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DEVELOPING FLOOD INDEX FROM PAST FLOOD HYDROGRAPHS AND USING IT AS A TOOL TO CHARACTERIZE FLOOD SEVERITY

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Abstract

The paper presents the development of a Flood Index (FI) based on the flood hydrograph characteristics, namely flood magnitude ratio, rising curve gradient and time to peak. These characteristic values are normalized to their respective values corresponding to a 100-year flood. The methodology developed to compute FI is applied to three case studies; Kentucky in USA, Oc-gok in the Republic of Korea and Haor in Bangladesh. The obtained results show advantages of the presented methodology over the existing ones. The computed FIs at different locations of the catchment corresponding to different exceedance probabilities provide the summarized understanding of the flooding characteristics of the catchment. The spatial and temporal variation of FI presents a snapshot of flood risk in a catchment and can be used in strategic decision making in flood risk management, for example, in spatial planning, flood zoning and flood event management. The developed methodology can be easily applied to poorly gauged catchments where it is difficult to build accurate flood forecasting models.

Key words: Flood Index, flood risk management, Haor, Kentucky, Oc-gok

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1. Introduction

Numerous flooding examples such as the 2010 floods in Pakistan, the 2011 floods in Australia and Thailand, the 2013 floods in Germany and the 2014 floods in the UK demonstrate that flooding is a major threat to society and a barrier to societal prosperity (Asgary et al., 2012; Blöschl et al., 2013; Croke et al., 2013; Haraguchi and Lall, 2014; Mongkonkerd et al., 2013). While major advancements have been achieved in flood modelling and forecasting from which many catchments have benefited (Gouldby et al., 2010; Hoa et al., 2017; Merkuryeva et al., 2014) there are still many areas around the world which are ungauged and where forecasting is hardly possible. Concerted actions, such as *predictions in un-gauged basins* (Grimaldi et al., 2013; Sivapalan et al., 2003; Swain et al., 2015) are taken to improve the predictions and understanding in un-gauged basins.

There are catchments where, due to climatological characteristics, model-based flood forecasting may have a relatively limited role, and flood event management will always need to be trusted upon. For example, in flash flood catchments, which may be tiny and ungauged with high rainfall variation, flood management often depends on approximate tools rather than on an elaborate flood forecasting system. For example, one of such tools, namely flash flood guidance (FFG) (Norbiato et al., 2009), is widely used in North America, which indicates a flooding possibility should the rainfall in a specified duration exceed a threshold value (Georgakakos, 2006). An FFG is not able to point out when exactly and where exactly flooding may start. Its role is rather in issuing a warning, which the emergency authority uses to find out the farther

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details. A statistical threshold based approach used in flash flood prediction (Martina et al., 2006; Villarini et al., 2010), a tool experimentally applied to Italian catchments, is conceptually comparable to FFG (Norbiato et al., 2008). These tools, though approximate, are helpful in flood event management in flashy catchments.

There are catchments fed largely by flood waters coming from upstream catchments, which are un-gauged, or due to data-sharing issues in trans-boundary catchments flow of information from upstream catchment is limited (Fatch et al., 2010; Green, 2009; Raadgever et al., 2008). Hydrological and hydraulic modelling of these downstream catchments will never be sufficient to provide any required forecasting lead time, and alternative tools to support flood event management will be required.

In FFG or similar approaches the primary motive is to provide an approximate guidance by synthesizing the historical data. A conceptually similar approach has been advocated by a group of researchers (Ahn and Choi, 2013) to characterize past flood hydrographs to determine a *flood index* (FI), which varies in space and time with flood magnitude and its propagation. This approach is particularly useful for catchments which are ungauged or partially gauged with a relatively short reaction time. Flood event management and flood zoning play important roles in such catchments as the availability of hydro-meteorological information makes development of an accurate flood forecasting system practically impossible. Often these catchments are small and tiny, and experiences flash floods. For such catchments metrological forecasts from numerical weather prediction models often may not be usable due to the inherent incompatibility between the spatio-temporal scales these forecasts and the required spatio-temporal scales of hydrological simulation. There is a clear requirement of the development of alternative and often "approximate" tools, such as FFG or FI, which can be used in flood risk management in similar catchments.

Bhaskar et al. (2000) and Ahn and Choi (2013) argue that important information about the flooding characteristics can be determined from the flood hydrograph. Specifically, the peak flood magnitude, the steepness of the rising limb of flood hydrograph and the time to reach the flood peak carry important information of flooding characteristics (Bhaskar et al., 2000). If the measured hydrographs, or, simulated hydrographs from a (partially) calibrated model are available, they can be used in computing FI. By studying the variation of the index the locations of high flood risk, requiring attention, can be earmarked beforehand. Such an approach can be very useful in flood risk management of catchments where information about hydro-meteorological variables is inadequate for any forecasting system.

This paper proposes computation of the FI by employing a new procedure. The results are compared with those based on the existing approaches for the following three case studies: four small catchments in Kentucky in USA, Oc-gok Basin in the Republic of Korea and the Haor region in Bangladesh. The developed methodology can be easily used as a tool in flood risk management in other catchments, and can be used in flood event management, spatial planning and flood zoning.

2. Methodology to compute Flood Index

The following three hydrograph characteristics are used in the literature for computing FI (Ahn and Choi, 2013; Bhaskar et al., 2000): flood magnitude ratio, rising curve gradient and time to peak. These characteristics are used by the procedure developed in this paper as well and are explained in the following sections.

2.1. Flood magnitude ratio

The flood magnitude ratio (M) is the ratio of the peak flood (Q_p) to the long-term average discharge (Q_a) in the river at the studied location (Eq. 1).

$$M = Q_p / Q_a \tag{1}$$

The parameter M conceptually defines the flood severity by considering only the peak flood discharge. It does not take into account the dynamic aspects of the flood propagation. With larger flood magnitudes understandably the value of the parameter M increases. Whereas the usage of Q_p in the numerator is undisputed the use of Q_a in the denominator is not accepted by everyone. Bhaskar et al. (2000), similar to Eq. (1), used Q_a for computing M. However, Ahn and Choi (2013) used the bank-full discharge (Q_b) for computing M arguing that Q_a may not be available in un-gauged catchments. Note that when Q_a and Q_b are computed based on a long period of time then they do not change much and the use of Q_a or Q_b both are possible as long as it is applied consistently for a catchment. If a long period of data is not available then it makes sense to compute Q_b by using a simple hydraulic model (e.g. using HEC-RAS) and to use it in Eq. (1). Moreover, as it is discussed later in this paper, that if the parameter M is normalized then the differences in computed M by using Q_a over Q_b (and vice-versa) are either negligible or are not there at all.

It is also noteworthy that the parameter M indicates the severity of a flooding 'source' in a typical *source-pathway-receptor* model (Narayan et al., 2012; Sayers et al., 2002; Schanze, 2007) used in flood risk management. However, the parameter M does not carry any information about the flooding impact as no information about the 'pathway' or 'receptor' is used in computing M. For example, floods with the same parameter M, for an area adjacent to a river, which is protected with embankments/ retention basins and/or has an enabled flood forecasting system, will lead to very different flooding impacts compared to an area without these facilities. Therefore, the same value of M may be associated with very different flooding risk computed using a commonly used *hazard-exposure-vulnerability* model (Birkmann, 2007; Kaźmierczak and Cavan, 2011; Kron, 2002).

Note that using Eq. (1) and any available flood frequency study the values of the parameter M can be computed for several Q_p values with varying exceedance probability. In the case studies considered in this paper the value of M varied from 10 to 79 with an average of 29 for the four small catchments in Kentucky and from 1 to 2.3 with an average of 1.3 for the Oc-gok catchment. In the Haor region M varied from 4.2 to 22.1. The range of possible values of M depends on the flooding and geomorphological properties of a catchment.

The large rivers in Asia and Americas have huge flood peaks compared to their annual average flows and as a result are expected to yield high M values. Compared to that the European and other relatively small rivers with lesser variation of discharges, may have lower values of M.

