Modified geomorphic flood index (GFI) using land use parameter and effective rainfall ratio at Cikapundung River

Asep Ferdiansyah1, Eka Oktariyanto Nugroho2*, Edi Riawan3, Agung Wiyono Hadi Soeharno2, Aditya Rivandi1, Mohammad Farid2, Arno Adi Kuntoro2, Asziola Asyrafli Nazhif4, and Mona Mahmoud Mostafa5

1Water Resources Engineering Master’s Program, Bandung Institute of Technology, Jl. Ganesha 10, Bandung, 40132, Indonesia
2Water Resources Engineering Research Group, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Jl. Ganesha 10, Bandung, 40132, Indonesia
3Earth Science and Technology, Bandung Institute of Technology, Jl. Ganesha 10, Bandung, 40132, Indonesia
4Water Resource Engineering and Management Undergraduate Program, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Jl. Ganesha 10, Bandung, 40132, Indonesia
5Civil Engineering Dept., Faculty of Engineering, South Valley University, Qena 83523, Egypt

Abstract. To determine the flood inundation area requires hydrological data and measurements of river cross sections. Those data are very limited and expensive. The Geomorphic Flood Index (GFI) can be used to identify the initial potential for inundation of an area. Until now, the GFI method only uses Digital Elevation Model (DEM) data and the return period cannot be known. GFI is then modified by using topographic, rainfall and land use maps to determine the potential flood inundation for each return period. Based on the results of the GFI analysis with an n value of 0.31, the result of flood inundation is quite close to the hydraulic approach with a return period of 100 years. To find out the inundation of floods in other periods (2 years to 50 years), it is necessary to modify the GFI by entering the weight in the analysis of the flow accumulation. The results of the modified GFI flood inundation show that the smaller the return period, the lower the flood height and the reduced flood inundation area in the affected areas. Thus, the GFI approach is still good enough for initial estimates in determining flood inundation with quick analysis and lower costs.

1 Introduction

In general, flood hazard maps are generated from a process of hydrological analysis to determine the amount of peak discharge that occurs in a river and are simulated using a hydraulic method to estimate the water level and the area of the inundation. In fact, in certain
areas insufficient data were found for both analyses. To accommodate this, Samela et.al [1] embedded the Geomorphic Flood Area (GFA) tools to detect areas that are prone to flooding, with input data in the form of topographical maps. This study will modify the GFI method by adding parameters of land use and effective rainfall ratio, in addition to topographic maps. With these modifications, a flood inundation map will be generated for each return period in an area. It is hoped that with this modification, it can answer the limited data constraints in the field, if want to do a flood inundation analysis quickly, with cheap funds.

The location of the research was carried out in the Cikapundung watershed. The Cikapundung Watershed is one of the Citarum Sub-watersheds which is very important because its function is to serve the needs of raw water and hydroelectric power and there are 1058 of them living on the banks of the Cikapundung River [2]. Therefore, a flood inundation mapping study is needed to determine the extent of the flood-affected area so that it can reduce the level of exposure to the disaster.

2 Literature Review of Geomorphic Flood Index (GFI)

Manfreda, et.al [3] identified indicators of potential flood exposure based on the geomorphology of a river area. The geomorphology of an area is shaped by many factors (for example, climate, water flow, geology, sediment transport, land cover, and land use). Based on these assumptions, in 2018, Samela et.al [4] used the geomorphic method by applying Digital Elevation Model (DEM)-based procedures to identify flood-prone areas at several test sites located in Europe, the United States, and Africa. The method is embedded in a tool called the GFA tool. This tool enables quick and cost-effective flood mapping by classifying linear binary. Taking into account both spatial and temporal changes in hazards, exposure, and susceptibility, this technique may aid in the performance and updating of risk assessments and management [5]. However, it is important to note that this geomorphological analysis does not take into account processes and interactions with infrastructure. Thus, the tool can only identify areas that are potentially flood-prone.

