Flood Hazard Assessment with High Spatial Resolution Under Climate Change Scenario

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Abstract. One of the important components in flood disaster risk reduction is the availability of spatial information on flood risk that include: (1) flood hazard component such as flood discharge \( q \), flood depth \( h \), flood extent \( A \), and flood duration \( t \), and (2) the loss value due to flood which could be quantified in the form of damage costs \( \theta \). Change in the value of risk \( f(h, A, t, \theta) \) was hypothesized to be sensitive to climate change and other environmental factors that exist at a river basin area. Therefore, it is quite important to control the flood disaster risk as a part of adaptation programs to the climate change impacts and to deal with the increasing pressure due to anthropogenic activities. Additionally, to support the action plan and to increase the understanding and awareness related to the flood disaster mitigation, spatial information on flood risk which having high resolution and precision is required. This study aimed to quantify the spatial information of flood hazard with high spatial resolution. Two Dimensional (2-D) flood-modelling system (e.g., rainfall-runoff-inundation) at the river basin scale has been used as the main method in quantifying the flood hazard dimension. Furthermore, this study was focused in the Batanghari River basin, Sumatra and 13 river catchments flow out through the Jakarta Capital City of Indonesia. Obtained hazard information forms the basis for long term management decisions on improving operational flood risk management, especially in order to cope with impacts of the future climate change.

1. Introduction

Geographically, Indonesia is very susceptible to the occurrence of various types of natural disasters especially those related to water-related hazards such as floods, droughts, and landslides. Indonesia, which has abundant water resources, has approximately 5,590 rivers and 600 of them are potentially at high risk of flooding. In total, the extent of flood prone areas within the main river reaches 1.4 million hectares. National Disaster Management Agency (BNPB) quantify the number of location, frequency and intensity of occurrence, as well as the value of losses from the flood disaster are continue to increase within the last 50 years.

Based on the BNPB information (http://www.satuharapan.com/read-detail/read/tren-bencana-banjir-meningkat-514-korban-setiap-tahun), floods and landslides in Indonesia tend to increase. BNPB mentioned that in 2003 there were 266 incidents of floods and landslides and increased to 822 incidents in 2013. In that period, there are 6,288 events or 572 events per year, cumulatively. The highest number of flood and landslide incidents occurred in 2010, which were 1433 events.
Many studies have demonstrated that there is two factors cause the floods occurrence. First, natural events such as very high rainfall (extreme weather) and sea level rise. This condition is exacerbated by the fact that many people live in locations with topographic conditions are lower than river water levels or below sea level. For example, flood event that occurred in some areas of DKI Jakarta Province due to excessive groundwater extraction process and land movement. Second, human activities that cause excessive pressure on land-use demands and later it effects the changes in ecosystem function and environmental degradation.

If there is less integrated and mitigation effort based on society participation then the changes in climate and land-use become more intensive in the future. Thus, it is hypothesized will to continue to contribute the increase of flood hazard and its risk, especially in river basins that have not yet national strategic value. Therefore, the implementation of adaptation program including disaster mitigation in response to climate change at the river basin scale is urgent to be carried out. In this regard, quantification of risks with a strong scientific basis and a higher level of spatial resolution and accuracy are necessary. Another fact, although climate change-related research is already underway, studies of climate change impact projection on flood hazard are still limited in Indonesia. Therefore this paper presents the concept of spatial quantification of flood hazard in river basin scale with high precision by considering the possible impact of future climate change.

2. Methodology

2.1. Study Area

Batanghari River basin (47,479.54 km²) that located in Sumatera Island, and 13 river catchments (6,070.00 km²) which are flowing through the DKI Jakarta Province, the capital city of Indonesia, were selected as study sites. According to the future climate projection result which focused on the change of average monthly rainfall depth, especially in December (peak of rainy season), these two selected study sites are hot spot locations that projected to be experienced with an increase in the number and intensity of rainfall during the future climate period [1].

![Projected changes in average monthly rainfall (%) for December in the period of 2075-2099 compared to the average rainfall of December in the period 1979-2004](image)

**Figure 1:** Projected changes in average monthly rainfall (%) for December in the period of 2075-2099 compared to the average rainfall of December in the period 1979-2004; (a) Batanghari River basin and (b) 13 river catchments flow out through Prov. DKI Jakarta, the capital city of Indonesia

The Batanghari River basin represents a large river basin area dominated by forests, plantations, and agriculture land-uses. An intensive conversion of land-use from forest to agriculture encountered in this basin. Meanwhile, 13 river catchments in DKI Jakarta Province
that classified into small to moderate catchment area. Type of land-use in this area is dominated by settlements, paddy fields, and moor. Along with the increase in population and economic activity, in these study areas, there has been a significant intensification of land-use conversion, especially from agricultural land-use to settlements. As a result, the two selected sites have the same relative problem of increasing the intensity and frequency of flood disasters although they have different flood types and characteristics.