2.2. Rising curve gradient

The second parameter used in characterizing flood hydrographs is the rising curve gradient (K), which expresses the steepness of the rising limb of the hydrograph (Ahn and Choi, 2013; Bhaskar et al., 2000). This parameter conceptually captures the dynamic aspect of a flood hydrograph. A flood level rises faster with higher values of K. The rising limb of a flood hydrograph can be approximated with an exponential equation of the following form (Eq. 2):

$$Q_t = Q_0 e^{Kt} \tag{2}$$

where Q_t denotes the flood discharge at time t till the flood peak Q_p is reached, Q_0 is the initial discharge and K is the rising curve gradient (day^{-1}). Similar to Bhaskar et al. (2000) we also recommend using Q_0 in Eq. (2). Ahn and Choi (2013) suggested using Q_b in a linear relationship that replaces Eq. (2) to compute K.

The parameter K also indicates the severity of the source component in the source-pathway-receptor model used in flood risk management. Flood hydrographs, with the same value of M (i.e. for the same flood magnitude), can have different values of K, which may occur due to different catchment conditions (for example, soil moisture) and/or meteorological factors. Therefore, the parameter K, together with M, brings more information than the component 'source' in the source-pathway-receptor model. However, similar to M, the parameter K does not carry any information about the flooding impact too as it does not have any information about the receptor.

In the case studies considered in this paper the value of K varied from 3 to 29 with an average of 11 day^{-1} for the four small catchments in Kentucky and from 1 to 12 with an average of 9 day^{-1} for the Oc-gok catchment. For the Haor region values of K varied from 0.16 to 1.8 day^{-1} at the upstream locations.

2.3. Time to peak

Yet another parameter used in characterising a hydrograph is the time to peak (TP) defined as the time in hours between a flooding starts (T_0) and the peak flood (T_p) occurs (Eq. 3):

$$TP = T_p - T_0 \tag{3}$$

Bhaskar et al. (2000) used Eq. (3) in computing TP. Ahn and Choi (2013) used T_0 as the time when the flood water goes above the bank level. We observed in the literature that TP has been also considered to be up to the time flood level recedes to the bank-full level (see, for example, Ahn and Choi, 2013). In flood management and hence in computing FI our focus is often the peak flood. This concern becomes somewhat underrated if TP is considered till the flood water recedes to the bank-full level. Moreover, the flood recession is usually a slower process than the rise of flood. As a result TP in Eq. (3) is considered as the time when the flood peak is reached.

The parameter TP, similar to K, conceptually captures the dynamic nature of the flood hydrograph and as a result for the same flood magnitude (same M) different TP values are obtainable. This is understandable as due to different catchment and meteorological conditions the hydrograph characteristics can be different for the same flood magnitude. Once again, the parameter TP does not carry any information about the flooding impact.

In the case studies considered in this paper the value of TP varied from 5 to 27 with an average of 13 hours for the four small catchments in Kentucky and from 0.5 to 3 with an average of 1 hour for the Oc-gok catchment. For the Haor region TP varied from 2 days to 15 days.

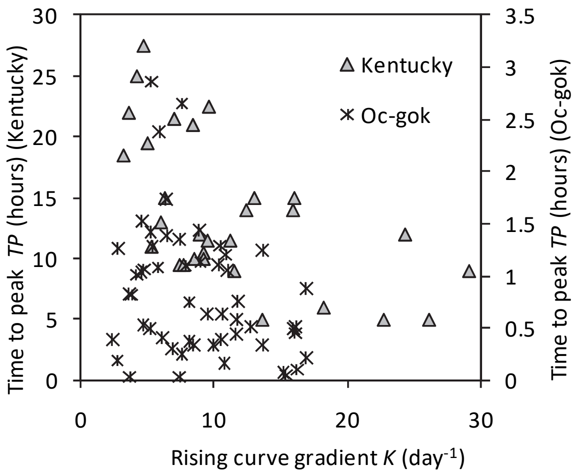

Fig. 1. Relationship between *rising curve gradient* (K) and *time to peak* (TP) for 30 flood events in four small catchments in Kentucky and 54 flood events in Oc-gok catchment in the Republic of Korea

It may be observed that the parameters K and TP may not be completely independent of each other.

For the same flood magnitude, if K decreases TP may decrease. It is good to investigate if the two parameters of the considered case studies are related or not. Fig. 1 shows the variation of TP with K for 30 flood events in the considered catchments in Kentucky and 54 flood events in the Oc-gok catchment. No obvious connectivity is observed. Moreover, in the literature both K and TP are used in computing FI, and we will follow this as well.

2.4. Flood index

FI is a combination of the three parameters and two of them are not dimension-free. Moreover, the ranges of parameters may substantially differ. Normalization of data and making parameters dimensionless makes it easier to combine them. Bhaskar et al. (2000) have adopted normalization by arbitrarily considering interval values of each of the above three parameters. Subsequent to the normalization they used the arithmetic sum of the three parameters as the way to calculate FI. Their normalization procedure is specific to their case study, which makes it difficult to apply the procedure to a new study. Ahn and Choi (2013) have used normalization of each of the three parameters on the (0 – 1) scale and then computed FI as their geometric mean. Their approach removes a lot of subjectivity of the normalization procedures used in previous approaches. It is noteworthy that FI is an aggregated index, which neither has direct physical interpretation nor it can be measured in the field. It can best be explained as a number relative to FI values of other floods and a relative severity of flooding can be interpreted. In this respect comparing FI for any flood to a well-known flood in the same catchment may be useful.

In flood risk management the 100-year flood is widely used in assessing risks and planning mitigation measures (Bell and Tobin, 2007). The Flood Directive of the European Union, which sets the direction of flood management in Europe, has also stressed upon using the 100-year flood in making risk assessment and planning mitigation measures (EC, 2007).

In computing FI, we propose computing the index relative to a *standard flood* and it is suggested to consider the 100-year flood as the standard flood. We further suggest computing the three indexing parameters M, K and TP for this standard flood. Subsequently, these indexing parameters M, K and TP for other floods are computed and normalized using Eqs. (4), (5) and (6), with respect to the standard (100-year) flood. Thus each normalized parameter for the 100-year flood becomes 1 (dimensionless). The values of these three parameters for any flood are then indicative of its relative severity compared to the standard flood (100-year flood). Note that values of these parameters can be more than 1 for floods more severe than the standard flood. The normalization procedure is illustrated in Eqs. (4), (5) and (6). The presented approach in this paper has been referred to as the Normalized Flood Index (NFI) approach.

$$M_n = M / M_{100} \tag{4}$$

$$K_n = K / K_{100} \tag{5}$$

$$TP_n = TP_{100} / TP \tag{6}$$

where M_n, K_n and TP_n are the normalised values of M, K and TP. M_{100}, K_{100} and TP_{100} refer to the M, K and TP values of the 100-year flood. Note that TP_n increases if TP decreases compared to the standard flood.

If in data scarce catchments the 100-year flood cannot be determined then it can be estimated using other mechanisms (e.g. regionalization method). In data-scarce catchments the maximum observed flood in a catchment can also be used as the standard flood. Once the normalized values of the parameters are computed using Eqs. (4), (5) and (6) FI can be computed as the geometric mean of them (Eq. 7). The geometric mean ensures that a percentage change of any parameter value has the same influence on FI.

$$FI = \sqrt[3]{(aM_n)(bK_n)(cTP_n)} \tag{7}$$

where a, b and c indicate three coefficients to assign any relative weight to the three parameters. Here we have considered a=b=c=1.

Note that a prime advantage of the proposed approach is in identifying severity of a flood in relation to a standard flood (100-year flood). By computing FI at different locations of the catchment a spatial variation of FI can be computed, and therefore, FI can be used for identifying risk locations. If a flood frequency study is available then FI can be computed for any flood magnitude with its known hazard probability. The spatial and temporal variation of FI provides a synoptic view of the variation of risk from flooding in the catchment and as a result can be useful in flood risk management.

3. Study areas

The study areas consist of the three different case study locations selected on the basis of varying catchment size and climatic conditions, as well as on the basis of previous studies and data availability. The Oc-gok basin in the Republic of Korea is a small basin with cold climatic conditions with about 1000 mm yearly rainfall (Fig. 2). The Kentucky catchments are of small to medium size with typically mild to moderate climate with about 1000mm yearly rainfall. The Haor catchment is relatively large with warm humid climate with yearly rainfall of about 2600 mm. The catchments were used as case study locations in the previous studies by Ahn and Choi (2013), Bhaskar et al. (2000) and Suman and Bhattacharya (2014).

The variety of catchments provided an opportunity to test the presented approach in different catchment conditions as well as to compare the results with previous studies. They are briefly described below.