The GFI model has been utilized by numerous researchers, as evidenced by the relevant literature, and it yields incredibly precise results [1, 4, 6-9]. But the thing that needs to be considered in the development of this Geomorphic Flood Index (GFI) model is the DEM data used. Surface elevation is a necessary component of the calculation, hence using the GFI approach depends on the high-resolution DEM that was added to the input program [10]. DEM is the basic data in this analysis, so the higher the resolution the DEM used, the higher the accuracy that will be produced. In the research conducted by Samela C, et.al [1], it is known that the flood inundation generated by the GFI method is wider than the flood inundation generated by the hydraulic approach method. In the hydraulics approach, there is a secondary flow that is not considered so that the flood inundation area is not as large as that produced by the GFI method. According to him, the inundation produced by GFI is close to the inundation conditions produced by the 100-year hydraulics approach, even though at a certain point there is no flood inundation as described by GFI. The value of n in the GFI method is 0.31. The average value from various literature [1] gives the value of n at about 0.3544.

The n index calculation compares each water depth point (variable \( h_r \)) with the difference in elevation \( H \) (Fig. 1). The \( h_r \) is calculated as a function of the area contribution \( (A_r) \). The flow accumulation is the closest point of the river network that is hydrologically connected to the tested point, with the equation \( \ln[h_r/H] \). The next process is to calculate the inundation height based on the equation:

\[
WD = h_r - H
\]

\[
h_r = b(A_r)^n
\]

Where:
WD : the inundation height  
$h_r$ : the potential water level in the river (the water depth)  
$H$ : the height difference between point one and the riverbed  
$A_r$ : the catchment area connected to the tested location  
n : the exponent that accommodates hydrological and hydraulic parameters that have not been included in the calculations  
b : a scale factor

Fig. 1. Conventional GFI classification in determining areas prone to flooding [11].

According to Samela, et.al [6] n value has some variation among different basins and ranges approximately between 0.24-0.45, whereas in a study conducted by Samela, et.al in [1] in Romania it produced an n value of 0.3544, so that Manfreda, et.al [7] explained that for areas that do not have a standard flood inundation map for GFI model calibration, the n value can be used, while the parameter b can be assigned equal to one.

In this case, the authors did not find a standard flood inundation map for the West Java region, so the authors also conducted a flood inundation analysis using a hydraulics approach. This hydraulic analysis requires input data in the form of flood discharge for each return period. For this reason, a hydrological analysis was also carried out to obtain hydrographs of upstream flood discharge and lateral inflow.

Research with conventional or unmodified GFI, was conducted with the results showing that the accuracy produced by the GFI method is not better than the hydraulics method using the HEC-RAS software. This is because the parameters used in the GFI method only consider topographical conditions, river cross sections and discharge [1].

Another study, conducted by Kubro in [12] and Raco in [13] by modifying GFI which included design rainfall in the flow accumulation shows that the flood inundation produced between GFI and modified GFI. The other idea for modification also has been done the modification to incorporate the gradually varied flow in the spatial analysis for the backwater case [10]. Based on those studies, it can be seen that spatial flood analysis is developed. Other examples include the use of GIS in flood risk assessment using the expert score-AHP method to obtain annual flood disaster risk regionalization [17] and a new spatial method has been developed to improve the parameterization of the spatial analysis method for watershed-scale flood hazard susceptibility mapping [18]. This proposed method is useful for doing a rapid assessment for flood risk analysis to support sustainable cities and human settlements in the Sustainable Development Goals (SDGs) number 11

3 Data and Methodology

3.1 Data collection

The data used in this study are topographical maps obtained from the Water Resources Service, West Java Province with a resolution is 10 m x 10 m, land use maps from the Ministry of Environment and Forestry, Rivers maps from the Geospatial Information Agency, hydrology data from the Regional Office Citarum River (BBWS Citarum) and
3.2 Hydrology analysis

Hydrology analysis is carried out to determine the amount of flood discharge generated in a watershed. The parameters needed to estimate the magnitude of the flood discharge are Land Use, Soil Type, Topography and Hydrological Data. This hydrological analysis uses the HEC-HMS tool with the help of schematic development by the HEC-GeoHMS tool. In principle, this modeling will divide the study area into several sub-watersheds so that each part of the characteristics of the watershed is described [14]. Hydrology analysis is then carried out in 5 stages, namely: (1) Delineation of the boundaries of the Cikapundung watershed; (2) Calculating the design rainfall for each rainfall post which is then carried out by Thiessen analysis for flood analysis and isohite analysis for GFI analysis; (3) Building an HEC-HMS scheme with the HEC-GeoHMS tool with input data in the form of DEM data, land use maps and soil types. Using the Soil Conservation Services (SCS) Curve Number analysis method; (4) Calibrating the HEC-HMS model with the observed flood data parameters using the Recession method; (5) Calculate the design flood discharge using rainfall with a duration of 6 hours using the PSA-007 distribution, for return periods of 2 years, 5 years, 10 years, 25 years, 50 years and 100 years.

