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Research papers

Impact assessment of upstream flooding on extreme flood frequency analysis by incorporating a flood-inundation model for flood risk assessment

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A B S T R A C T

Flood frequency analysis (FFA) is fundamental for providing hazard probability of flood risk assessment as well as for determining design flood. It is often the case that mega cities are located along downstream reaches of a large river basin in many areas of all over the world, and their extreme flood frequencies are assumed to be highly affected by dam operation and river overflow of its upstream areas. In particular, when upstream areas are also protected by river dike system, historical discharge samples cannot represent the impact of upstream river overflow on downstream extreme flood frequencies because it rarely occurs. FFA without this consideration, especially in large river basins which include several potential floodplains, would lead to inappropriate assessment of flood risk. To deal with this issue, FFA needs to incorporate flood-inundation modelling of upstream areas; however, previous studies on FFA have focused on smaller watersheds and combined rainfall-runoff models. Therefore, this study examined the impact of river overflow and dam operation of upstream areas on downstream extreme flood frequencies through a case study of the Yodo River basin (7280 km^2). To achieve FFA in a large river basin, this study combined a flood-inundation model of upstream Kyoto City area to a rainfall-based flood frequency model (RFFM) which accounts for the probability of spatial and temporal rainfall pattern over the river basin in a practical manner. The RFFM was validated with reproduced discharge samples of historical storm events and then applied to extreme flood frequency estimation. The application clarified that upstream river overflow causes much more drastic change of downstream flood frequencies beyond the design level than dam operation, which indicates that FFA for flood risk assessment needs to consider river overflow of its upstream areas otherwise flood risk of downstream areas will be overestimated. Furthermore, the scheme also produced the cumulative distribution function of flood area, which represents flood risk of upstream areas.

1. Introduction

A design flood determines the capacity of flood control structures, which is usually estimated from the probability distribution of annual maximum flood peak discharge (AMF). For this purpose, flood frequency analysis (FFA) played a major role to determine a T-year quantile of flood peak discharge. Recently, risk based analyses are more and more important in flood risk management (Apel et al., 2009; Few, 2003) so that there are increasing number of flood risk assessment studies (Apel et al., 2006; Ernst et al., 2010; Gain and Hoque, 2013). In these studies, FFA is used to provide flood hazard probabilities at upstream boundary gauges of the study area. The methods of FFA are classified into two approaches: rainfall-runoff simulation of flood peak discharge combined with rainfall generators (rainfall-based approach) and FFA of historical discharge data (discharge-based approach). The discharge-based approach, which has been called as Bulletin 17B (Hydrology Subcommittee, 1982) and now Bulletin 17C (England et al., 2015), is the most straightforward and thus standard method for determining design flood. For the purpose of estimating supposed flood frequencies in the natural flow conditions, discharge-based approaches remove the effect of existing flood control facilities. On the other hand, in flood risk assessment, we need to provide flood frequencies in the present situation. Discharge samples before the construction of dams/river dikes do not represent the present (regulated) flood frequencies; thus, discharge-based

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approaches have difficulty in estimating the present flood frequencies. In particular, the estimation of extreme flood frequencies beyond the design level of upstream levees are assumed to be much more difficult because such floods rarely occur, i.e. they are not included in flood record data, especially in highly protected river basins. In contrast, rainfall-based approaches are capable of considering the anthropogenic impact on flood frequencies by incorporating the effect of flood control facilities into hydrologic/hydraulic models.

In past decades, a number of rainfall-based approaches have been proposed. First it was proposed as a theoretically derived flood frequency model by Eagleson (1972) which modelled a probability function of rainfall intensity and duration by using an exponential distribution and then combined it with rainfall-runoff modelling in an analytical manner for providing flood frequencies. This type of point-process models has been widely applied and developed (Foufoula-Georgiou, 1989; Li et al., 2016; Smith, 1983) for estimating flood frequencies (Boughton and Droop, 2003). Point process approaches have been also expanded to Poisson-cluster models such as Neyman-Scott model (Valdes et al., 1985) and Bartlett-Lewis rectangular pulse model (Onof and Wheater, 1993), which modelled the occurrence of each rainfall cell (summarized in Onof et al. (2000)). These rainfall-based models have been mainly applied to upstream watersheds ($\sim$1000 km^2). As Merz and Blöschl (2008) mentioned, the reasons for this are that shorter records tend to be available in smaller catchments. Furthermore, large uncertainty is expected in flood frequency modelling of large river basins due to complicity of spatial rainfall modelling (Rogger et al., 2012), hydrologic variability and anthropogenic impact.