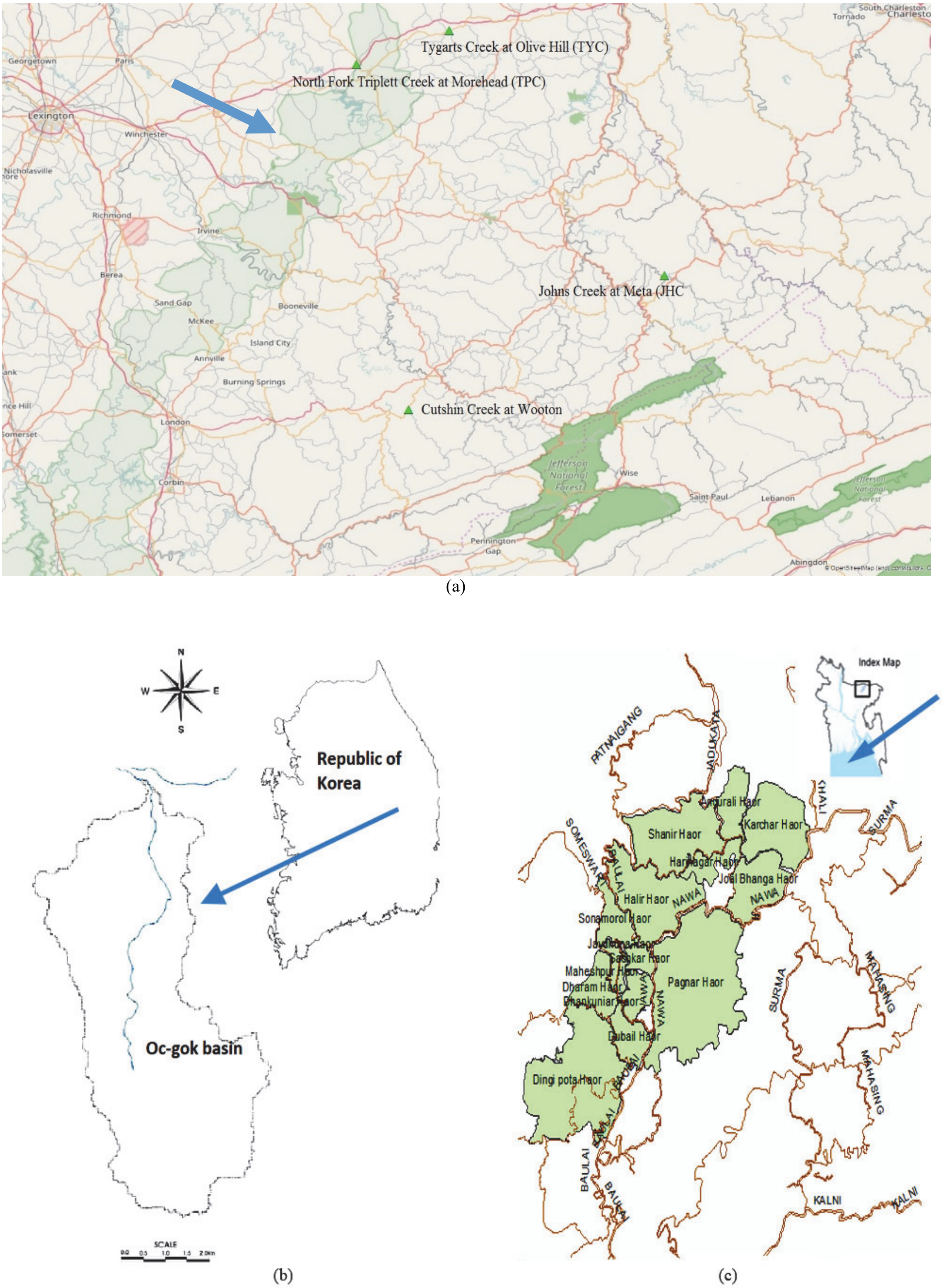

Fig. 2. The location map of the three case-study areas: (a) Eastern Kentucky catchments (with its gauging sites) (source: Google Map); (b) Oc-gok basin in the Republic of Korea (source: Ahn and Choi, 2013) and (c) The Haor catchment in the north-east of Bangladesh

3.1. Eastern Kentucky catchments

This case study is based on four small catchments from eastern Kentucky. The catchments are named as: Cutshin Creek at Wooton (CTC), John's Creek at Meta (JHC), North Fork Triplett Creek at Morehead (TPC) and Tygarts Creek at Olive Hill (TYC). The discharge data of these channels were gathered from the website of United States Geological Survey (http://water.usgs.gov/data/). In particular, the USGS gauging stations numbered 03280700, 03210000, 03250100 and 03216800 were considered respectively for the CTC, JHC, TPC and TYC catchments. The drainage areas are 158.8, 145.8, 219.4 and 154.4 km^2 respectively for the CTC, JHC, TPC and TYC catchments (Ruhl and Martin, 1991). More information about the catchments can be found in (Bhaskar et al., 2000; French et al., 1996).

3.2. Oc-gok River basin

The Oc-gok River basin is a small catchment and is a part of the Nak-dong River basin in the Republic of Korea. It has an area of 23.48 km^2. The information of this catchment and the relevant data are taken from Ahn and Choi (2013). For this catchment Ahn and Choi (2013) gathered hourly rainfall data and developed a lumped conceptual hydrological model using HEC-HMS and a hydraulic model using HEC-RAS. More information about this catchment can be found in Ahn and Choi (2013).

3.3. Haor region

The Haor region is located at the north-eastern part of Bangladesh. The area is about 19000 km^2 with about 400 so-called haors which are depressions used for agriculture during the dry period (December to mid-May) and as floodplains (and as fisheries) during the wet period (mid-May to November). Big haors may have a dimension of 20-25 km length and 10-15 km width. The upstream catchments are in the hilly regions of India, which receive large amount of rainfall and contribute to some flashy discharges in the rivers of the Haor region. The region is not studied or modelled well. Numerical inundation model was only used to characterize flooding process of *Hakaluki Haor* in this region (Taro et al., 2002). Further studies are reported by (Suman and Bhattacharya, 2013, 2014). Characterization of the general flooding situation in Bangladesh can be found in, for example, Mirza (2013). The limitation of flood forecasting is reported by Paudyal (2002).

Pre-monsoon flooding in the Haor region causes agricultural damages. Due to the geographical location of the catchment and the terrain hydrological modelling provides short forecast lead time. The upstream Indian catchments are largely un-gauged. Information from measured/simulated hydrograph in this region is expected to be helpful in defining the flooding characteristics and in developing flood event management plans. More information about the catchment can be found in (Suman and Bhattacharya, 2013, 2014).

4. Results and discussions

The presented NFI approach has been applied to compute FI for the case studies and compared with the results of Bhaskar et al. (2000) and Ahn and Choi (2013). The results are presented separately for the three case studies.

4.1. Eastern Kentucky catchments

In this case study 30 flood events in the four catchments in Kentucky during the period 1990 to 1995 have been considered. The FI values, according to the presented NFI approach, were computed for these flood events and compared with Bhaskar et al. (2000) and Ahn and Choi (2013). Table 1 presents the most relevant data of the 30 flood events for this case study. More data are available in Bhaskar et al. (2000).

The indexing parameters M, K and TP were computed using Eqs. (1), (2) and (3) respectively. It may be noted that these values are the same as in Bhaskar et al. (2000). The largest flood in the dataset, with a peak flood discharge 236 m^3/s occurred on 22/3/1991, was considered as the *standard flood* and the indexing parameters were normalized with respect to this flood using Eqs. (4), (5) and (6). The FI values (Table 1) were computed using Eqs. (7). For the approach of Bhaskar et al. (2000) the parameters were normalized using their normalization procedure.

For the approach of Ahn and Choi (2013) the parameter M was computed considering the long-term average discharge (Q_a) as the bank-full discharge (Q_b) was not available. Note that though Ahn and Choi (2013) have recommended the use of Q_b in computing M but as they have used normalization of M based on the minimum and maximum values of it, the use of Q_a or Q_b should yield the same normalized value of M. The parameter K was also computed using Q_a (instead of Q_b) which increases the value of K but once again due to the normalization the difference is negligible. The parameter TP was computed using the hydrograph data. The computed parameters and their normalized values are shown in Table 1. The FI values in Table 1 quantitatively associate the FI number with a peak flood discharge and express the flood severity. Note that for the same flood magnitude different FI values are possible as due to varying catchment conditions different flood hydrographs for the same flood magnitude may be generated.