3.3 Hydraulic analysis

Hydraulic analysis was carried out using the HEC-RAS method with unsteady analysis. The input data used are in the form of flood plan hydrographs, river cross sections and DEM maps. The expected output in this analysis is a flood inundation map for each return period in a watershed. In this HEC-RAS, two equations are used, namely the continuity equation and the momentum equation.

3.4 Modified Geomorphic Flood Index (GFI) analysis

The modified GFI analysis was performed as same as the conventional GFI using GFA Tools with the help of the QGIS Geographic Information System program version 2.14.22. The input data from this device is DEM processed data such as Fill DEM, Flow Direction, and Flow Accumulation.

Based on this scheme Fig. 2, the GFI modification is carried out on the \( h_r \) equation which is the water depth in a river basin area with the input data in the form of a value of flow accumulation which is the accumulation of flows that occur in a certain area. So the modified GFI equation used is as follows:

\[
 h_r = b(RR)^n \tag{3}
\]

where RR is the volume of rainfall that has gone through the infiltration process in each return period and b is the coefficient that accommodates variations in the value of effective rainfall in each region.

In this study, the coefficient of runoff and extreme rainfall was used which had been calculated for the RR component so that the b coefficient could be ignored. Thus, the GFI equation in this study is modified to become:

\[
 h_r = (RR)^n \tag{4}
\]

where RR is the accumulated flow of each effective rainfall value in each grid. The calculation of effective rain value for each grid is calculated by involving the values of the curve number.
Curve number is a value that describes the condition of loss of rainfall as a result of resistance by the type of land use above ground level. The initial step before carrying out the modification was to compare the results of the GFI inundation with the 100-year return period flood inundation using a hydraulic analysis approach. If the results of the two analyses are close, the n value in the GFA Tool can be used to calculate the GFI Modification development in the Bandung Region and can be used in areas with the same topographical characteristics.

**Fig. 2.** Modification of the geomorphic flood index (GFI).

To calculate the GFI flood inundation for return periods of 50 years, 25 years, 10 years, 5 years and 2 years, it is necessary to modify the GFI by adding a parameter to the process flow accumulation in the form of ratio of effective rainfall of 2 years and 100 years (for GFI 2 years), ratio of effective rainfall of 5 years and 100 years (for GFI of 5 years) ratio of effective rainfall of 10 years and 100 years (for GFI of 10 years) and ratio of rainfall effective rainfall of 25 years and 100 years (for a 25-year GFI) and an effective rainfall ratio of 50 years and 100 years (for a 50-year GFI), using the previously known value of n.

To obtain effective rainfall, it is necessary to map isohite design rainfall in raster form for each return period. In order for this calculation to take into account the conditions of land use and soil type, the following is an equation for calculating the effective rainfall of each design rainfall with the equation:

\[
P_e = \frac{(P - 0.2S)^2}{P + 0.8S}
\]

where \(P_e\) is Rain effective, \(P\) is the Design rainfall, \(S\) is Maximum storage and \(CN\) is the Curve number. With this equation, the effective rainfall distribution will be generated throughout the Cikapundung watershed and then the ratio for each return period will be calculated with the equation:

\[
Ratio = \frac{P_{ef \times year \ return \ period}}{P_{ef \times 100th}}
\]

where \(P_{ef \times year \ return \ period}\) is an effective rainfall of 2 years to 50 years and \(P_{ef \times 100th}\) is 100-year effective rainfall.

### 4 Result and Discussion

#### 4.1 Hydrology analysis

Based on the delineation results of the Cikapundung watershed, the area of the watershed is 144.91 km². The results of the identification that has been carried out, 5 rainfall stations can
be used in the Cikapundung watershed area. The five posts include the rainfall posts Margahayu I, Lembang, Kayu Ambon, Dago Pakar-Bengkok and Bandung.

