HEC-HMS Model for Urban Flood Analysis in Belik River, Yogyakarta, Indonesia

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ABSTRACT The rapid development of Yogyakarta has made city development increase. This construction continues to expand the reach of impervious surfaces. As a result, surface runoff and maximum discharge have increased, overflowing up to urban drainage. This study aimed to analyze the maximum discharge of the watershed based on design storms with 2, 5, 10, and 25-year return periods, used for flood control considerations. The urban flood was modelled using HEC-HMS. The results showed that the contribution of discharge flow in each segment is influenced by the dominance of land use, in which the segment dominated by dense settlements has a high contribution to the maximum discharge. The flow contribution is due to the high curve number value, which corresponds to the high surface runoff. The peak discharge of watersheds with return periods of 2, 5, 10, and 25 years are 8 m³/s, 20.1 m³/s, 29.9 m³/s, and 44.1 m³/s, respectively.

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1. INTRODUCTION

The concept of space utilization in Indonesia is regulated by the Regional Spatial Plan (Rencana Tata Ruang Wilayah), which factors in Floor Area Ratio (FAR). FAR draws on hydrological assumptions that emphasize water conservation to achieve a quantitative balance in rainfall partitioning into infiltrated water and runoff. In developing regions, the prominent obstacle to such an objective is uncontrolled building permits (Izin Mendirikan Bangunan), creating discordance between spatial developments and water conservation principles.

The rapid development of Yogyakarta, a city in Indonesia, has led to changes in space utilization. According to Prihatin (2015), its tourism, trade, and service industries have multiplied intensively, as evident from the development of transportation infrastructure and increased space utilization from single to multiple occupations. Yogyakarta holds the titles of Student City, Tourism City, and Cultural City, which implies a potentially soaring number of people moving into it. As such, there is an increasingly high demand for land to accommodate housing, investment, warehousing businesses, industrial estates, and tourism. Development in the city can continuously widen the extent of impervious surfaces.

Built-up land decreases the ability of a watershed to absorb, retain, and store rainwater, thus increasing surface runoff and maximum discharge (Maria and Lestiana 2014; Nainggolan et al. 2015; Marko and Zulkarnain 2018; Suprayogi et al. 2020). An impermeable soil surface prevents water from infiltrating into the soil. This means that rainfall is mostly partitioned into runoff and can cause rainwater to overflow urban drainage channels. Flooding in urban areas is also caused by the lack of retention and drainage capacity available in the city (Jamali et al. 2018). Some of the areas that were inundated by the overflow of Belik River were around Colombo Street and Kampung Klitren (Suprayogi et al. 2019). Based on local news, events that were quite detrimental were in 2012, 2018, and early 2020. Water overflowed to residents’ houses because the embankment was broken due to not being able to withstand the swift river water.

Flood studies mostly use HEC-HMS (Hydraulic Engineering Center–Hydrologic Modeling System) models for various hydrological simulations in different watersheds. HEC-HMS was created by the US Army Corps of Engineers (USACE) to simulate precipitation–runoff processes. HEC-HMS runs programs for studying watershed physical descriptions, meteorology descriptions, and hydrologic simulations (USACE 2018). According to Bajwa (2002), there are four main contents of HEC–HMS. First, it provides an analytical model for runoff calculation. Second, the components of the hydrological system are graphically represented and illustrated with interactive features. Third, it is a system that can store and manage long time-series data. And fourth, it provides a means of presenting and reporting the model output.

The HEC–HMS model is used to determine the flood discharge of a watershed, so the input data used is simpler than the HEC–RAS model because it does not require river geometric data. Abushandi and Merkel (2013) applied HEC-HMS to reproduce a flood event in an arid catchment, while Halwatura and Najim (2013) used it to simulate runoff in a tropical catchment. Building a HEC-HMS model, Majidi and Shahedi (2012) could synthesize the rainfall–runoff process in a watershed in southern Iran, and Yusop et al. (2007) predicted runoff in an oil palm catchment. In a watershed, periodic floods can occur as streamflow that exceeds channel...
capacity. The Belik Watershed is located in an urban area and is mainly used for residential purposes. Extreme rain events often lead to overflows onto the banks of Belik River. This research is important as one of the inputs in the form of the maximum discharge (flood) of the watershed, so that it can be used to evaluate the capacity of the water channel. This research set out to analyze the maximum discharge of the watershed based on design storms with 2, 5, 10, and 25-year return periods. The analysis results provide consideration for flood control in urban areas.