As such the absolute values of FI from the three different methods are not so much comparable but their variation with different flood events provides useful information. Fig. 3 shows the variation of FI with flood magnitudes. The trend lines have the following R^2 values for Bhaskar et al. (2000), Ahn and Choi (2013) and the presented NFI approach are respectively 0.52, 0.77 and 0.75.

Table 1. Thirty flood events in the Kentucky catchments and the corresponding flood indexing parameters computed based on the three approaches

Flood number	Stream gauge	Flood date	Flood peak Q_p (m^3/s)	Indexing parameters as per Bhaskar et al. (2000)							Indexing parameters as per the presented approach				Indexing parameters as per Ahn and Choi (2013)					
				Rising curve gradient K (day^{-1})	Flood magnitude ratio M [-]	Flood response time TP (hour)	Normalised parameters			FI [-]	Normalised parameters			FI [-]	K_n (day^{-1})	TP_n (hour)	Normalised parameters			FI [-]
							K_n [-]	M_n [-]	TP_n [-]		K_n [-]	M_n [-]	TP_n [-]				K_n [-]	M_n [-]	TP_n [-]	
-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15	-16	-17	-18	-19	-20	-21
1	CTC	12/23/19	50.1	9.2	18.6	10.5	2	4	7	13	0.38	0.3	0.88	0.46	0.0284	36.8	0.25	0.12	0.24	0.2
2	CTC	12/28/19	67.1	9.2	24.9	10	2	5	7	14	0.38	0.4	0.83	0.5	0.0406	35	0.39	0.22	0.22	0.26
3	CTC	3/23/199	82.4	7.4	30.6	9.5	2	7	7	16	0.3	0.49	0.79	0.49	0.0528	33.3	0.53	0.3	0.2	0.32
4	CTC	5/18/199	211.4	12.4	78.5	14	3	16	6	25	0.51	1.25	1.17	0.91	0.0939	49	1	1	0.4	0.74
5	JHC	12/28/19	49	8.9	24.7	12	2	5	6	13	0.37	0.39	1	0.52	0.0269	42	0.23	0.21	0.31	0.25
6	JHC	12/2/199	63.1	9.5	31.8	11.5	2	7	6	15	0.39	0.51	0.96	0.57	0.0365	40.3	0.34	0.32	0.29	0.31
7	JHC	7/1/1992	50.9	11.2	25.7	11.5	3	6	6	15	0.46	0.41	0.96	0.57	0.0292	40.3	0.26	0.23	0.29	0.26
8	JHC	12/23/19	22.3	6.3	11.3	15	2	3	5	10	0.26	0.18	1.25	0.39	0.0093	52.5	0.03	0.02	0.44	0.06
9	JHC	3/4/1993	44.7	3.6	22.5	22	1	5	3	9	0.15	0.36	1.83	0.46	0.0133	77	0.07	0.18	0.76	0.21
10	JHC	3/24/199	56.9	6	28.7	13	2	6	6	14	0.25	0.46	1.08	0.5	0.029	45.5	0.25	0.27	0.36	0.29
11	JHC	5/18/199	73	7.7	36.8	9.5	2	8	7	17	0.32	0.59	0.79	0.53	0.0513	33.3	0.51	0.39	0.2	0.34
12	TPC	2/6/1991	45.8	4.7	12.2	27.5	1	3	1	5	0.19	0.19	2.29	0.44	0.007	96.3	0	0.03	1	0
13	TPC	2/14/199	75.8	7	20.2	21.5	2	4	3	9	0.29	0.32	1.79	0.55	0.0153	75.3	0.1	0.15	0.73	0.22
14	TPC	3/22/199	236	24.3	62.7	12	5	13	6	24	1	1	1	1	0.0882	42	0.93	0.77	0.31	0.61
15	TPC	1/21/199	38.5	9.6	10.2	22.5	2	2	3	7	0.4	0.16	1.88	0.49	0.007	78.8	0	0	0.78	0
16	TPC	2/21/199	217.3	13	57.7	15	3	12	5	20	0.53	0.92	1.25	0.85	0.0649	52.5	0.67	0.7	0.44	0.59
17	TPC	3/4/1993	102.2	3.2	27.1	18.5	1	6	4	11	0.13	0.43	1.54	0.44	0.0243	64.8	0.2	0.25	0.6	0.31
18	TPC	3/17/199	76.1	5	20.2	19.5	1	4	4	9	0.21	0.32	1.63	0.48	0.0169	68.3	0.11	0.15	0.64	0.22
19	TPC	4/26/199	51.8	8.5	13.8	10	2	3	7	12	0.35	0.22	0.83	0.4	0.0219	35	0.17	0.05	0.22	0.13
20	TYC	12/18/19	122	8.4	49	21	2	10	3	15	0.35	0.78	1.75	0.78	0.0369	73.5	0.34	0.57	0.71	0.52
21	TYC	1/7/1991	29.4	4.2	11.8	25	1	3	2	6	0.17	0.19	2.08	0.41	0.007	87.5	0	0.02	0.89	0.01
22	TYC	3/26/199	57.2	18.2	23	6	4	5	8	17	0.75	0.37	0.5	0.52	0.0591	21	0.6	0.19	0.04	0.17
23	TYC	12/3/199	169.8	15.9	68.2	14	4	14	6	24	0.65	1.09	1.17	0.94	0.0774	49	0.81	0.85	0.4	0.65
24	TYC	5/9/1992	30.6	5.3	12.3	11	1	3	7	11	0.22	0.2	0.92	0.34	0.0166	38.5	0.11	0.03	0.27	0.1
25	TYC	1/5/1993	47.3	26.1	19	5	6	4	9	19	1.07	0.3	0.42	0.51	0.058	17.5	0.59	0.13	0	0
26	TYC	3/31/199	53.2	11.5	21.4	9	3	5	7	15	0.47	0.34	0.75	0.49	0.0365	31.5	0.34	0.16	0.18	0.21
27	TYC	8/13/199	59.1	16	23.8	15	4	5	5	14	0.66	0.38	1.25	0.68	0.0244	52.5	0.2	0.2	0.44	0.26
28	TYC	5/18/199	70.5	22.7	28.3	5	5	6	9	20	0.93	0.45	0.42	0.56	0.0881	17.5	0.93	0.27	0	0
29	TYC	6/12/199	48.7	13.6	19.5	5	3	4	9	16	0.56	0.31	0.42	0.42	0.0598	17.5	0.61	0.14	0	0
30	TYC	8/6/1995	87.4	29.1	35.1	9	6	7	7	20	1.2	0.56	0.75	0.8	0.0611	31.5	0.62	0.36	0.18	0.34

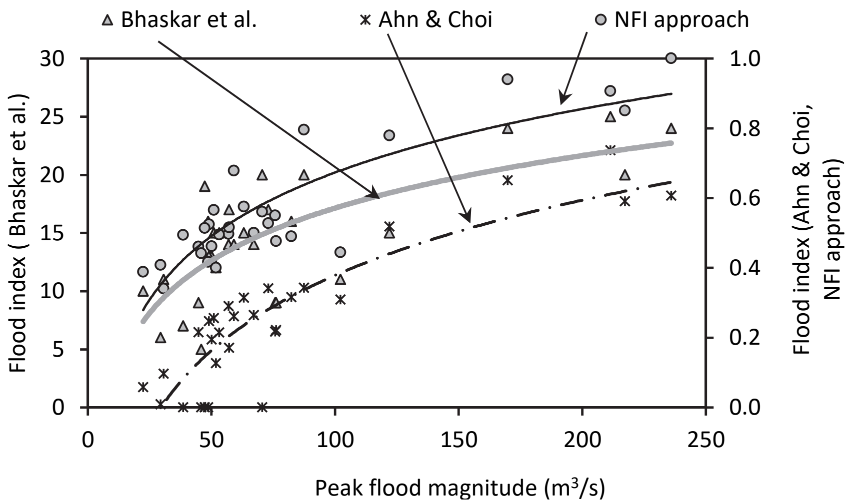

Fig. 3. Flood indices computed for the different flood events in the Kentucky catchments by the three different approaches. The NFI approach refers to the presented approach

Fig. 3, particularly when developed with a large variety of flood events, can be used to estimate the FI for a measured, estimated or design flood magnitude. In order to cater for the differences in hydrograph characteristics (due to different catchment responses) for the same flood magnitude an interval of FI values may be found out. The range of possible FI values depends upon the catchment characteristics and can be estimated from Fig. 3 when a long series of flood events is available. If the interval(s) is computed then FI for a given flood magnitude may be estimated with a pre-set likelihood (e.g. 90% likelihood). As we did not have a large dataset, we did not explore the possibility of determining an interval of FI. Fig. 3 also points out that it can be connected to a flood frequency study of the catchment and the FI values corresponding to the flood magnitude of any return period can be computed. All the three methods show reasonably similar trends though the advantage of referring to a standard flood by the presented NFI approach leads to an easier interpretation of the FI values. Fig. 3 refers to a particular location of the catchment, and similar charts, if needed, can be constructed for a number of locations of a catchment to study the spatial progression of FI values in a catchment.