The rainfall data will be analyzed as input data for two analyses, namely the flood calculation and flood inundation analysis using the modified GFI method. The results of the design rainfall calculation for each return period for the five rainfall posts can be seen Table 1. SCS analysis requires a Curve Number map generated from a table of the relationship between HSG values and land use, as shown in Table 2. Simultaneously, the HEC-HMS scheme is also produced, which contains the Curve Number values for each Sub DAS (Fig. 3).

Table 1. Resume of design rainfall in the Cikapundung Watershed.

<table>
<thead>
<tr>
<th>Tr</th>
<th>Dago Pakar-Bengkok</th>
<th>Kayu Ambon</th>
<th>Lembang</th>
<th>Margahayu I</th>
<th>Bandung</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>96.7</td>
<td>84.9</td>
<td>87.8</td>
<td>81.8</td>
<td>87.2</td>
</tr>
<tr>
<td>5</td>
<td>123.0</td>
<td>98.8</td>
<td>110.8</td>
<td>112.1</td>
<td>111.3</td>
</tr>
<tr>
<td>10</td>
<td>141.4</td>
<td>106.7</td>
<td>128.5</td>
<td>136.4</td>
<td>129.5</td>
</tr>
<tr>
<td>25</td>
<td>165.9</td>
<td>115.5</td>
<td>153.9</td>
<td>172.4</td>
<td>155.6</td>
</tr>
<tr>
<td>50</td>
<td>185.1</td>
<td>121.2</td>
<td>175.3</td>
<td>203.5</td>
<td>177.4</td>
</tr>
<tr>
<td>100</td>
<td>204.9</td>
<td>126.4</td>
<td>199.0</td>
<td>238.7</td>
<td>201.3</td>
</tr>
</tbody>
</table>

To determine the reliability of the hydrological model that has been built, a calibration is needed based on the flood events that have occurred. There were 3 flood events identified at the Komplek Radio water estimating post, namely on March 30 2020 and November 10 2021. The calibration results that have been carried out show that the parameters of the HEC model -The HMS that has been built is already able to approach events in the field. This is shown by the Nash-Sutcliffe values of 0.891 (Fig. 5) for the 30 March 2020 incident and 0.913 (Fig. 6) for the 10 November 2021 incident.

The calculation is then continued by calculating the return period flood discharge at the points used for flood inundation analysis with the HEC-RAS device consisting of 1 point on the main river, namely at the Cikapundung-Maribaya water level station (Fig. 4) and 4 lateral inflow points.

Fig. 3. Map of the distribution of CN values in the Cikapundung Watershed.
Fig. 4. Flood discharge return period PDA Cikapundung-Maribaya.

Table 2. CN values based on HSG values and land use [15].

<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>HSG</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>Primary Dryland Forest</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>Secondary Dryland Forest</td>
<td>45</td>
<td>66</td>
<td>77</td>
<td>83</td>
</tr>
<tr>
<td>3</td>
<td>Primary Mangrove Forest</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>Secondary Mangrove Forest</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td>Primary Swamp Forest</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>6</td>
<td>Secondary Swamp Forest</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>7</td>
<td>Secondary Swamp Forest</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>8</td>
<td>Plantation Forest</td>
<td>57</td>
<td>73</td>
<td>82</td>
<td>86</td>
</tr>
<tr>
<td>9</td>
<td>Plantation</td>
<td>57</td>
<td>73</td>
<td>82</td>
<td>86</td>
</tr>
<tr>
<td>10</td>
<td>Settlement</td>
<td>61</td>
<td>75</td>
<td>83</td>
<td>87</td>
</tr>
<tr>
<td>11</td>
<td>Mining</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>12</td>
<td>Dryland Farming</td>
<td>45</td>
<td>66</td>
<td>77</td>
<td>83</td>
</tr>
<tr>
<td>13</td>
<td>Mixed Dryland Agriculture</td>
<td>35</td>
<td>56</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>14</td>
<td>Swamp</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>15</td>
<td>Savana</td>
<td>68</td>
<td>79</td>
<td>86</td>
<td>89</td>
</tr>
<tr>
<td>16</td>
<td>Ricefield</td>
<td>62</td>
<td>71</td>
<td>78</td>
<td>81</td>
</tr>
<tr>
<td>17</td>
<td>Shrubs</td>
<td>30</td>
<td>48</td>
<td>65</td>
<td>73</td>
</tr>
<tr>
<td>18</td>
<td>Shrubs/Swamp</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>19</td>
<td>Pond</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>20</td>
<td>Open Land</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>21</td>
<td>Water Body</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>
4.2 Hydraulic analysis

Hydraulic analysis using HEC-RAS software with input data in the form of flood hydrographs from HEC-HMS, cross-sectional maps of the Cikapundung River and topographical data of the Cikapundung watershed. The inundation results for the 100-year return period which will then be compared with the GFI results can be seen in Fig. 7.

