A new assessment methodology for flood risk: a case study in the Indus River basin

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Abstract In this paper, the authors suggest a new flood risk assessment based on extreme discharge of the end-of-the-21st century scenario, and developed a model based on the concept of flood hazard that was composed of extreme discharge in climate change scenarios, saturation deficit during the extreme discharge, and flood periphery related to the flood disaster. The purpose of this study was to estimate, on a national scale, the number of the population possibly affected by flooding with each additional metre of inundation. The Indus River basin in Pakistan was selected as the prime research focus area. As a result, our integrated analysis was capable of predicting disaster damage caused by a hazard in a given area, considering the occurrence probability of the hazard and the vulnerability of the area. This approach is expected to play an important role in emergency response on a national level.

Key words flood hazard; extreme discharge; saturation deficit; inundation depth

INTRODUCTION

Background

Flood effects can be local, only impacting a local community, or they can be very large, affecting an entire nation. Floods may be caused by frequent localized torrential downpours, occasional severe typhoons, or by many other causes. A 100% safety by flood risk prevention is impossible. Flood risks are everywhere in our life. Flood risks should be examined in terms of possible climate scenarios, assessing the spatial distribution of property damages, social and economic disruption and other losses within regions that might be affected. Methods for such flood risk assessment (FRA) have not been well established (Waarts & Vrouwenvelder, 2004; Stokkoma & Wittera, 2008). FRA in current practice is mainly on rainfall and river flood frequency estimation (Calver, 2009). More recent FRA approaches take into account other aspects such as economic impacts integrating a wide variety of flood control measures in a floodplain (Ichikawa et al., 2007; Yoshimura et al., 2008; Hara et al., 2009).

For climate change assessment, a super-high-resolution atmospheric general circulation model (MRI-AGCM3.1S) with a horizontal grid size of about 20 km, has been developed based on the Japan Meteorological Agency (JMA) numerical weather forecast model (Kitoh et al., 2009). The grid size of MRI-AGCM3.1S is approximately 10 times as fine as that of most climate simulations previously done, such as CMIP3 coupled climate models, medium resolution with grid spacing of about 120 km (Parry et al., 2007). Therefore, the MRI-AGCM3.1S model is expected to reproduce extreme events such as heavy precipitation more realistically than other models. Blockwise TOPMODEL (BTOP model, Takeuchi et al., 2007) is an extension of the TOPMODEL concept (Beven & Kirkby, 1979) made applicable in a grid-based framework for distributed hydrological simulation of large river basins. This extension was developed by redefining topographical indices by using an effective contributing area per unit grid cell area instead of the upstream catchment area per unit contour length and also by introducing the concept of mean groundwater travel distance. Using daily precipitation derived from MRI-AGCM3.1S simulations as input data for the BTOP model, the authors developed and proposed the daily runoff and saturation deficit (SD) of each grid in many basins around the world.
Objective
The purpose of this study was to estimate the number of the population possibly affected by flooding with different levels of inundation depth in Pakistan. The inundation depth was estimated by using a model with a simplified geomorphologic algorithm. The estimation method was validated by comparing flood peripheries resulting from the current extreme discharges estimated in the BTOP model based on present, near-future and end-of-the-21st century simulations using MRI-AGCM3.1S.

Study area
The Indus River basin in Pakistan was selected as the prime research focus area. The Indus River is a major river which flows through the full length (its length is about 2900 km, and its area is 1 165 500 km²) of Pakistan. It is located at latitude 23°45′N to 36°50′N and longitude 60°55′E to 75°30′E. The selected area suffered from a huge, severe flood caused by abnormally heavy rainfall from late July to early August in 2010. The Pakistan Meteorological Department reported that Khyber Pakhtunkhwa Province received 9000 mm of rainfall, 10 times as much as the province normally receives in the course of an entire year (UNIFEM, 2010). These intensive rainfall events contributed to further swelling of major rivers, which had already swelled due to rainwater surging down from the highland areas. An estimated 1200 people were killed in the disaster, with approximately 20 million becoming refugees.

FLOOD RISK ASSESSMENT

Definition of flood risk
Flood risk ($RISK_{flood}$) was defined as the expected disaster damage caused by a hazard in a given area considering the occurrence probability of the hazard and the vulnerability of the area. The authors developed a model based on the concept of flood hazard ($Hazard_{flood}$) which was composed of extreme discharge in climate change scenarios, saturation deficit (SD) derived from the extreme discharge, and flood inundation area, as described below:

$$RISK_{flood} = Hazard_{flood} \times Vul_{population}$$  

where $Vul_{population}$ is the vulnerability expressed by population in the affected area based on the LandScan™ Global Population Database (1 km-mesh) developed by the Department of Energy’s Oak Ridge National Laboratory (ORNL). The “×” represents GIS-based overlay and raster calculation.

