Flash Flood Disaster Reconstruction for Estimating the Available Warning Time, the Case in Sempor River on 21st of February 2020, Mt. Merapi Slope, Yogyakarta Special Region

K Sathya, A P Rahardjo and R Jayadi

1 Civil and Environmental Engineering Department, Universitas Gadjah Mada, Indonesia
2 Master Student, Civil and Environmental Engineering Department, Universitas Gadjah Mada, Indonesia

*Corresponding author: rahardjo.adam@ugm.ac.id

Abstract. Flash floods are hazardous events characterized by short response times. The occurrences of flash flood disasters have increased significantly in the last few years, producing a remarkable casualty number globally. On February 21st, 2020, a flash flood occurred in the Sempor River of the Mount Merapi slope, Special Region of Yogyakarta, Indonesia, causing a significant death of high school students. This study aims to reconstruct the river's hydrologic and hydraulic conditions and identify the available warning time based on the flash flood event. This study extracted the catchment configuration from a Digital Elevation Model (DEM) using the GIS technique. A simulation of flood hydrograph at a control point used the HEC-HMS model, the SCS Curve Number Loss method, and the SCS Unit Hydrograph. The simulated flood hydrograph was inputted into the one-dimensional unsteady flow model of HEC-RAS to simulate water depth and flow velocity. The calibration process adjusts both models' parameters by comparing the simulated peak discharge with the surveyed data. The modelling results provide warning time components. The results of this study can support the decision-making in flash flood risk mitigation for the local communities.

Keywords: Calibration, flash flood, flood reconstruction, hydrologic and hydraulic simulation

1. Introduction

Flash floods are hazardous events that are characterized by short response time [1]. It creates destructive effects worldwide. The occurrences of flash flood disasters have increased significantly in the last few years, causing a remarkable casualty number globally [2]. Around 90% of global death due to flash floods are in Asia, with nearly 200% of occurrences were estimated to increase by 2050 [3]. The severity of flash floods can be influenced by several factors, including soil type, slope, land use/land cover, antecedent rainfall, etc. Flash floods can occur within the small catchment where a low infiltration rate with the steep slope area or the response time of drainage is short [4]. The gathering activities in the mountainous area, including tourist activity and the local population, can be considered a high risk of flash floods [5]. The rainfall range from about 10 minutes in a small catchment to few hours in the more extensive catchment can cause a flash flood [6].
The physical and non-physical efforts of disaster risk reduction are required in disaster prone areas [7]. Early warning information is an essential criterion in disaster mitigation and adaptation [8]. Due to the significant damages and losses caused by flash floods worldwide, flash several researchers in different locations have done flood warning analysis and application. Flash flood study can be carried out using varying methods depending on available resources, data, time, and knowledge [9].

On February 21st, 2020, a flash flood occurred in Sempor River in a sub-catchment of Mount Merapi slope area, Donokerto village, Turi district, Sleman Regency, in Indonesia’s Special Region Yogyakarta. Based on National Disaster Mitigation Agency (BNPB), 257 high school student students took part in scouting activities alongside the river without the attention of weather conditions. Suddenly, the flood with torrential currents swept away the students while ten students were reported to death. This study aims to reconstruct the river’s hydrologic and hydraulic conditions as the method that can be used to identify the available warning time based on the flash flood event with limited data. The result of the study will assist decision-making on disaster preparedness and mitigation plan to reduce that destruction caused by flash floods in future occurrences in the disaster location.

2. Material and Method

2.1. Description of Study Area
This study was conducted into two parts which are hydrological and hydraulic models. The study area of the hydrological model is from the disaster area to the upstream of Sempor river, which is located in Sleman district, Yogyakarta city, Java Island, Indonesia. This basin is located between 7°40'05″S to 7°35'55″S latitude and 110°22'20″E to 110°25'04″E longitude. The Sempor river basin has an elevation range from 351 meters to 1040 meters above sea level. This basin covers an area of 11.14 km². The study area of a hydraulic model of HEC-RAS is located downstream of the catchment with a river length of 3.62 km, as shown in Figure 1. The elevation is between 350 to 472 m above sea level. The average slope of the river is 0.033.