The results of the flood inundation analysis using the hydraulics approach show that there are flood inundations in the downstream part of the Cikapundung Watershed. This area will be reviewed further and will be compared with the Modified GFI results.

4.3 Modified Geomorphic Flood Index (GFI)

The results of the conventional GFI analysis using DEM data with an n value of 0.31 indicate that flood inundation is visible in the middle and downstream parts of the Cikapundung
watershed. The results of another study [1] show that with an average n value of 0.3544, it is close to the value of flood inundation using a hydraulic approach with a return period of 100 years.

Fig. 8. Comparison of GFI analysis inundation (black) and 100-year return period hydraulics (red).

The results show that the inundation generated by conventional GFI is wider than the inundation generated by HEC-RAS (Fig. 8). This is the same as that produced by Faridani, et.al in [16]. However, at the same point, it can be seen that the area of the inundation that is between GFI and HEC-RAS is quite close.

The next step is to analyze the Modified GFI inundation for return periods of 2 years, 5 years, 10 years, 25 years and 50 years. Modified GFI analysis begins by preparing data such as a Curve Number raster map and an Isohit Map of the design rainfall for each return period to obtain an effective rainfall map and ratio for each return period. The formula used in the calculation of effective rainfall is written in equations (7) and (8).

Following are the results of the analysis of the effective rainfall map (Fig. 9) and the effective rainfall ratio map for 2- and 100-year periods (Fig. 10).

Fig. 9. (a) The effective rainfall return period of 100 years maps. (b) The ratio of rainfall for the return period of 2 and 100 years.

The ratio map will be used in the Modified GFI analysis by including the map in the Flow Accumulation analysis. Following are the results of the Modified GFI for 5 years, 10 years, 25 years and 50 years return period.

The results of the analysis (Fig. 10) which have been carried out indicate that with the decreasing return period, the area of the flood inundation will decrease. To find out the reliability of this Modified GFI model, the locations of the flood events that occurred on December 12, 2022, should be identified based on information from the affected people. The results of recording rainfall at that time were 39 mm at the Dago Pakar rainfall station.
Fig. 10. The inundation of GFI modifications of various return periods.

When compared with the results of the rainfall design calculation, the amount of rainfall is included in the return period of less than 2 years. Hence, the Modified GFI results on the 2-year return period (Fig. 11) can be used to verify the flood on that date.

Fig. 11. Comparison of flood height in the field with modified GFI.

Regions A and B are floods caused by a blockage of the air surface in the drainage leading to the river. Meanwhile, Region C, was caused by river overflow at the bridge and river water entering through irrigation gates.

5 Conclusion

The results of the Modified GFI analysis for the 100-year return period with an n value of 0.31 produce an inundation that is quite close to the inundation produced by a 100-year return period flood inundation with a hydraulic approach. This n value then can be used for analysis in other places, especially in the Bandung area and can also be used in areas with the same topographical characteristics. The results of the analysis show that the Modified GFI method can be used as a solution related to flood inundation analysis for areas that lack data and require fast and cost-effective analysis. Although the results of Modified GFI tend to be greater than the results obtained from identification in the field. The result of GFI is very dependent on elevation data so there are possible points that are not under the conditions in the field. However, this is the first step for the development of analysis in estimating inundation areas based on spatial data.

The acknowledgements

Thanks to DAPT-EQUITY Program, Lembaga Pengelola Dana Pendidikan (LPDP), Ministry of Finance, Indonesia for supporting this publication.
References

2. BNPB, Modul Teknis Penyusunan Kajian Risiko Bencana Banjir (Deputy for Systems and Strategy, Indonesia, 2019)
17. J. Guo, J. Wang, and X. Zhao, Risk Assessment of Flood Disaster in Sichuan Province Based on GIS, in Proceeding of the 9th International Conference on Energy Materials and Environment Engineering, ICEMEE, 8-10 June 2023, Kuala Lumpur, Malaysia (2023)