Furthermore, we chose four flood events, which are subjectively representative of the range of flood magnitudes recorded during the study period in the Kentucky catchments. In particular the following four floods were considered: largest flood, second largest flood, smallest flood and a flood close to the median value of the available flood magnitude dataset. Table 2 shows the considered flood events and Fig. 4 shows the variation of normalized values of *M*, *K*, *TP,* and FI for the considered four flood events.

The normalization procedures respective to the three methods were adopted in computing the normalized values presented in Fig. 3. As per the presented NFI approach a value of 1 was assigned for FI corresponding to the largest flood. The FI values for the other flood events were subsequently calculated. As a consequence the comparative severity of other floods can be interpreted easier than the other two approaches allow. Based on the approach of Bhaskar et al. (2000) and Ahn and Choi (2013) it will be difficult to connect an analysis to future flood events or with design flood analyses, or, to answer questions such as what is the FI for floods of 50 years return period? In flood management studies regional flood frequency (Jingyi and Hall, 2004; Micevski et al., 2015), probabilistic flood envelope (Castellarin et al., 2005; Castellarin, 2007) or similar approaches can be used where the flood magnitude is estimated based on pooled data of flood events and is associated with a hazard probability. As a result any flood management tool, such as FI, should ideally allow the use of any flood magnitude with a specific exceedance probability. Moreover, such possibilities allow comparing FI values over a region or between different catchments.

For any future flood event in the Kentucky catchments if the flood magnitude is estimated and the data for computing the indexing parameters are not available then the FI can be estimated from the following regression equation according to the presented NFI approach. Note that Eq. (8) provides just a regression equation and any physical interpretation of the coefficients is not possible.

$$FI = 0.2627 \; Ln(Q_p) - 0.5364 \tag{8}$$

where Q_p denotes the estimated/ measured peak flood magnitude (in m^3/s) and *Ln* stands for natural logarithm.

Due to varying catchment or climatological conditions the same Q_p may lead to slightly different indexing parameters and FI values and therefore, additional information about the nature of any particular flood should be gathered to judge whether FI values for the flood may tend to be higher (or lower) compared to the FI values estimated from Eq. (8).

Table 2. Four representative flood events in the Kentucky catchments and the corresponding FI values computed based on the three approaches

Flood type	***Flood magnitude***	***Flood index***		
		Bhaskar et al. (2000)	***Ahn and Choi (2013)***	***The presented NFI approach***
Largest flood	236	24	0.61	1.00
2nd largest flood	217.3	20	0.59	0.85
Median flood	59.3	14	0.26	0.68
Smallest flood	22.3	10	0.06	0.39

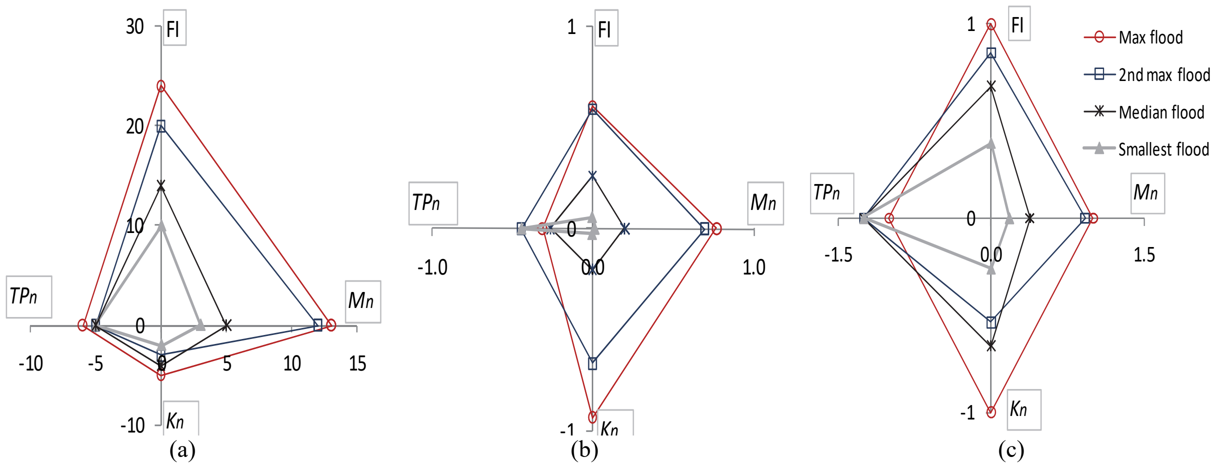

Fig. 4. Comparison of the normalized flood indexing parameters for four different floods in Kentucky as per the three different approaches: (a) Bhaskar et al. (2000); (b) Ahn and Choi (2013); and (c) the presented NFI approach

This judgement can be made more formal by constructing, for example, three regression equations similar to Eq. (8) with one each for high, low and average *K* values. This, however, is only possible if a good database of flood events is available. It was not explored in this study and could be recommended for future studies.

The variation of the computed FI values with the total rainfall for each flood event was analyzed. A weak trend (with R^2 about 0.3) for all the three approaches was noticed. Unfortunately, the hourly rainfall data was not available. The rainfall data with a lag appropriate for the catchment may perhaps show higher R^2 values between computed FI and rainfall.

4.2. Oc-gok River basin

Ahn and Choi (2013) considered 54 peak-over-threshold flood events in the Oc-gok catchment during the period 1973 to 2008. Flood indices for these 54 flood events were computed as per the presented NFI approach and compared with the FI values computed by Ahn and Choi (2013) (Table 3).

Due to the unavailability of the average discharge data and starting discharge value of each flood event the bank-full discharge Q_b (used by Ahn and Choi) was used in computing the parameters *M* and *K* in the presented NFI approach. As the computed values of *M* were normalized subsequently so this assumption does not have significant influence on M_n. The computation of parameter *K* may be influenced if the hydrograph steepness up to the bank-full level is very different from the steepness from the bank-full level to the peak flood. However, the normalization of *K* subsequently reduced influences of this assumption. For the Oc-gok basin the extent of this influence is unknown and is assumed not to influence the normalised parameter K_n substantially.

Due to the unavailability of the discharge data at the start of each flood event and the average discharge data the FI values according to the approach of Bhaskar et al. could not be computed. Note that the normalization procedure used by Bhaskar et al. (2000) makes it less adaptable to another location. Table 3 lists the 54 flood events in the Oc-gok basin considered in this study and the corresponding flood indexing parameters.

Fig. 5 shows the variation of FI with flood magnitudes. It is discernible that both methods show a general increase of FI with flood magnitude and they follow a comparable trend. The FI values computed based on the presented NFI approach superbly follow a logarithmic trajectory with Eq. (9):

$$FI = 0.945\, Ln(Q_p) - 3.93 \tag{9}$$

where Q_p is the peak flood and *Ln* stands for natural logarithm.

Eq. (9) fits the computed values with R^2=0.97 and can be used in estimating FI values for future flood events or for design flood magnitudes. The authors again point out the advantage of referring to such newly computed values to a standard flood (e.g. 100-year flood).

