Emam et al. [70] in the Upper Ciliwung River (Jakarta). Based on 180 reports on application of the HEC-HMS model in Indonesia, studies on climate change are still limited compared to those related to land-use changes. This information can also be seen as a prospect for the HEC-HMS model to analyze climate change.

8. Conclusions

The HEC-HMS model can simulate the rainfall-runoff process in a watershed. It can be applied to several studies, such as flood studies, reservoir spillway design, river flow forecasts, urban drainage, future urbanization impacts, and water quality. In the last five years, the use of the model has been prevalent. The highest peak of its use in 2020 is 46 times for various purposes of analysis objects such as land-use change, climate change, flood analysis, and others. Nowadays, Indonesian modelers have challenges developing hydrological models, such as the lack of availability of time series data records in the field. However, with sufficient and uniformly dispersed data, Indonesia may be able to apply hydrological modeling to previously unmodeled regions or islands. As a result, the purpose of the model analysis will be more diverse, such as climate and land change, flood, and other analyses.

This review study will be the groundwork for developing the HEC-HMS model and research in the future. It provides a comprehensive overview of the use of HEC-HMS applications and the distribution of their uses. The limitation of this study is not capturing the performance of the model applied in Indonesia, as most of the articles or publications do not report on the calibration and validation process. Therefore, the future review can be extended to include the classification of hydrological modeling used based on year, region, watershed sizes, and performance of models.

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