2.2. Flood Hazard as Natural Component of Flood Risk
The amount of flood risk determines the magnitude of the disaster and the level of losses. Generally, the formulation of flood risk in this study is based on the equation as below [2]:

\[
\text{Flood Risk} = \frac{\text{Flood Hazard} \times \text{Exposure} \times \text{Susceptibility}}{\text{Control Measures}}
\] (1)

Flood risk value is affected by the magnitude of the flood hazard; biophysical condition of river basin which is represented by the vulnerability factor, and; existing flood control measures. Dynamics changes of the flood hazard values are quantified based on the changes of flood dimension that consists of: flood depth \((h)\), flood extent \((A)\), and flood duration \((t)\). Flood hazard dimension is strongly influenced by the duration and intensity of extreme rainfall with probabilities of occurrence \(P\). The vulnerability factor of river basin biophysical component can be explicitly determined by the exposure and susceptibility. Nevertheless, both components (exposure and susceptibility) could be implicitly quantified in the form of damage costs (\(\theta\)). If flood risk unit given in the form of loss value with nominal of rupiah (\(Rp\)) then equation 1 can be simplified as follow:

\[
\text{Flood Hazard} = f(P[h, A, t])
\] (2)

\[
\text{Flood Risk} = f(P[h, A, t], \theta)
\] (3)

Figure 2: Schematic diagram of physically-based distributed rainfall-runoff model linked with flood inundation model

2.3. Spatial Quantification of Flood Hazard Dimension under Climate Change
As mentioned above, this study focused on spatial quantification of flood hazard dimension at river basin scale for both selected study areas. Herein, to address the objective of study an integrated rainfall-runoff and flood inundation model made at the Research Centre for Limnology, LIPI and DPRI Kyoto University has been employed to transform the observed, simulated, and projected rainfall extremes into hydrological responses and flood hazard information. This linked model is based on a one-dimensional kinematic wave equation
for rainfall-runoff routing at the hillslopes (Modified Cell Distributed Rainfall-Runoff Model, CDRMV) and two-dimensional dynamic wave and shallow water equations for rainfall-runoff-inundation simulation (Rainfall-Runoff-Inundation, RRI) in the river, plain, and urbanized areas (see Figure 2). Detailed information of both models can be seen in these references [3], [4]. The model accepts spatial information at "grid" scale in terms of topography, soil property, land-use, and meteorological data. The advantage of the proposed model is applicable to be run on either a single river basin or multi river basins such as in the study region.

The rainfall-runoff model was based on a kinematic wave approach and simulates three lateral flow mechanisms including subsurface and surface flows [5]. The model simulates: (1) subsurface flow through capillary pores; (2) subsurface flow through non-capillary pores; and (3) surface flow on the soil surface.

2.4. Climate Change Data

The rainfall data used in analyzing the climate change impact on flood hazard was retrieved from the super-high-resolution Atmospheric General Circulation Model (AGCM) 3.2 output with a 20-km grid and 1-h spatio-temporal resolution, called MRI AGCM3.2 20-km which is a new version of MRI-AGCM [6]. Moreover, the climate change data used were made by the Meteorological Research Institute (MRI) of Japan Meteorological Agency (JMA) and collected through the collaborative research work between the Kyoto University Japan and the Indonesian Institute of Sciences (LIPI). Herein, the present (1979-2003) and future (2075-2099) averaged daily rainfall data were applied in this study as the forcing data input for the model.

The framework to assess and evaluate the impact of climate change on rainfall extremes and flood hazard/risk is shown in Figure 3. The propagation of flood risk will be processed across meteorological (rainfall), hydrological, infrastructural, social-economic impacts and responses with considering historical flood disasters.