Data used
A quantitative assessment of flood hazard was conducted by using GIS-based flood hazard parameters which were converted from source output data, as shown in Table 1.

Extreme discharge Extreme discharge is an indicator of flood hazard that indicates how potentially destructive the flood peak discharge is. In this study, the flood risk was evaluated by the expected disaster damage caused by the maximum discharge during 25-year simulations. The extreme discharge was calculated by the BTOP model using the precipitations of 25-year simulated MRI-AGCM3.1S data sets for present-day (daily data from 1980 to 2004), near future (daily data from 2015 to 2039) and end-of-the-21st century (daily data from 2075 to 2099) (Kitoh et al., 2009). For calculation by the BTOP model, there are some discrepancies between MRI-AGCM3.1S precipitation output and observation. The bias is corrected by the simple statistical bias correction method proposed by Inomata et al. (2011).

Saturation deficit SD is the saturation deficit of the soil layer of the ground which indicates a remaining capacity to saturation level to become a contributing area for discharge occurrence:
Table 1 GIS-based flood hazard parameters.

<table>
<thead>
<tr>
<th>Flood hazard parameters</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme discharge</td>
<td>Maximum discharge</td>
<td>Bias corrected precipitation (Inomata et al., 2010)</td>
</tr>
<tr>
<td></td>
<td>20-km mesh</td>
<td>BTOP model (Takeuchi et al., 2008)</td>
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<tr>
<td>Saturation deficit</td>
<td>Soil moisture storage deficit</td>
<td>BTOP model (Takeuchi et al., 2008)</td>
</tr>
<tr>
<td></td>
<td>20-km mesh</td>
<td></td>
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<tr>
<td>Flood inundation depth</td>
<td>Accumulated flood level index</td>
<td>DEM, River, Flow direction</td>
</tr>
<tr>
<td></td>
<td>250-m mesh</td>
<td>HydroSHED15S (SRTM from USGS)</td>
</tr>
</tbody>
</table>

\[ SD = -m(\ln r_k + \gamma + \ln D) \]
where \( m \) is the discharge decay factor, \( r_k \) (m/d) is the spatially homogeneous recharge rate over the block, \( \gamma \) is the topographical index, and \( D \) (m/d) is the groundwater dischargeability. The smaller the \( SD \) value, the easier it is to saturate areas around the channel. The \( SD \) values range from \(-1.0\) to \(1.0\). The smallest \( SD \) value, \(-0.63\), indicates higher vulnerability than any other grid saturation along the stream in the Indus River basin.

**Potential flood inundation depth** Flood surface elevations can be mainly determined from the undulations and roughness of a ground surface. The periphery of flooded areas is directly correlated with an inundation depth around the river. Therefore, it is clear that potential flood inundation depth (\( FID \)) indicates the depth due to overflowing the banks of a river and can be defined as the accumulated level index. Kwak & Kondoh (2010) developed and proposed potential \( FID \) for basin-wide flood risk assessment at the national level. Potential \( FID \) was determined based on DEM and the highest water level (\( HWL \)) of the main stream, as shown below:

\[
H_{i,j,FID} = H_{i,j(DEM)} - H_{i,j(HWL \ of \ river)}
\]

(2)

where, \( H \) is the height of surface, \( i \) is the number of pixels, and \( j \) is the number of lines.

Fig. 1 Schematic diagram of the overflow estimation algorithm for computing the potential flood inundation depth using DEM, flow direction and river network.
Actual calculation of FID required a data set composed of DEM, flow direction and river network. First, the main stream was set as 0 metre (FID = 0 m) after the DEM of the target pixel was subtracted from HWL. Second, another target pixel with a depth of 2 m found the main stream along the flow direction. Third, the differential height of a target pixel was defined the flood inundation depth (FID = +2 m, Fig. 1). Finally, the accumulated depth of the target pixel was raised by 1 m. However, the FID model has some weaknesses. The, the model is only capable of expressing depth with accuracy as good as 1 m due to the limitation of HydroSHED15S/DEM. Also, these DEM data are not capable of expressing main-stream banks (including artificial embankments), which also affects the accuracy of the FID model. Another problem is the difference found in expressing receding floodwaters between the FID model and the Q–H curve (flow vs height) or a hydrological model. The model also needs validation for time series and dynamic flood events. These problems need further consideration in the future to ensure the accuracy of the FID model though the accuracy limitation can be solved by applying linear interpolation.