Table 3. Fifty four flood events in the Oc-gok catchments and the corresponding flood indexing parameters computed based on two approaches

Date	*Flood peak Q_p (m^3/s)*	*Start time (hour)*	*Peak time (hour)*	*FI (Ahn & Choi) [-]*	*The presented NFI approach*						
					Flood magnitude ratio M [-]	*Rising curve gradient K (day^{-1})*	*Flood response time TP (hour)*	*M_n [-]*	*K_n [-]*	*TP_n [-]*	*FI [-]*
7/26/06	199.6	2.35	5	0.77	2.32	7.63	2.65	1	1	1	1.00
7/15/92	175.1	0.75	2	0.68	2.04	13.65	1.25	0.88	1.79	0.47	0.90
9/2/84	162.1	7.14	10	0.6	1.88	5.32	2.86	0.81	0.70	1.08	0.85
9/6/02	159.8	0.12	1	0.68	1.86	16.90	0.88	0.80	2.22	0.33	0.84
08/16/98	154.4	5.62	8	0.55	1.80	5.90	2.38	0.77	0.77	0.90	0.81
08/29/89	150.9	2.71	4	0.57	1.75	10.46	1.29	0.76	1.37	0.49	0.80
08/3/05	148	8.8	10	0.59	1.72	10.86	1.2	0.74	1.42	0.45	0.78
07/5/84	146.8	4.56	6	0.49	1.71	8.91	1.44	0.74	1.17	0.54	0.78
08/6/76	139.1	0.95	2	0.47	1.62	10.99	1.05	0.70	1.44	0.40	0.74
9/29/02	138.6	0.89	2	0.49	1.61	10.32	1.11	0.69	1.35	0.42	0.73
8/26/00	136.9	6.26	8	0.45	1.59	6.41	1.74	0.69	0.84	0.66	0.72
7/22/83	131.4	12.87	14	0.43	1.53	9.00	1.13	0.66	1.18	0.43	0.69
6/7/87	130.6	2.65	4	0.46	1.52	7.43	1.35	0.65	0.97	0.51	0.69
8/4/04	125	1.24	2	0.43	1.45	11.81	0.76	0.63	1.55	0.29	0.65
8/14/82	124.8	16.62	18	0.39	1.45	6.48	1.38	0.63	0.85	0.52	0.65
8/12/08	123.5	2.9	4	0.36	1.44	7.90	1.1	0.62	1.04	0.42	0.64
9/15/07	121.1	2.49	3	0.46	1.41	16.11	0.51	0.61	2.11	0.19	0.63
9/12/90	119.1	12.51	13	0.46	1.38	15.95	0.49	0.60	2.09	0.18	0.61
7/30/73	117.3	2.58	4	0.3	1.36	5.25	1.42	0.59	0.69	0.54	0.60
7/21/09	116.2	2.55	3	0.45	1.35	16.05	0.45	0.58	2.11	0.17	0.59
6/22/81	115.3	2.48	4	0.3	1.34	4.63	1.52	0.58	0.61	0.57	0.59
8/7/77	114.7	17.72	19	0.29	1.33	5.40	1.28	0.57	0.71	0.48	0.58
8/30/81	114.1	16.42	17	0.34	1.33	11.70	0.58	0.57	1.53	0.22	0.58
8/15/08	114.1	1.36	2	0.32	1.33	10.60	0.64	0.57	1.39	0.24	0.58
8/21/03	112.8	4.49	5	0.37	1.31	12.77	0.51	0.57	1.67	0.19	0.57
8/25/95	111.7	1.92	3	0.27	1.30	5.81	1.08	0.56	0.76	0.41	0.56
7/15/09	110.9	1.25	2	0.28	1.29	8.14	0.75	0.56	1.07	0.28	0.55
8/13/93	110.7	8.36	9	0.3	1.29	9.47	0.64	0.55	1.24	0.24	0.55
9/17/07	106.5	5.56	6	0.3	1.24	11.66	0.44	0.53	1.53	0.17	0.51
8/23/74	106	2.94	4	0.24	1.23	4.73	1.06	0.53	0.62	0.40	0.51
4/16/02	104.8	8.96	10	0.24	1.22	4.56	1.04	0.53	0.60	0.39	0.50
9/3/04	104.3	1.66	2	0.31	1.21	13.62	0.34	0.52	1.79	0.13	0.49
9/9/03	102.6	2.99	4	0.2	1.19	4.19	1.01	0.51	0.55	0.38	0.48
8/3/73	102.1	0.61	1	0.3	1.19	10.56	0.39	0.51	1.38	0.15	0.47
8/31/77	100.4	0.78	1	0.3	1.17	16.89	0.22	0.50	2.21	0.08	0.45
6/25/86	99.8	16.74	18	0.17	1.16	2.83	1.26	0.50	0.37	0.48	0.45
6/27/00	99	15.66	16	0.25	1.15	9.94	0.34	0.50	1.30	0.13	0.44
6/29/83	98.1	2.18	3	0.16	1.14	3.85	0.82	0.49	0.51	0.31	0.43
9/13/03	97.6	5.17	6	0.16	1.13	3.66	0.83	0.49	0.48	0.31	0.42
7/18/90	97.5	0.63	1	0.16	1.13	8.14	0.37	0.49	1.07	0.14	0.42
9/5/07	97	3.66	4	0.22	1.13	8.50	0.34	0.49	1.11	0.13	0.41
8/6/75	95.7	7.51	8	0.14	1.11	5.23	0.49	0.48	0.69	0.18	0.39
8/2/93	95.5	6.59	7	0.17	1.11	6.13	0.41	0.48	0.80	0.15	0.39
8/3/76	95.4	2.47	3	0.14	1.11	4.70	0.53	0.48	0.62	0.20	0.39
9/27/91	93.7	8.7	9	0.14	1.09	6.86	0.3	0.47	0.90	0.11	0.36
7/13/04	93.1	1.75	2	0.12	1.08	7.62	0.25	0.47	1.00	0.09	0.35
7/19/08	92.4	0.84	1	0.13	1.07	10.77	0.16	0.46	1.41	0.06	0.34
8/8/06	92	0.9	1	0.18	1.07	16.19	0.1	0.46	2.12	0.04	0.33
7/26/90	89.9	0.93	1	0.13	1.05	15.21	0.07	0.45	1.99	0.03	0.29
8/7/02	89.4	9.61	10	0.07	1.04	2.39	0.39	0.45	0.31	0.15	0.27
8/28/07	88.8	1.95	2	0.15	1.03	15.38	0.05	0.44	2.02	0.02	0.26
7/15/88	87.9	2.81	3	0.05	1.02	2.76	0.19	0.44	0.36	0.07	0.23
8/26/78	86.8	0.97	1	0.03	1.01	7.41	0.03	0.43	0.97	0.01	0.17
7/18/06	86.4	7.97	8	0.02	1.00	3.71	0.03	0.43	0.49	0.01	0.13

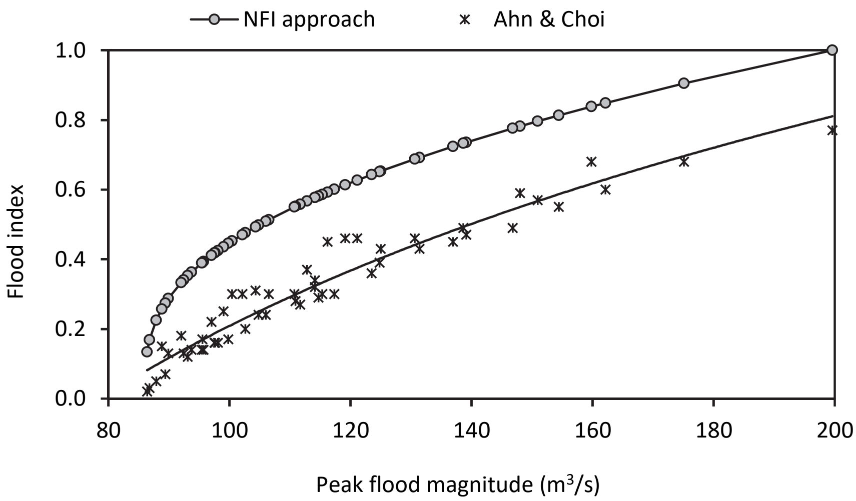

Fig. 5. Flood indices computed for the Oc-gok catchment by the approaches of Ahn and Choi (2013) and the presented NFI approach

Similar to the analysis in Kentucky catchments the following four representative flood events were considered for the Oc-gok catchment: largest flood, second largest flood, smallest flood and a flood close to the median value. Fig. 6 shows the FI values with the corresponding indexing parameters for the four flood events. Both approaches show changes in the indexing parameters in the same direction but with different magnitudes. Fig. 7 shows the variation of FI with 3-hour catchment rainfall. A comparable trend for both approaches is discernible. For the Kentucky catchment we did not have the hourly rainfall and as a result the relationship between rainfall and FI was not clearly demonstrated. Fig. 7 suggests that FI is well connected with the rainfall-runoff dynamics of the catchment.