2. METHODS

2.1 Study area

The HEC-HMS model was applied to the maximum discharge analysis of the Belik Watershed, part of an urban area of Yogyakarta. This watershed covers an area of 8.31 km$^2$, with a river length of 6.93 km. The research began with partitioning the Belik Watershed into three segments based on estimated flood-prone sites; this segmentation is presented in Figure 1. Segment 1 has an area of 2.98 km$^2$ with a river length of 2.23 km, while segment 2 is 1.67 km$^2$ in extent and has a river length of 1.11 km. Segment 3 covers an area of 3.46 km$^2$, and the river is 3.59 km in length.

2.2 HEC-HMS model

The HEC-HMS model applied to the Belik Watershed was comprised of four components, namely a basin model (describing the physical watershed and river network topology), a meteorological model (simulating precipitation data), a control specification (defining the time constraints of the model), and time-series data. A basin model contains the modeling components that describe canopy interception, surface storage, infiltration, surface runoff, baseflow, channel routing, and lakes (USACE 2018). The basin model was created in ArcGIS 10.4 using the HEC-GeoHMS 10.4 extension. The meteorological model was built using a specified hyetograph, where each segment was simulated and assigned with precipitation data. The control specification and time-series data were created with a one-minute interval. The components of the HEC-HMS model were built with the specifications listed in Table 1.

2.3 Curve number (CN) determination

The Belik Watershed is composed mostly of built-up land used for offices and residential areas. Due to this, there is increasingly less rainwater infiltrating the soil, and, thus, a larger portion of rainfall transforms into surface runoff. Details on land use and soil enable the estimation of curve numbers (CN), an input of the HEC-HMS model. The Soil Conservation Service-Curve Number (SCS-CN) was used in this study because it offers a relatively easy method of predicting the quantity of rainwater that changes into runoff. Its requirements are also straightforward: land use data and hydrologic soil conditions. The CN in hydrology is used to predict runoff potential (Castro and Maidment 2020). Here, the SCS-CN value refers to the TR-55 land use description, as summarized in Table 2.

2.4 Maximum discharge analysis

In the HEC-HMS model, the generation of a unit hydrograph requires time-series rainfall records, which in this case were peak storms potentially occurring at a given return period. These data were obtained from the design storm that had an equal duration to the time of concentration (Tc). Tc is the time required for rain falling on the farthest part of a watershed area to reach its outlet. Every segment has a storm duration that is different from the Tc. Total rainfall volume is the design storm assumed to have constant intensity (mm/minute) during Tc. The design storm intensities, serving as the input to the simulation, are presented in Tables 3 and 4.

3. RESULTS AND DISCUSSION

HEC-HMS models are reliable for various hydrological simulations. Although they appear to be straightforward, they are nonetheless deemed to be accurate at predicting floods (Oleyibilo and Li 2010). Sarminingsih et al. (2019) agree that, based on their research in the Garang Watershed, HEC-HMS shows relatively good performance in modeling the rainfall–runoff process. Ud Din et al. (2018) add that the same level of performance even applies to rural watersheds.

TABLE 1. Components of the HEC-HMS model for the maximum discharge analysis of the Belik Watershed.

| No. | Model       | Method            |
|-----|-------------|-------------------|
| 1   | Precipitation| Specified Hyetograph|
| 2   | Transformation| SCS's UH         |
| 3   | Runoff Volume| SCS-CN (TR-55) |
| 4   | Baseflow    | Not Calculated    |
| 5   | Routing     | Lag               |
The percentage of water discharged directly is greater than that which is absorbed into the soil. This condition can subsequently be incorporated into the management of the Belik Watershed. Land use conditions in the Belik watershed in 2013 were dominated by settlements, covering an area of 204.42 ha (Suprayogi et al. 2019). Construction continues to this day, both repairing roads and other infrastructure, as well as construction of new buildings. The decrease in the surface layer of the soil that is replaced by paving, cast block, and asphalt, results in the water catchment area decreasing. The percentage of water discharged directly is greater than that which is absorbed into the soil. This condition can be seen from the CN value (USDA-SCS 1986), areas with population density, commercial, industrial, and asphalt/paved areas have a greater CN value. This means that the greater CN value, the greater the direct runoff. The CN value of the watershed observed was calculated from the land use condition in 2019, as derived through remote sensing image interpretation. The Belik Watershed has a uniform hydrologic soil group, that is, Class A. After calculating the SCS-CN for the entire watershed (as mapped in Figure 5), the analysis continued with estimating the CN value of each segment. The results showed that segments 1, 2, and 3 had average CNs of 68.06, 72.15, and 71.22, respectively. The 5-year design storm simulation resulted in an estimated peak discharge at the outlet of the Belik Watershed was 20.1 m$^3$/s. Segments 1, 2, and 3 accordingly yielded peak discharges of 2.9 m$^3$/s, 8.4 m$^3$/s, and 18.4 m$^3$/s, respectively. The flood hydrograph at the watershed outlet for the design storm with a 5-year return period is presented in Figure 3.