2.2. Data Acquisitions
Rainfall data are available in the Remote Monitoring Hydraulics Laboratory of Civil and Environmental Engineering Department of Universitas Gadjah Mada website. Data from three automatic rainfall recorders were used in this study. A Digital Elevation Model (DEM) data file was obtained from an open-source website http://tides.big.go.id/DEMNAS/ which provides high-resolution data of 8.25 meters resolution cover almost all over Indonesia country. This national DEM data set was built from several data sources, including IFSAR (5m resolution), TERRASAR-X (5m resolution), and ALOS PALSAR (11.25m resolution). The elevation data of the river bed data was extracted from the DEM data. Land use data, including low residential and agricultural areas, were downloaded from the Indonesian Government website and adjusted using Google Earth Pro. The Harmonized World Soil Database Viewer (HWSD Viewer) application was adjusted using extract soil type data. Cross Section (CS) data and maximum water level data in the 21st, February 2020 flash flood event were observed in the field survey from some watermarks.

Figure 1. Map of the study area
2.3. Average Catchment Rainfall

Thiessen polygon method is used to calculate the mean rainfall of the catchment base on several rainfall stations. This method assumed that the amount of rainfall halfway close to the station equal to the observed rainfall of that station [10]. Then the average rainfall over the catchment is given by:

\[
\bar{P} = \frac{\sum_{i=1}^{M} P_i A_i}{A} = \frac{\sum_{i=1}^{M} P_i A_i}{\sum_{i=1}^{M} A_i} = \sum_{i=1}^{M} \alpha_i P_i
\]

(1)

where \( i \) is station number, \( P_i \) is rainfall magnitude of the station \( i \), \( A \) is total catchment area, \( A_i \) is the area of catchment \( i \), \( \alpha_i \) is the weight factor of each station.

2.4. Hydrologic Model of HEC-HMS

2.4.1. The Soil Conservation Service Curve Number (SCS-CN)

The Soil Conservation Service Curve Number (SCS-CN), developed by USDA Soil Conservation Service, is documented in the SCS National Engineering Handbook section.4 Hydrology and revised in 1964, 1965, 1971, 1986, and 1993. This method is used to estimate the direct runoff from a known rainfall event. The CN value depends on the various land cover and soil type conditions [11]. The SCS-CN method was applied in different countries such as Argentina, India, China, South Korea, Malaysia, and Indonesia [12], [13]. The SCS Curve Number Loss method and the SCS Unit Hydrograph were applied in this study. The accumulated precipitation excess at time \( t \) (\( P_e \)) can be determined by the following equations [14]:

\[
P_e = \frac{(P - I_a)^2}{P - I_a + S}
\]

(3)

where \( P \) is accumulated rainfall depth at the time \( t \), \( I_a \) initial abstraction (initial loss), \( S \) is potential maximum retention.

where

\[
S = \frac{25400 - 254CN}{CN}
\]

(4)

CN value can be estimated using Runoff curve numbers for selected agricultural, suburban, and urban land uses antecedent moisture condition II, \( I_a = 0.2S \) [15]

2.4.2. The Control Point

In this study, the hydrological model was carried out in the sub-basin of the Sempor river basin. Five river basins were delineated from Digital Elevation Data (DEM) using ArcHydro tools of ArcGIS. GeoHMS application was used for creating basin configuration. The simulated flood hydrograph of junction 130 is used for the upstream boundary condition hydraulic model, while the output hydrograph of sub-basin W150, W170, and W180 is used for lateral inflow. The calibration location of the hydrologic and hydraulic model was 300 m downstream of the outlet of sub-basin W180, as shown in Figure 2.
2.5. Hydraulic Model of HEC-RAS

One dimensional unsteady flow regime in the HEC-RAS model can compute water surface elevation, discharge, average velocity, and energy slope by using the combination of mass and momentum equations as shown in the following equation [16]:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_i = 0
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial Z}{\partial x} + S_f\right) = 0
\]

where \( Q \) is inflow, \( A \) is cross-sectional flow area, \( x \) is the distance along the channel, \( t \) is time, \( q_i \) is lateral inflow per unit length of the channel, \( V \) is velocity, \( Z \) is water surface elevation, \( S_f \) is friction slope, and \( g \) is the acceleration of gravity.