4.3. Haor region

The FI values for 24 flood events in the Haor region were computed as per Ahn and Choi (2013) and the presented NFI approach. Once again due to the specific normalization procedure of Bhaskar et al. (2000) the authors were not able to compute the FI values as per their approach. Due to the unavailability of the bank-full discharge data the initial discharge and average discharge were used in computing the parameters K and M for the approach of Ahn and Choi (2013). This assumption, as has been pointed out earlier, has limited influence on the normalized values of K and M. The studied region has twelve rivers with substantial variation of discharge. The FI values for each of these rivers are computed. In order to save space we have not included the table with the flood data with their corresponding FI values for the Haor region (similar to Table 1). In general, the pattern of the FI values of both methods is comparable (not shown to save space). We argue once again that as the FI values as per the presented approach are computed related to the 100-year flood so the FI values provide easier understanding of the flooding severity. Furthermore, we considered the following four representative flood events: largest flood, second largest flood, smallest flood and a flood close to the median value. The comparison of the computed FI values (Fig. 8) of the two approaches shows once again that interpretation of FI values by referring to the 100-year flood makes better sense.

The authors explored further possibilities of making use of the computed FI values. Large variation of the FI values in the Haor region can be observed. The large catchment size and the varying flooding characteristics of the 12 rivers of the region are the prime reasons behind this. Fig. 9 clearly shows the existence of two groups of rivers, which are grouped based on their FI values. Group 1 consists of the following rivers: Surma, Nawa, Someswari, Baulai, Patnaigang, Piyan, Lower Kansha. Group 2 consists of the following rivers: Jadukata, Nandiagang, Baulal, Jhalukhali, Jaduka.

The spatial and temporal variation of FI in the catchment was subsequently analysed. For all the rivers of the Haor region the FI values were computed at a number of locations along the length of the rivers. Fig. 10 shows the variation of the FI values. In general, it can be observed that the FI values decrease in the downstream direction, indicating lower risks. The extent of this decrease is a characteristic of a river. In another catchment it is possible to notice that the FI values increase in the downstream direction.

Subsequently, we computed the temporal variation of the FI values for the Haor region. As FI was calculated from flood hydrograph, it should change with flood of different return periods. By carrying out flood frequency analysis of the Haor region flood magnitudes of different return periods for each of the rivers were computed. For each river and for varying flood magnitudes the FI values were computed using Eqs. (1) to (7) (Fig. 11). The spatial (Fig. 10) and temporal variation (Fig. 11) of FI of the catchment provides a synoptic view of the flooding characteristics of the Haor region.

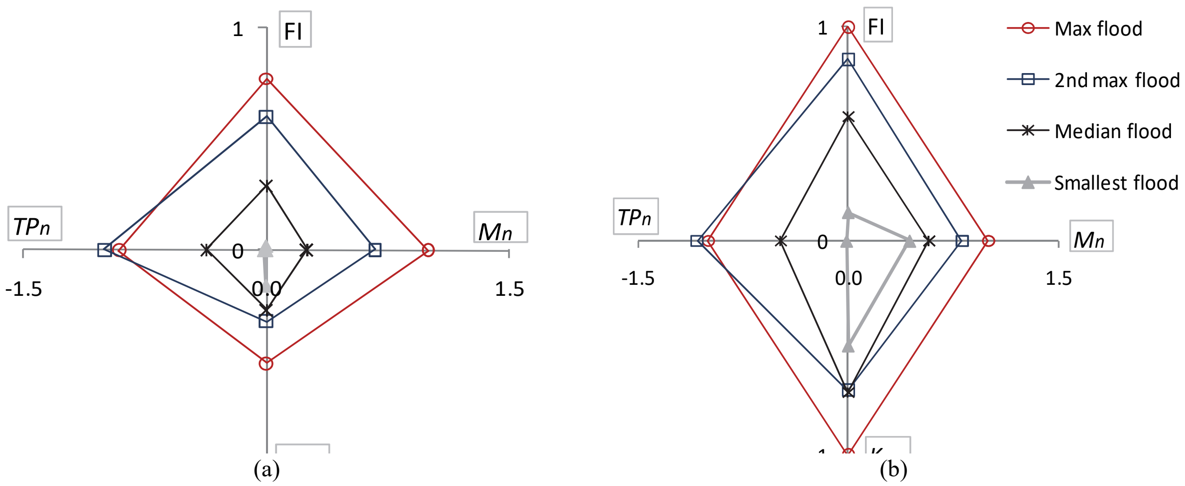

Fig. 6. Comparison of the normalized flood indexing parameters for four different floods in the Oc-gok catchment as per (a) Ahn and Choi (2013); and (b) the presented NFI approach

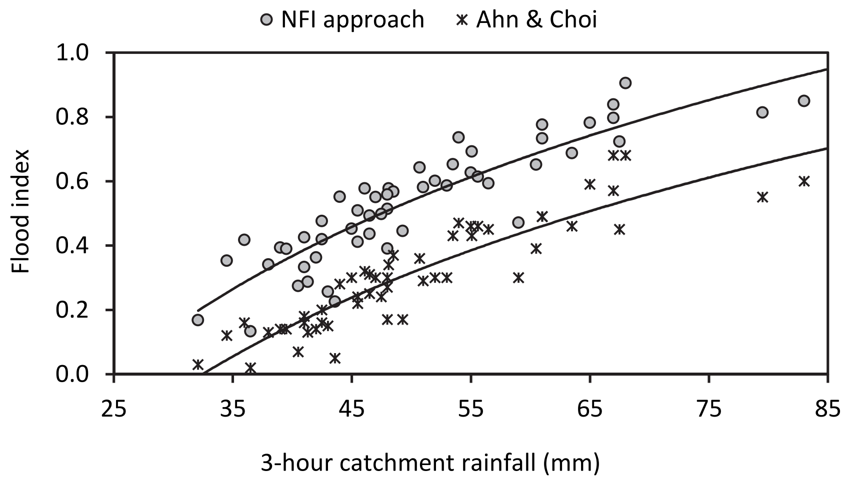

Fig. 7. Relationship between flood indices and 3-hourly catchment rainfall for the Oc-gok catchment

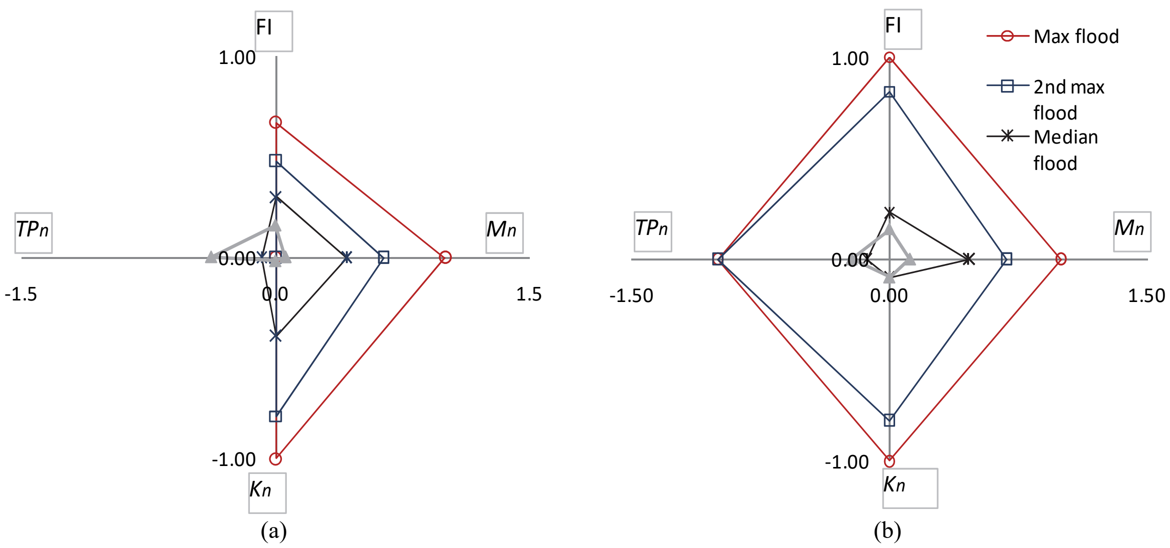

Fig. 8. Comparison of flood indexing parameters for four floods in the Haor region as per (a) Ahn and Choi (2013); and (b) the presented NFI approach