### Table 2. SCS-CN values based on the TR-55 land use description (USDA-SCS 1986).

| Land use description          | TR-55 land use description and curve numbers | CN for hydrologic soil group |
|------------------------------|----------------------------------------------|-----------------------------|
|                              | Cover type and hydrologic condition           | % impervious areas | A | B | C | D |
| Agricultural                 | Row crops - straight rows + crop residue cover - good condition | 64 | 75 | 82 | 85 |
| Commercial                   | Urban districts: commercial and business      | 85 | 89 | 92 | 94 | 95 |
| Forest                       | Woods - good condition                       | 30 | 55 | 70 | 77 |
| Grass/pasture                | Pasture, grassland, or range - good condition | 39 | 61 | 74 | 80 |
| High-density residential     | Residential districts by average lot size: 1/8 acre or less | 65 | 77 | 85 | 90 | 92 |
| Industrial                   | Urban district: industrial                    | 72 | 81 | 88 | 91 | 93 |
| Low-density residential      | Residential districts by average lot size: 1/2 acre lot | 25 | 54 | 70 | 80 | 85 |
| Open spaces                  | Open space (e.g. lawns, parks, golf courses, and cemeteries, etc.) - fair condition (grass cover 50% to 70%) | 49 | 69 | 79 | 84 |
| Parking and paved spaces     | Impervious areas (e.g. paved parking lots, roofs, and driveways, etc. excluding right-of-way) | 100 | 98 | 98 | 98 | 98 |
| Residential 1/8 acre         | Residential districts by average lot size: 1/8 acre or less | 65 | 77 | 85 | 90 | 92 |
| Residential 1/4 acre         | Residential districts by average lot size: 1/4 acre | 38 | 61 | 75 | 83 | 87 |
| Residential 1/3 acre         | Residential districts by average lot size: 1/3 acre | 30 | 57 | 72 | 81 | 86 |
| Residential 1/2 acre         | Residential districts by average lot size: 1/2 acre | 25 | 54 | 70 | 80 | 85 |
| Residential 1 acre           | Residential districts by average lot size: 1 acre | 20 | 51 | 68 | 79 | 84 |
| Residential 2 acres          | Residential districts by average lot size: 2 acre | 12 | 46 | 65 | 77 | 82 |
| Water/wetlands               |                                              | 0 | 0 | 0 | 0 | 0 |

### Table 3. Design storms and times of concentration (Tc) of every segment of the Belik Watershed.

| Segment | Tc (min) | Return period (mm) |
|---------|----------|--------------------|
|         | 2-year   | 5-year  | 10-year | 25-year |
| 1       | 41.29    | 38.25   | 54.26   | 64.49   | 77.39  |
| 2       | 27.97    | 49.59   | 70.35   | 83.61   | 100.33 |
| 3       | 67.91    | 27.45   | 38.94   | 46.29   | 55.54  |

### Table 4. Rainfall durations and intensities as the inputs to peak discharge simulations at every segment of the Belik Watershed.

| Segment | Duration (min) | Intensity (mm/min) |
|---------|----------------|--------------------|
|         | 2-year | 5-year | 10-year | 25-year |
| 1       | 41     | 0.93   | 1.31    | 1.87    | 1.87   |
| 2       | 28     | 1.77   | 2.51    | 3.59    | 3.59   |
| 3       | 68     | 0.40   | 0.57    | 0.82    | 0.82   |

### 3.1 Peak discharge with 2-year return period

Based on the 2-year design storm, the calculated peak discharge at the outlet of the Belik Watershed was 8.0 m$^3$/s. Segments 1, 2, and 3 produced peak discharges of 0.4 m$^3$/s, 2.3 m$^3$/s, and 7.8 m$^3$/s, respectively. The flood hydrograph at the watershed outlet for the design storm with a 2-year return period is presented in Figure 3.