The river system, including stream centre line, riverbank, and distance between CS was constructed using the RAS Mapper tool in the HEC-RAS. Three inline structures (weir) were input into Geometry data at CS 1.8, 4.8, and 014, while a bridge at the disaster location, which was the calibration location, was located between CS 5.1 and 5.5. The result of the flood hydrograph of junction 30 was applied for upstream boundary conditions at CS 21. The flood hydrograph of sub-basin W150, W170, and W180 was inputted as lateral inflow hydrograph at CS 20.455, 017, and 009. Due to data availability, the
normal depth was selected as the downstream boundary condition at CS 001. The average bed slope of the surrounding CS 001 was used as an estimated energy slope [17]. The average bed slope which was extracted from the DEM data was 0.03. The Manning’s n value was assumed uniformly distributed along the river. By comparing the river bed photograph with the table of Manning’s n value of Chow’s book “Open-Channel Hydraulics”, the Manning’s n value 0.049 was selected in this study [18].

2.6. Calibration
The calibration process is an essential part of the model study. It is required in the hydraulic model for providing a reliable model. It adjusts model parameters by minimizing the difference between the simulation result and the actual observation result [19]. The maximum water level from the HEC-RAS simulation was used for comparing the field observed maximum water level under the bridge at the disaster location. If the simulated peak discharge is not close to the observed data, the calibration was performed by adjusting initial abstraction, lag time, Muskingum K, and Muskingum X parameters in the hydrologic model of HEC-HMS.

2.7. Warning Threshold
In this study, the warning water level was designed to provide warning information to people who take activities in the river. The stability of standing in the river flow does not only depend on hydraulic parameters, but the characteristic of human also involves instability including surface material, actions, experience and training and physical attribute [20]. The flash flood warning threshold was considered base on flood classification using depth-velocity parameters developed by the U.S. Department of the Interior Bureau of Reclamation. The danger levels were divided into the low danger zone, judgement zone, and high danger zone, as shown in Figure 3. People were assumed to be safe in the low danger zone and assumed in jeopardy in the high danger zone. The judgement zone is the gap between both low and high danger zone. In this zone, the necessary safety measures should be included while using the river, and the tourist activity should be stopped to minimize the threat of floodwater.

![Figure 3: Depth-velocity flood danger level for adults. Reprinted from [21]](image)

2.8. Warning Components
The study of warning time components provides a better understanding of the effectiveness of the available resources for flash flood warnings. The warning time components, including maximum potential warning time \( T_{wp} \), detection time \( T_r \), and maximum mitigation time \( T_w \) was calculated as following equation [22]:

\[
T_{wp} = t_{st} - t_{st} \quad T_r = t_{st} - t_{st} \quad \text{and} \quad T_w = t_{st} - t_{st}
\]  

(7)
where $t_{st}$ is the time of starting rainfall, $t_c$ is the time exceedance of threshold, and $t_{et}$, time rainfall causing exceedance of the threshold
Time of starting rainfall, time of rainfall causing exceedance threshold, and time of water level reaches the threshold was simulated using developed hydraulic and hydrological model as following
1. The starting rainfall is at 13:20 February 21st, 2020
2. The first 10-, 20-, 30-minute, until the end of the rainfall event were inputted to get water level and velocity trigger by the cumulative time of 10-minute rainfall. So, the time of rainfall causing exceedance threshold and time of water level reach the threshold can be identified

3. Results and discussions

3.1. Average Catchment Rainfall
Thiessen polygon method was utilized to calculate the influent of each observed rainfall station for average basin rainfall calculation using GIS tools in ArcGIS 10.4.1. The computed Thiessen polygon area is shown in Figure 4. The weight factor of BE-D4, BO (Donoharjo), and Museum Merapi station were 0.34, 0.11, and 0.54, respectively.

The rainfall data of each station has a different observed interval. Therefore, rainfall data from each station were converted to 10 min interval data by using the linear interpolation method. The result of average catchment rainfall from 13:20 to 14:20 in February 21st, 2020 is shown in Figure 5.

![Figure 4. Thiessen’s polygon area](image)

![Figure 5. The average catchment rainfall in February 21st, 2020](image)

3.2. HEC-HMS Result
In this study, the flood hydrograph was simulated using HEC-HMS by using the input average catchment rainfall data of three rainfall stations around the catchment on February 21st, 2020. Figure 6 shows the simulated discharge at the control point from 13:00 February 21st, 2020 to 00:00 February 22nd, 2020, which was used to input into the HEC-RAS model. The simulated peak discharge at junction J30, sub-basin W150, and W170 are 8, 1.7, and 1.4 m$^3$/s. The outflow discharge of sub-basin W180 did not increase and remained at the base flow with a discharge of 0.1 m$^3$/s in the whole simulation.
Figure 6. Simulate flood hydrograph of each sub-basin on February 21\textsuperscript{st}, 2020