On the other hand, flood risk assessment mainly focuses on downstream urban areas of large river basins because it comprises large assets and population. In such areas, upstream river overflow from levees are assumed to be an important issue because they may have several large floodplains in upstream areas whose river dikes are also designed at large return periods. If the impact of upstream river overflow is quite large, FFA without this consideration will result in the overestimation of downstream flood risk and thus relatively underestimate flood risk of upstream cities, which would lead to inappropriate decision making on flood risk management of the whole river basin. Nevertheless, the evaluation of anthropogenic impact on flood frequencies are limited to flow regime change due to dam construction (e.g. Lee et al., 2017; Maingi and Marsh, 2002), and the impact of upstream river overflow from levees on flood risk assessment has not been discussed. This study, therefore, newly discusses this issue in terms of downstream flood risk assessment by quantitating the impact of upstream river overflow on extreme FFA; namely, we proposes a scheme to estimate extreme flood frequencies under the actual flood controls by combining a probabilistic rainfall model with a hydrologic-hydraulic model that reflects the effect of flood controls and inundation due to their limitation in extreme flooding.

To achieve the above objective, 1) rainfall-based FFA applicable to large river basins and 2) introduction of flood-inundation models into FFA are needed. To deal with spatial variability of rainfall in probabilistic rainfall modelling, Tanaka et al. (2015a) proposed a derived flood frequency approach that directly uses spatial-temporal rainfall patterns of past storm events over the upstream area of the target gauge. The rainfall model is based on a simple rainfall-based design flood model (RDF) that has been applied to design flood estimation in large river basins in Japan (Ohmachi, 2004). Instead of constructing probabilistic models of spatio-temporal distribution of a storm event, the RDF represents spatiotemporal structure of rainfall by using spatiotemporal storm patterns of a large number of historical event samples. The direct use of historical temporal patterns (dimensionless time series of rainfall intensity) has been already applied in literature, e.g. Rahman et al. (2002) and Caballero and Rahman (2014). The RDF is the one expanded to spatial rainfall representation as well as temporal pattern. After that, Tanaka et al. (2015a) incorporated the dependence structure between total basin rainfall and the duration of a generated storm patterns to the RDF, as similar to the above studies. The proposed method (hereinafter referred to as a rainfall-based flood frequency model (RFFM)) was applied to the upstream area of the Yura-gawa river basin (755 km^2) and well reproduced flood frequencies within the range of observed flood peaks (and within the design level). Although the RFFM is potentially applicable to large river basins, it has not been validated yet. As for flood-inundation modelling, recent intensive development of flood-inundation models enabled to compute broader floodplains from large river basins to international rivers (Nguyen et al., 2016; Sampson et al., 2015) and global flood modelling (Yamazaki et al., 2011). However, the application of flood-inundation models to rainfall generators in FFA has not been performed as far as the authors know and typically rainfall-based FFA is coupled with rainfall-runoff models (e.g. Charalambous et al., 2013; Candela et al., 2014; Tanaka et al., 2015a).

Therefore, to demonstrate the impact of upstream river overflow on downstream extreme FFA, this study proposes an extreme FFA scheme that combines the RFFM with a flood-inundation model and estimate flood frequencies affected by flood controls and upstream inundation supposed in extreme flooding. The Yodo River basin (7280 km^2) was selected as a target river basin because it covers the Kyoto city area in the upstream of the Hirakata discharge gauge station where FFA was performed. For quantitative evaluation of the impact of upstream river overflow, the application result of the RFFM to the Hirakata station with a large upstream area was first validated with discharge-based FFA from historical discharge data and then compared with the result of the RFFM combined with only a rainfall-runoff model. Since incorporating a flood-inundation model also provides flood area, their frequencies are also derived for rainfall-based flood risk assessment.

In a changing climate, non-stationary FFA is also an inevitable issue for appropriately capturing expected flood risk (Milly et al., 2008); therefore, non-stationary FFA has been intensively studied until now (Cheng and AghaKouchak, 2013; Cheng et al., 2014; Strupczewski et al., 2001; Vallarini et al., 2009). This study, however, did not deal with non-stationarity of flood frequencies because this study focused on anthropogenic impact in FFA that is a common issue in stationary/non-stationary conditions and a non-stationary RFFM has not been developed yet. Instead, in this study stationarity, i.e. independence of historical discharge samples, were ensured by using the Mann-Kendall test (Ferguson et al., 2000) as described in Section 6.

2. Study area

The proposed method was applied to flood frequency estimations at the Hirakata discharge gauging station. An upstream area of the Hirakata station in the Yodo River basin (7280 km^2) is shown in Fig. 1. The Yodo River basin is composed of three tributary river basins: Katsura, Uji and Kizu River basins. The Yodo River basin has seven dam reservoirs: the Hiyoshi, Amagase, Takayama, Nunome, Murou, Hinachi and Shorenji Dams. In addition, the Uji River has the Seta Weir on outflow of Lake Biwa, and the Katsura and Kizu Rivers have the Kameoka and Ueno retarding basins, respectively. These two retarding basins are often flooded during past heavy rainfall events. The Kyoto City area (the rectangular red domain in Fig. 1) is rarely flooded because it is protected by dike system, many dam reservoirs and retarding basins, except small areas