### 3.2 Peak discharge with 5-year return period

The 5-year design storm simulation resulted in an estimated peak discharge at the outlet of the Belik Watershed was 20.1 m$^3$/s. Segments 1, 2, and 3 accordingly yielded peak discharges of 2.9 m$^3$/s, 8.4 m$^3$/s, and 18.4 m$^3$/s, respectively. The flood hydrograph of the Belik Watershed outlet based on the design storm with a 5-year return period is displayed in Figure 4.

### 3.3 Peak discharge with 10-year return period

Meanwhile, based on the 10-year design storm, the estimated peak discharge at the outlet of the Belik Watershed observed was 29.9 m$^3$/s. Segments 1, 2, and 3 yielded peak discharges of 5 m$^3$/s, 13.7 m$^3$/s, and 26.5 m$^3$/s, respectively. The flood hydrograph at the watershed outlet for the design storm with a 10-year return period is presented in Figure 5.
3.4 Peak discharge with 25-year return period

Based on the 25-year design storm, the estimated peak discharge at the outlet of the watershed observed was 44.1 m$^3$/s. Segments 1, 2, and 3 yielded peak discharges of 8.9 m$^3$/s, 21.5 m$^3$/s, and 36.58 m$^3$/s, respectively. The flood hydrograph at the watershed outlet for the design storm with a 25-year return period is shown in Figure 6.

Segment 2 was found to have a high rainfall intensity value as well as high CN value compared with the other segments. However, the highest peak discharge belonged to segment 3. Segment 3 contributed the most to the total peak discharge, which can be attributed to the high CN value and rain volume identified in this segment. A high CN value means that less water is absorbed by the soil, and most portions of the rain landing on the surface transform into runoff. Accordingly, the solution to flood management issues at the studied watershed should involve structures that can capture more rainwater, including infiltration wells and drainage channels constructed with dimensions proportional to the catchment. The longer return period in the calculation of the peak discharge, the greater the peak discharge. The potential for peak discharge can be used as a long-term consideration when constructing waterways or building houses around rivers (floodplains). This consideration is made to reduce future losses.

Efforts to overcome urban floods are not only through structural development. If slowing the flow rate by constructing water structures is constrained, as a result of the lack of vacant land in urban areas, then non-structural mitigation is necessary. Non-structural research was carried out by (Shih et al. 2019), who found that the peak discharge from the modeling results cannot be accommodated by urban waterways, so efforts that can be made to reduce the risk of flooding include mapping the flood inundation areas and making a warning water level. This mitigation method can be applied to the Belik watershed, with modifications. However, this study can only provide peak discharge values, which means the mapping of inundation locations can be reexamined using other methods, one of which is HEC-RAS, to trace the water level along the water channel.

4. CONCLUSIONS

The peak storm discharges of the Belik Watershed for the return periods of 2, 5, 10, and 25 years were 8.0 m$^3$/s, 20.1 m$^3$/s, 29.9 m$^3$/s, and 44.1 m$^3$/s, respectively. The largest flow contribution to these discharges came from Segment 2, which also had a high CN value. The simulation of peak discharge data can be used for flood management, an example of which is the evaluation of the capacity of urban drainage channels, so that when the river overflows it does not inundate housing. Furthermore, peak discharge data simulations can also be used in flood mitigation efforts. Flood control can include harvesting more rainwater by building structures such as infiltration wells or increasing the capacity of drainage channels.
ACKNOWLEDGMENTS

This research was completed with the financial support of the Faculty of Geography, Universitas Gadjah Mada, Indonesia, through the independent research grant program. The authors would like to thank the faculty leadership for the opportunities given and support in this research.

AUTHORS’ CONTRIBUTIONS

SS, R, and RL jointly coordinated and designed the research. R and RL collected data in preparation for field surveys. R conducted a field survey. Meanwhile, data analysis and manuscript writing were done together. All authors read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

REFERENCES

Abushandi E, Merkel B. 2013. Modelling rainfall runoff relations using HEC-HMS and IHACRES for a single rain event in an arid region of Jordan. Water Resour Manage. 27(7):2391–2409. doi:10.1007/s11269-013-0293-4.

Bajwa H. 2002. Towards immersive virtual environments for GIS based hydrologic modeling [Master’s thesis]. [Ames]: Iowa State University. doi:10.31274/rtd-20200803-11.