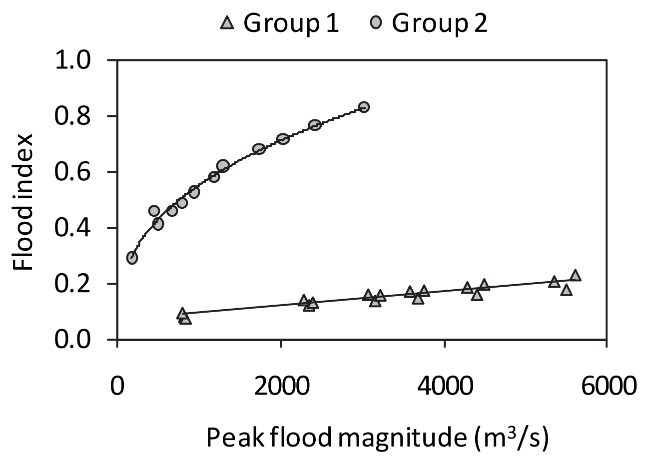

Fig. 9. Variation of flood indices with peak flood discharge in the Haor region computed as per the presented NFI approach. Group 1 and 2 refers to two groups of rivers in the Haor region

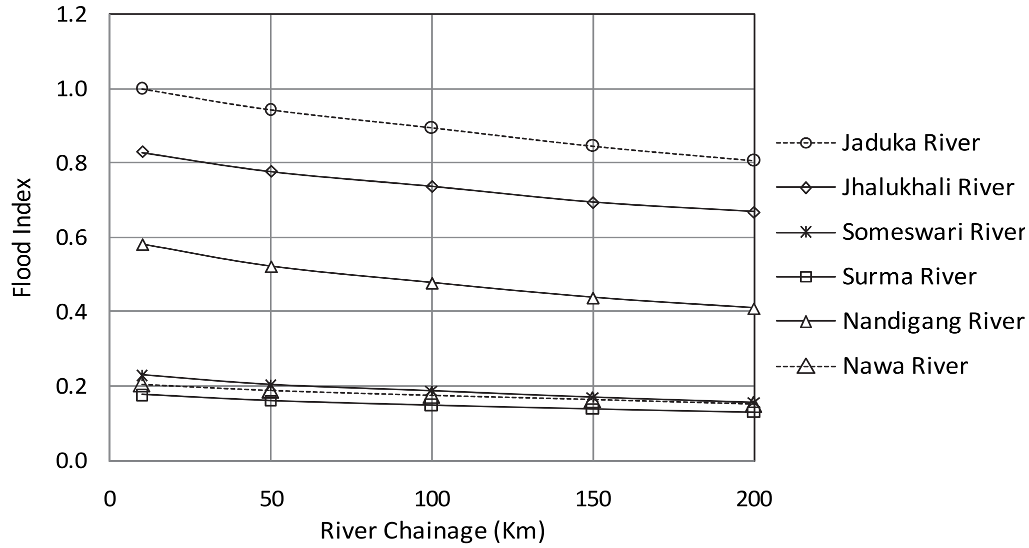

Fig. 10. Spatial variation of flood index in various rivers of the Haor area computed as per the presented NFI approach

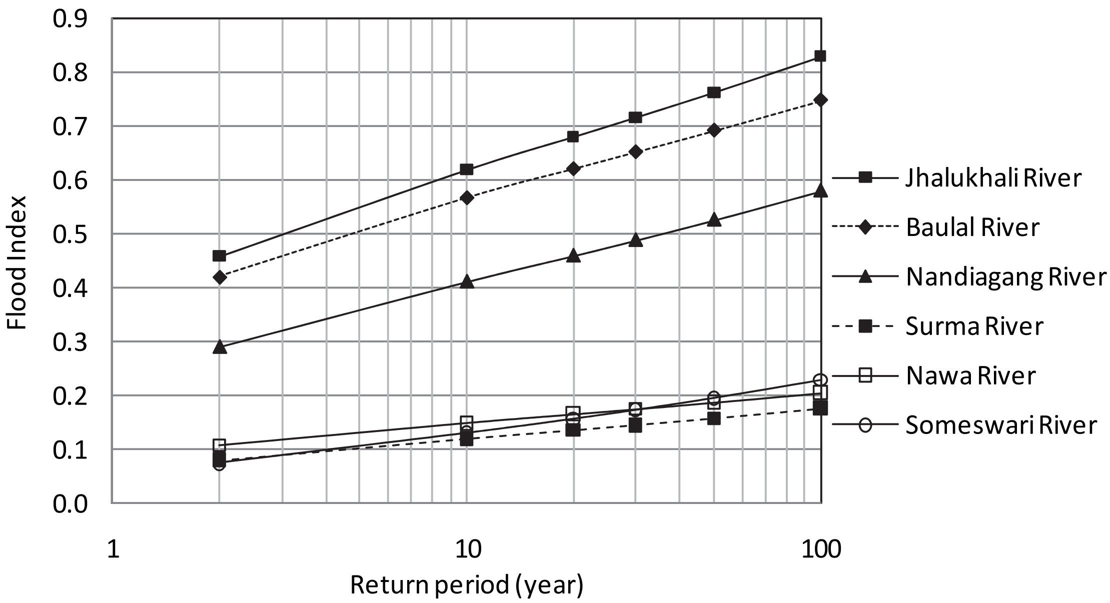

Fig. 11. Temporal variation of flood index in different rivers of the Haor region for different return periods computed as per the presented NFI approach

The results of the three case studies present the possibilities for the usage of FI in flood risk management. In particular, for catchments which are ungauged or partially gauged and exhibit short reaction time FI can be seen as a valuable tool. The spatial and temporal variation of FI can be used in flood zoning, spatial planning and flood event management. It is argued that the presented approach is an improvement over the existing ones as it presents FI corresponding to the flood with the 100-year return period. As a result the FI values can be connected to the flood exceedance probabilities of a catchment.

We also need to realize that FI is an aggregated number with limited physical significance and is only meaningful if we want to understand the comparative severity of a flood at a particular location. It is further argued that the comparison should be done with respect to the 100-year flood (or the maximum available flood magnitude).

Unavailability of past flood hydrographs (measured, or simulated) may limit the possibility of applying this method. A limitation is that varying catchment conditions may lead to slightly different FI values for the same flood magnitude. Thus for a particular flood event additional information (e.g. catchment wetness) may therefore be collected to infer whether FI for that flood event may be higher or lower compared to the estimated FI (e.g. based on Eq. 8). If data from a large number of past flood events is available or a simulations model is run with varying catchment conditions then this limitation may be avoided. For example, by developing three regression equations similar to Eq. (8) with one for high, low and average K values. An alternative may be to construct three regression equations similar to Eq. (8) for three catchment wetness conditions (dry, wet and medium).

5. Conclusions

This paper presents a novel method to compute a flood index using the combination of the past flood hydrograph and/or simulated hydrograph characteristics.

In un-gauged catchments or catchments where climatological conditions necessitate flood event management to play an important role FI can be used as a useful tool in identifying the flood risk hot-spots. FI as a number does not have any physical significance but in comparison to FI values corresponding to different flood magnitudes it can be used to express the relative severity of a flood. The variation of FI in space and time presents flooding characteristics of a catchment and as a result FI can serve as a useful tool in flood risk management.

In case of a probable flood, the spatial variation of FI corresponding to any flood magnitude, can help in identifying locations requiring attention. This tool, however, cannot help in knowing when the flood may occur or what could be the likely flood water level; it rather helps in raising an alert.

The presented approach is developed by modifying existing methodologies on computing FI. It is argued that by computing FI in relation to the 100-year flood helps in identifying the relative severity of a flood. The developed methodology was applied to three case studies: four small catchments in eastern Kentucky, USA; Oc-gok River basin, in Korea and the Haor region in Bangladesh. The results and its analyses were qualitatively found to be useful in identifying locations of high flood risks. With the Haor case study it is shown that it is possible to analyze the spatial and temporal variation of FI, which presents the spatio-temporal variation of flood risk. Future studies may consider comparing the presented approach with the source-pathway-receptor-consequence model used in flood risk management and in identifying the relative advantages of both approaches.

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