**Risk analysis methodology**

The authors suggested a new flood risk assessment based on extreme discharge of the end-of-the-21st century scenario using MRI-AGCM3.1S under the A1B emissions scenario by using a 20-km mesh atmospheric general circulation model developed by the Metrological Research Institute (MRI) and Japan Meteorological Agency (Kitoh et al., 2009). For the determination of flood risk assessment, quantitative assessment was divided into two steps. In the first step, Hazardflood was calculated as the function of three hazard parameters and overlays raster map layers – extreme discharge in channel (Q_{extreme}), SD and FID – as follows:

$$\text{Hazardflood} = f (Q_{extreme}, SD, FID)$$  \hspace{1cm} (3)

The authors then applied extreme analysis to the calculation results according to the following conditions: the maximum discharge ranges from 3000 to 5584 m$^3$/s, SD ranges from 0.0 to –0.63 m, and FID ranges from –1 m to 9 m. The calculation was repeated to find combination parameters for the flood-affected areas determined from previous floods. Based on the Hazardflood results, the second step was conducted to identify expected disaster damage per 1-km mesh applying the population to Hazardflood. Finally, the corresponding disaster damage was compared to the references of UN agency and Pakistan Government considering the flood extent within FID.

**RESULTS**

The analysis focused on flood hazard risk, especially expected disaster damage caused by a hazard in a given area considering the occurrence probability of the hazard and the vulnerability.

First, the authors estimated extreme discharges based on present, near-future and future MRI-AGCM3.1S data and conducted the comparison of 25-year simulations of the present-day climate and future change under the A1B emissions scenario by using the MRI-AGCM3.1S model. The scenario is related to climate change (e.g. frequency and magnitude of flood events) and change on the floodplain (e.g. potential FID and overflow). Concerning the MRI-AGCM3.1S simulation of future change, extreme discharge (Q_{extreme\_future}) was predicted to occur 10 times more frequently than the present discharge (Q_{present}). Figure 2 shows that Q_{extreme\_future} (e.g. 5584 m$^3$/s) was also twice the volume with the same frequency. The authors further found and confirmed the correlation between extreme discharge and precipitation under the scenario.

Second, discharge and SD as flood parameters make a positive contribution to discharge ratio. Examining the relationship between overflow and extreme discharge under the scenario, it was found that the peak discharge of 3398 m$^3$/s was recorded on 5 August 2010 in the Kabul River thorough the Indus River basin. The present discharge under the scenario (Q_{extreme\_present}) was also estimated to be 3000 m$^3$/s. The authors further estimated the discharge based on potential FID (Q_{overflow}) under the condition of FID = 3 m, which resulted in 3040 m$^3$/s. These results confirmed the validity of Q_{overflow}. In addition, when FID = 4 m, a future discharge based on FID (Q_{extreme\_future})
was estimated to be 6610 m$^3$/s, 5584 m$^3$/s under the scenario, and 6600 m$^3$/s from the ground data. This also suggests the validity of potential FID-based discharge.

Third, potential FID was considered as a major influencing factor on flood areas. It was used to predict flood extent in lowlands and near-zero gradients along the stream in the Indus River basin. People who live in the lowlands were more affected by potential FID than those in other places. Figure 3 shows the spatial distribution of flood risk. The number of affected people ranges from 0 to 42 thousand per pixel. An estimated 31.2 million people (18.36% of the population) were affected within a total flood area of 101,074 km$^2$ with potential FID ranging between –1 and 2 m. The Office for the Coordination of Humanitarian Affairs (UN, 2010) reported that over 20 million were affected in the Pakistan flood from late July to early August in 2010. Although the
Youngjoo Kwak et al.

estimated number of affected people exceeded the number released by the UN agency, this does not deny the validity of our method. In this study, the study area included the entire Indus River basin, which means that areas with little intensive rainfall were also included. For example, the Lahore district located east of the Indus River was little affected by intensive rainfall and thus suffered almost no damage, but it was still included as part of the study area. Therefore the number affected by the flood was estimated and added to the total number. This overestimation should be easily avoided by dividing the basin into several sections and conducting the estimation.

CONCLUSION

Flood risk assessment has focused on reduction of the susceptibility to nationwide flood damage. To consider regional flood risk assessment, the authors improved accuracy in identification of a vulnerable inundation area and eliminated disparity of flood risk assessment using integrated risk parameters. In this study, the authors successfully identified flood-affected areas at the national level in a short period of time, and estimated damage they would suffer by using a model with a simplified geomorphologic algorithm. Although heavy rainfall events and typhoons may behave highly unpredictably due to ongoing climate change, this developed approach can be a very useful tool in emergency response efforts since it can conduct extreme value analysis and predict when and in what size a flooding event may occur. In the future, the authors are planning to improve the proposed assessment to be applicable on a global, as well as a national, level.

Acknowledgements This work was conducted under the framework of the “assessment of the impact of climate change on flood disaster risk and its reduction measures over the globe and specific vulnerable areas (C-09)” under the “projection of the change in future weather extremes using super-high-resolution atmospheric models” (PI: Akio Kitoh) supported by the Innovative Program of Climate Change Projection for the 21st century (KAKUSHIN) of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT).

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