Castro CV, Maidment DR. 2020. GIS preprocessing for rapid initialization of HEC-HMS hydrological basin models using web-based data services. Environ Model Softw. 130:104732. doi:10.1016/j.envsoft.2020.104732.

Halwatura D, Najim MMM. 2013. Application of the HEC-HMS model for runoff simulation in a tropical catchment. Environ Model Softw. 46:155–162. doi:10.1016/j.envsoft.2013.03.006.

Jamali B, Löwe R, Bach PM, Urich C, Arnbjerg-Nielsen K, Deletic A. 2018. A rapid urban flood inundation and damage assessment model. J Hydrol. 564:1085–1098. doi:10.1016/j.jhydrol.2018.07.064.

Majidi A, Shahedi K. 2012. Simulation of rainfall–runoff process using Green–Ampt method and HEC–HMS model (case study: Abnama watershed, Iran). Int J Hydrol Eng. l(1):5–9.

Maria R, Lestiana H. 2014. Pengaruh penggunaan lahan terhadap fungsi konservasi air tanah di sub DAS Cikapundung [Effect of land use on groundwater conservation function in Cikapundung sub-watershed]. Jurnal Riset Geologi dan Pertambangan. 24(2):77. doi:10.14203/risetgeotam2014.v24.85.

Marko K, Zulkarnain F. 2018. Pemodelan debit banjir sehubungan dengan prediksi perubahan tutupan lahan di daerah aliran Cileungsi hulu menggunakan HEC-HMS [Modelling of flood discharge based on the prediction of land cover change in upper cileungsi catchment area using HEC-HMS]. Jurnal Geografi Lingkungan Tropik. 2(1). doi:10.7454/jgltrop.v2i1.31.

Nainggolan J, HYL, Sutikno S. 2015. Analisis dampak perubahan tata guna lahan DAS Siak bagian hulu terhadap debit banjir [The effect of land use change on the flood discharge in upper Siak watershed]. Jurnal Online Mahasiswa (JOM) Bidang Teknik dan Sains. 2(2):1–9. https://jom.unri.ac.id/index.php/JOMFTEKNIK/article/view/8010.

Oleyibio JO, Li ZJ. 2010. Application of HEC–HMS for flood forecasting in Misai and Wan’an catchments in China. Water Sci Eng. 3(1):14–22. doi:10.3882/j.issn.1674-2370.2010.01.002.

Prijatin RB. 2015. Alih fungsi lahan di perkotaan (study kasus di kota Bandung dan Yogyakarta) [Land use changes in urban area (case study of Bandung and Yogyakarta city]. Aspirasi: Jurnal Masalah-masalah Sosial. 6(2):105–118. doi:10.46807/aspirasi.v6i2.507.

Sarminingsih A, Rezagama A, Ridwan. 2019. Simulation of rainfall–runoff process using HEC–HMS model for Garang Watershed, Semarang, Indonesia. J Phys Conf Ser. 217(1):012134. doi:10.1088/1742-6596/1217/1/012134.

Shih SS, Kuo PH, Lai JS. 2019. A nonstructural flood prevention measure for mitigating urban inundation impacts along with river flooding effects. J Environ Manage. 251:109533. doi:10.1016/j.jenvman.2019.109533.

Suprayogi S, Latifah R, Marfai MA. 2020. Preliminary analysis of floods induced by urban development in Yogyakarta City, Indonesia. Geogr Techn. 15(2):57–71. doi:10.21163/gt_2020.152.07.

Suprayogi S, Marfai MA, Cahyadi A, Latifah R, Fachrurohman H. 2019. Analyzing the characteristics of domestic wastes in Belik River, the Special
Region of Yogyakarta, Indonesia. ASEAN J Sci Technol Dev. 36(3). doi:10.29037/ajstd.591.
Ud Din S, Muhammad NK, Israr M, Nabi H, Mansoorullah K. 2018. Runoff modelling using HEC HMS for Wural watershed. Int J Adv Eng Res Dev. 5(3):434–439.
[USACE] US Army Corps of Engineers Hydrologic Engineering Center. 2018. Hydrologic modeling system HEC-HMS user's manual version 4.3. Davis: US Army Corps of Engineers Hydrologic Engineering Center. https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_4.3.pdf.
[USDA-SCS] US Department of Agriculture - Soil Conservation Service. 1986. TR-55: urban hydrology for small watersheds. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=stelprdb1042925.
Yusop Z, Chan CH, Katimon A. 2007. Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. Water Sci Technol. 56(8):41–48. doi:10.2166/wst.2007.690.