**Figure 3:** Concepts (frameworks) for spatial quantification of flood hazard and risk at river basin scales under scenarios of global climate change impact
3. Results & Discussion

3.1. Existing Flood Hazard (Risk) Made by BNPB

![Figure 4](image)

**Figure 4:** The existing flood hazard index for DKI Jakarta Province (left) and the Batanghari River basin that belong to Jambi Province, Sumatera (right)

Spatial information of flood risk in the Batanghari River basin and DKI Jakarta Province in the form of hazard maps had been made by the BNPB in cooperation with several related agencies (Figure 4). Based on Figure 4 can be summarized that the shortage of these existing flood risk maps as follow: (1) the information was qualitatively provided, i.e. in the form of hazard levels, which are low, medium and high; (2) the spatial resolution is relatively low, given in administrative units such as districts or sub-districts generally serve as the smallest unit of risk identification, and (3) climate change factors have not been included as important variables in the flood risk map delineation process. In order to detail the existing map, the concept of flood hazard quantification conducted in this study was designed to obtain flood hazard maps with high spatial resolution. The map provides spatially quantitative information on flood hazard dimension, in especially in the form flood depth and inundated area.

3.2. Rainfall-Runoff Linked Inundation Model Performance

Model calibration was done by adjusting the model parameters in order to obtain the best fit between the model output and the observed data. Then, the same calibrated model parameter are used in the next model application. Observed water level data from Ancol Station which located at the Batanghari River segment of the Jambi City (Kota Jambi) during November-December 2003 had been used for the model calibration process. Figure 5 shows the comparison between the simulated water level and its observed data in response to the observed rainfall that induced the worst flood occurred in 2003. The model calibration was explored with using three sources of rainfall data, namely: (1) rainfall data from Balai Besar Wilayah Sungai (BBWS) Sumatera VI, (2) rainfall data as the product of Global Satellite Mapping of Precipitation (GSMaP); and (3) rainfall data from the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG). The model output performance was measured using an index, namely Relative Error (RE). The simulated water level that using GSMaP rainfall data input resulted the lowest RE of -2%. Negative value means that the simulation slightly underestimated. Nevertheless, the error is much closer to 0 value, means that the model is applicable to the next condition.
Figure 5: Observed and simulated water levels at the Ancol Station, Jambi City during calibrated period (flood in Nov-Dec 2003) using three rainfall data sources, as follows: (1) gauging station data collected from BBWS Sumatera VI; (2) gauging station data obtained by BMKG; and (3) satellite-based rainfall product, called as reanalysis GSMaP

3.3. High Spatial Resolution of Flood Hazard Map at River Basin Scale under Present Climate

Calibrated the linked Rainfall-Runoff Model (Advanced CDRMV) and Inundation Model (RRI) has been applied to both selected study area to delineate flood hazard map under present climate condition with high spatial resolution. For the case of large river basin such as Batanghari River, 500-m grid resolution was used, while for 13 DAS in Jakarta used smaller resolution, 90-m grid resolution. For example, the manufacture of spatial flood hazard distributions under present climatic conditions for the Jakarta case and the Batanghari River basin are presented in Figures 6 & 7, respectively. The flood incident of February 2002 in Jakarta and the flood incident of December 2003 in the Batanghari River basin was chosen as the basis for the selection of extreme rainfalls under present climate, as used for the model input in assessing their flood hazard.

Subsequently, by using the calibrated linked rainfall-runoff and inundation distribution model, the spatial information of the flood hazard components in unit $h$ and the flood area could be quantified. The initial flood hazard simulation results in both study sites show high spatial information. For example, at the Batanghari River basin, obtained flood hazard dimension covered those hot spots which had been categorized into flood-prone areas with medium to high category (see Figure 4). Those areas spread from the middle to downstream of the basin. Likewise for Jakarta, the propagation of flood hazard dimensions through the locations which frequently flooded, namely the downstream of the catchments, especially North Jakarta, West Jakarta, and Central Jakarta. In summary, the flood hazard map with high spatial resolution is expected to help the stakeholders of flood disaster management, especially BNPB, by integrating this detail information flood hazard map with those had been made previously (Figure 4).

Figures 8 & 9 show the impact of climate change on flood hazard dimension in the Batanghari River basin. The model was run using daily rainfall data input from two periods of climatic data from MRI AGCM3.2 20-km. The model outputs then processed to account the future changes on inundated area, flood frequency, and flood water volume. Figure 8 clearly shows that future climate change affects significantly the dimension of flood hazard, such as flood inundation frequency and its total area. In general, the flood hazard level in the future condition is predicted to be higher compared to the baseline condition (present).
Figure 6: Flood hazard spatial information for the Jakarta Capital City of Indonesia, it was delineated from the simulated flood inundation depth (m) occurred in February 2002. The spatial information of the inundation pattern can be compared with the observed inundation pattern (observed; bottom left picture). ’Tinggi Genangan’ means flood depth, as listed in the figure.