3.3. HEC-RAS Result

3.3.1. Simulated Water Level
Figure 7 illustrates the simulated depth of the February 21\textsuperscript{st}, 2020 flash flood in Sempor river at CS 004, 005, 006, and 007. CS 005 had the highest water depth compared to the other three CSs due to the location of this CS is between the bridge and weir. The water surface elevation of CS 005 was affected by the weir downstream. The maximum depth of CS 004, 005, 006, and 007 was 0.75, 1.69, 0.59, and 0.65 m, respectively, as shown in Figure 8.

Figure 7. The simulated water level of CS 004, 005, 006 and 007

Figure 8. The simulation results of CS 004, 005, 006 and 007 during maximum water
3.3.2. Simulated Velocity

Figure 9 illustrates the simulated velocity of the February 21st, 2020 flash flood in Sempor river at CS 004, 005, 006, and 007. The CS 007 had the fastest velocity compared to other CSs with the maximum velocity of 1.64 m/s at 14:50, followed by CS 006 with the maximum velocity of 1.36 m/s at 14:50. The maximum velocity of CS 004 and 005 were 0.7 and 0.36 m/s, respectively. The increasing water level causes the slow velocity of the 005 due to the effect of backwater from the downstream weir.

![Figure 9. The simulated velocity of CS 004, 005, 006 and 007](image)

3.4. Calibration

The calibration of the hydrologic and hydraulic model was carried by adjusting the initial abstraction and lag time of each catchment and Muskingum K and Muskingum X parameters of each reach in the HEC-HMS model. In the calibration process, the initial abstraction was decreased to the lowest value to increase the runoff from each sub-basin. Lag time is an essential parameter for calculating the peak discharge [23]. In this study, the lag times of each sub-basin were calibrated by using the Optimization tool of HEC-HMS. The result of the best fit value of HEC-HMS parameters is shown in Table 1. The Muskingum method was applied for channel routing calculation. The channel routing in this study was used to assist the calibration process since the opsonization point was downstream of the study area. The calibrated Muskingum parameters are shown in Table 2. The simulated maximum water depth at the bridge downstream was 1.69 m at 14:50 compare to the survey water maximum water level from local people, approximately 2 m, and from recorded video was between 1.6 and 1.9 m at 15:00. The result of this calibration could be accepted due to the limitation of information.

| Sub-basin | Initial Abstraction (mm) | Lag Time (min) |
|-----------|--------------------------|----------------|
| W130      | 1.0                      | 20.873         |
| W140      | 1.0                      | 36.48          |
| W150      | 1.0                      | 23.599         |
| W170      | 1.0                      | 34.351         |
| W180      | 1.0                      | 27.73          |

Table 1. Optimized initial abstraction and lag time parameters of HEC-HMS model

| Reach Name | Muskingum K | Muskingum X |
|------------|-------------|-------------|
| R60        | 0.1         | 0.35        |
| R70        | 0.1         | 0.3         |
| R80        | 0.1         | 0.25        |

Table 2. Optimized Muskingum K and Muskingum X parameters of HEC-HMS model

3.5. The February 21st, 2020 Flash Flood

Figure 10 illustrates the depth-velocity of the February 21st, 2020 flash flood event at CS 004, 005, 006, and 007 compared to the warning threshold for adults. The depth-velocity of CS 004 started at the low danger zone and reacted to the judgment level of warning at 14:20 February 21st, 2020 with a depth of 0.55 m and velocity of 0.49 m/s. For the CS 005, the depth-velocity of the base flow was in the judgment
zone and increased to the high danger zone at 14:00 with the depth of 1.44 m and the velocity of 0.13. The depth-velocity of CS 006 started at the low danger zone and increased to the judgment zone at 14:10 with the depth of 0.36 m and velocity of 0.89 m/s and reached the high danger zone at 14:40 with the depth of 0.59 m and the velocity of 1.36 m/s. For the CS 007 the relationship of depth-velocity started at the judgment zone and increased to the high danger zone with a depth of 0.56 m/s and velocity of 1.47 m/s at 14:30.

Figure 10. The comparison between the depth-velocity of CS 004, 005, 006, and 007 on February 21st, 2020 flash flood event and flood danger level threshold for adults

3.6. Flood Detection
The depth-velocity of CS 004 and 006 reaches the judgment zone at the first 50 min and 30 min of input rainfall, respectively. The hydraulic conditions of CS 004 increased to judgment level at a depth of 0.58 m and the velocity of 0.49 m/s, while the CS 006 reached the judgment level at a depth of 0.34 m and velocity of 0.85 m/s as shown in Figure 11.

Figure 11. The comparison between depth-velocity of CS 004 and 006 using first 50- and 30-min input rainfall, respectively, and flood danger level threshold for adults

The depth-velocity of CS 004 did not reach the high danger warning level. As shown in Figure 12, the depth-velocity of CS 005 reached the high danger level of flood warning with the depth of 1.44 m and velocity of 0.13 m/s using the first 30 min of input rainfall simulation, while the depth-velocity of CS 006 and 007 reached the high danger level by input the first 60 min and 50 min of rainfall, respectively.
3.7. Warning Components

Figure 13 and 14 show that the time of starting rainfall was 13:20 on February 21st, 2020, and the time of rainfall causing the flow to exceed the threshold was 14:00, while the time of flow exceeds the threshold was 14:20 at the CS 004. At CS 006, the time of starting rainfall was 13:20, and the time that rainfall caused the flow to exceed the threshold was 13:40. The relationship of depth-velocity of CS 004 and 006 on February 21st, 2020 flash flood reaches the threshold at 14:20 and 14:10, respectively. The summary of the warning time components of the judgement level is shown in Table 3.

| Cross-section | Maximum warning potential, $T_{wp}$ (min) | Detection time, $T_r$ (min) | Maximum mitigation time, $T_w$ (min) |
|---------------|------------------------------------------|-----------------------------|-------------------------------------|
| 004           | 60                                       | 40                          | 20                                  |
| 005           | -                                        | -                           | -                                   |
| 006           | 50                                       | 20                          | 30                                  |
| 007           | -                                        | -                           | -                                   |

In the high danger level of warning, people are not allowed to conduct any activity in the river. The U.S. Department of the Interior (1988) suggested that almost any size of adult in the flood high danger zone
is in danger from floodwater. Since the river bed is filled with stone, people can be hit by the block of stone and causing injury in the river. Figure 15, Figure 16, Figure 17 show that starting rainfall is 13:20 February 21st, 2020 at all CSs. The rainfall caused the depth-velocity of CS 005, 006, and 007 to exceed the threshold at 13:30, 14:10, and 14:10, respectively. The depth-velocity of CS 005, 006, and 007 reached the threshold at 14:00, 14:50, and 14:30 for, respectively. The summary of warning time components of the high danger level is shown in Table 4.

| Cross-section | Maximum warning potential, $T_{wp}$ (min) | Detection time, $T_r$ (min) | Maximum mitigation time, $T_w$ (min) |
|---------------|------------------------------------------|-----------------------------|-------------------------------------|
| 004           | -                                        | -                           | -                                   |
| 005           | 40                                       | 10                          | 30                                  |
| 006           | 90                                       | 50                          | 40                                  |
| 007           | 70                                       | 50                          | 20                                  |

**Figure 15.** The warning time components at CS 005 of the high danger level

**Figure 16.** The warning time components at CS 006 of the high danger level

**Figure 17.** The warning time components at CS 007 of the high danger level

**Table 4.** The warning time components of the high danger level of February 21st, flash flood event in Sempor River at CS 005, 006 and 007
4. Conclusion
The method of flash flood reconstruction was proposed in this study and the analysis of warning time components. The study of the previous disaster events can provide a better understanding of the characteristic of the disaster and the weakness of the system. The analysis of average catchment rainfall using the Thiessen’s Polygon Method showed that the Museum Merapi rainfall station has the highest contribution to the average catchment rainfall with the factor of 54 percent. The combination of the hydrologic model of HEC-HMS and the hydraulic model of HEC-RAS shown good performance for developing the hydraulic simulation in the Mount Merapi slope area. The February 21st, 2020 flash flood event was not caused by an extreme rainfall event and almost no rainfall at the downstream station. Even though this rainfall caused the high danger level of the depth-velocity at some CSs, this condition created difficulty for people to detect the upcoming flood. The simulation result showed that the warning using hydrologic and hydraulic models would provide a sufficient time of the maximum warning potential, but the maximum mitigation time is very short. Furthermore, the improvement of the effectiveness and accuracy in the further study should be done due to the limitation of information in this study. The more reliable observed water level or stage hydrograph should be used for calibration. A detailed study of the danger level of standing in the floodwater, including the weight and height of people who use the Sempor River with proper statistical analysis, should be done to improve the warning threshold effectiveness.