Furthermore, the temporal dynamics of the flood hazard dimension for each location (grid) under both climatic conditions can be converted into the unit of risk values (Figure 10) using Equation 3 based on defined rainfall data input (Tabel 1) and flood-damage curve relationship curves (Figure 9). The values of damage and losses can be made based on the inventory data of losses generated from the historical flood disaster that ever happened.

4. Summary
The concept of spatial risk formulation by incorporating aspects of climate change and river basin characteristic, had been made and applied in the Batanghari River basin and 13 River Catchments flow out through the Jakarta city. Physically-based distributed hydrological modeling system, by coupling a rainfall-runoff model and flood inundation model, was used as the main method in quantifying the flood hazard dimensions (q, h, A, t). The flood hazard map with high spatial resolution was designed to help the stakeholders related with flood disaster management, such as BNPB. Potentially, it has capability to provide detail information to the existing flood hazard map as made by BNPB.
Figure 7: Flood hazard spatial information in the Batanghari River basin delineated from the simulated flood inundation depth (m) occurred in December 2003. ‘Tinggi Genangan’ means flood depth, as typed in the figure.

Figure 8: Comparison flood inundation frequency in the Batanghari River basin for present (1979-2003, left figure) and future climate (2075-2099, right figure) conditions. Flood occurrence at each grid is calculated if flood depth ($h$) is more than 50 cm.

Figure 9: Changes in flood hazard dimension $A$ and $h$ (flood area and flood volume/depth) in the Batanghari River basin for present (blue color, SP-BC) and future climate (red color, SF-BC) conditions.
Table 1: Design rainfall depth for 15-day duration ($t$) and different return periods for present & future climates

| Return Period | Present | Future RCP 8.5 |
|---------------|---------|---------------|
| 10 years      | 234.0   | 323.8         |
| 30 years      | 245.1   | 463.9         |
| 50 years      | 249.7   | 562.8         |
| 100 years     | 256.0   | 756.9         |
| 200 years     | 262.0   | 1047.1        |

Figure 10: Flood depth - damage cost ($h-\theta$) curve functions for agriculture and residential area in the Batanghari River basin [7]

Figure 11: Simulated flood risks (Equation 3) for the present and future climate with 100-Year rainfall return period and 15-day duration within residence (left) and agriculture (right) areas in the Batanghari River basin

In order to investigate the impacts of climate change, at least two different climatic periods, the current and forward-looking conditions, was used in the analysis. Future climate change was projected to have significant impact on increasing the level of hazard in terms of flood frequency, area and depth as well as its flood risk as detected in both study areas.

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References

[1] Apip. 2014. “20-km, 1-jam MRI-AGCM3.x” Model Iklim dengan Resolusi Tinggi: Potensi Aplikasinya untuk Proyeksi Dampak Perubahan Iklim terhadap Cuaca Ekstrim dan Kondisi Perairan Darat di Indonesia. Warta Limnologi. No.52/Tahun XXVII, Juni 2014, pp. 9-14.

[2] Tariq MAUR, Hoes OAC and Van de Giesen NC. 2013. Development of a Risk-based Framework to Integrate Flood Insurance. Journal of Flood Risk Management, Vol. 7, pp. 291-307.

[3] Apip, Takara K, Yamashiki Y, Ibrahim AB, Sassa K, and Fukuoka H. 2010. A distributed hydrological–geotechnical model using satellite-derived rainfall for shallow landslide warning in a large basin. Landslides, ISSN 1612-510X, Vol. 7, No. 3, pp. 237-258. DOI 10.1007/s10346-010-0214-z.

[4] Sayama T, Ozawa G, Kawakami T, Nubesaka S and Fukami K. 2012. Rainfall-Runoff-Inundation Analysis of Pakistan Flood 2010 at the Kabul River Basin. Hydrological Sciences Journal, 57(2), pp. 298-312.

[5] Tachikawa Y, Nagatani G, and Takara K. 2004. Development of stage-discharge relationship equation incorporating saturated-unsaturated flow mechanism, Annual Journal of Hydraulic Engineering, JSCE 48, pp. 7-12 (Japanese with English abstract).

[6] Mizuta R, Yoshimura H, Murakami H, Matsueda M, Endo H, Ose T, Kamiguchi K, Hosaka M, Sugi M, Yukioto S. 2012. Climate simulations using MRI-AGCM3. 2 with 20-km grid. J Meteorol. Soc. Jpn. Ser II 90:233–258. https://doi.org/10.2151/jmsj.2012-A12

[7] Huizinga J, Moel HD, Szewczyk W. 2017. Global flood depth-damage functions. JRC Technical Reports, European Comission, pp. 1-114.