References
[1] Penna D, Borga M, and Zoccatelli D 2013 Analysis of Flash-Flood Runoff Response, with Examples from Major European Events Treatise on Geomorphology 7 ed J F Shroder 95-104
[2] Yao Q, Xie J, Guo L, Zhang X, and Liu R 2016 Analysis and Evaluation of Flash Flood Disasters: A Case of Lingbao County of Henan Province in China Procedia Eng. 154 835–43
[3] Shahabi H, Shirzadi A, Ronoud S, Asadi S, Pham B T, Mansouripour F, Geertsema M, Clague JJ and Bui D T, 2020 Flash flood susceptibility mapping using a novel deep learning model based on deep belief network, back propagation and genetic algorithm Geosci. Front. 12 95-104
[4] Doswell C A 2015 Hydrology, Floods and Droughts: Flooding Encycl. Atmos. Sci. 3 201–8
[5] Chen Y, Wang Y, Zhang Y, Luan Q, and Chen X 2020 Flash floods, land-use change, and risk dynamics in mountainous tourist areas: A case study of the Yesanpo Scenic Area, Beijing, China Int. J. Disaster Risk Reduct. 50 1-10
[6] Corral C, Berenguer M, Sempere-Torres D, Poletti L, Silvestro F and Rebora N 2019 Comparison of two early warning systems for regional flash flood hazard forecasting J. Hydrol. 572 603–19
[7] Styawan A P, Rahardjo A P and Sujono J 2018 Warning Time Analysis of Nasiri River Flash Flood due to Several Possible Natural Dam Break Events J. Civ. Eng. Forum 4 1-12
[8] Huang W, Cao Z, Huang M, Duan W, Ni Y and Yang W 2019 A new flash flood warning scheme based on hydrodynamic modelling Water (Switzerland) 11 1–15
[9] Khattak M S, Anwar F, Saeed T U, Sharif M, Sheraz K and Ahmed A, 2016 Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River Arab. J. Sci. Eng. 41 1375–90
[10] Thiessen A H 1911 Precipitation averages for large areas Mon. Weather Rev. 39 1082–9
[11] Soulsis K X and Vlantzas J D 2012 SCS-CN parameter determination using rainfall-runoff data in heterogeneous watersheds-the two-CN system approach Hydrol. Earth Syst. Sci. 16 1001-15
[12] Shafuan M F A, Nurhidayu S and Kamarudin N 2016 SCS-CN in Tropics: Is It Reliable? Pertanika J. Sch. Res. Rev. 2 1–21
[13] Sari A N, Sujono J and Jayadi R 2016 Perhitungan Hujan Efektif Dengan Metide SCS-CN DAN Pengaruhnya Terhadap Hidrograf Satuan 8 27–38
[14] HEC 2000 Hydrologic Modeling System HEC-HMS Technical Reference Manual
[15] Chow V T, Maidment D R and Mays L W 1998 Applied Hydrology Chow 1–294
[16] Wang J, Zhang Z, Greimann B and Huang V 2018 Application and evaluation of the HEC-RAS– riparian vegetation simulation module to the Sacramento River Ecol. Modell. 368 158–68
[17] Brunner G W and CEIWR-HEC 2016 HEC-RAS River Analysis System User’s Manual. US Army Corps of Engineers–Hydrologic Engineering Center 1–790
[18] Chow V T 1959 Open-channel hydraulics McGraw-Hill Civ. Eng. Ser.
[19] Zimoch I and Bartkiewicz E 2018 Process of hydraulic models calibration E3S Web Conf. 59 1–5
[20] Takagi H, Mikami T, Fujii D, Esteban M and Kurobe S 2016 Mangrove forest against dyke-break-induced tsunami on rapidly subsiding coasts 2009 1629–38
[21] USBR 1988 Downstream Hazard Classification Guidelines ACER Technical Memorandum 19-33
[22] HEC 2008 Hydrologic Modeling System Applications Guide
[23] Watt W E and Chow K C A 1985 A general expression for basin lag time Can. J. Civ. Eng. 12 294–300