Analysing the effect of land-use/cover changes at sub-catchment levels on the downstream flood peak: a semi-distributed modelling approach with sparse data

By

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Abstract

This paper aims to evaluate how varying degrees of land use/cover (LULC) changes across sub-catchments affects the flood peak at the catchment outlet. The Kona catchment, a part of the upper Damodar Basin in eastern India, was the study site. A HEC-HMS model was set up to simulate rainfall-runoff processes for two LULC scenarios three decades apart. Because of sparse data at the study site, we used the Natural Resource Conservation Service (NRCS) Curve Number (CN) approach to account for the effect of LULC and soil on the hydrologic response. Although a weak (r = 0.53) but statistically significant positive linear correlation was found between sub-catchment wise LULC changes and the magnitude of flood peak at the catchment outlet, a number of sub-catchments showed marked deviations from this relationship. The varying timing of flow convergence at different stream orders due to the localised LULC changes makes it difficult to upscale the conventional land use and runoff relationship, evident at the plot scale, to a large basin. However, a simple modelling framework is provided based on easily accessible input data and a freely available and widely used hydrological model (HEC-HMS) to check the possible effect of LULC changes at a particular sub-catchment on the hydrograph at the basin outlet.

Keywords: Land use/cover change, peak discharge, NRCS CN, HEC-HMS, Sub-catchment, Flow Convergence Timing.

1 Introduction

Soil, topography and land cover are the most important factors that control rainfall-runoff processes at the scale of single flood events for river basins. As alterations in soil and topography are insignificant in the short term, changes in land cover are considered to be the key element in modifying rainfall-runoff processes (Miller et al., 2002). Land-use/land-cover (LULC) change and any consequent hydrological response have been prominent topics of research in recent years (Chen et al., 2009; Amini et al., 2011; Fox et al., 2012). With changing climate and the increasing frequency of flooding events across the world (Collins 2009; Hurkmans et al. 2009; Xu et al. 2009), the effects of LULC changes on extreme runoff events are likely to draw more attention.

Wan and Yang (2007) concluded that anthropogenic land use change is one of the major drivers of an increased frequency of flooding incidents. At small spatial scales (< 2 km^2) deforestation was reported to have strong correlation with increase in flooding (Bosch and Hewlett, 1982). However, the picture is less clear for larger catchments, where a number of studies have reported no significant change in flooding pattern with deforestation (Beschta et al., 2000; Andréassian, 2004) while others have observed even a negative trend in flood occurrence with reductions in forest cover (Hornbeck et al., 1997). Wei et al. (2008) reported an increase in the peak flow with deforestation but also observed that reforestation on the cleared land has limited effect on reducing the peak flow. Van Dijk et al. (2009) came to the conclusion that the empirical evidence and theoretical arguments for increased flood intensity with removal of forest are not very convincing. Shi et al. (2007) reported that high antecedent moisture conditions reduce the effect of increased urbanization on runoff in a small 56 km^2 catchment in Shenzhen, China.

A number of studies have attempted to analyse the impact of land-use change on storm runoff at the event scale (Chen et al., 2009; Ali et al., 2011; O'Donnell et al., 2011). LULC scenario-based studies have used past and present LULC states or radical LULC change scenarios in event-scale hydrological models to assess the hydrological response of catchments (Camorani et al., 2005; Olang and Furst, 2011). Chen et al. (2009) coupled a LULC scenario-generation model with a hydrological model and concluded that increasing urban areas led to increase in the total runoff volume and peak discharge of storm runoff events. Ali et al. (2011) conducted an event-scale experiment in a predominantly urbanised catchment containing the city of Islamabad in Pakistan and had similar findings. It is noted that this type of study is generally restricted to small urban catchments, partly due to the easy availability of hydrological data near urban centres, the urgency of mitigating flooding problems in the centres of large population concentration and the general perception that expansion of built-up areas hampers infiltration and contribute a to the flood peak. It is not surprising that the finding of these studies coincide with the conventional wisdom that reduction in forest or increase in paved surface leads directly to increased runoff. An over-emphasis on the effect of afforestation and urbanization and lack of interest in examining the LULC changes in river basins with diverse LULC types have been the characteristics of recent research on the effect of land-cover change in flooding (Wan and Yang, 2007).

The contribution of streamflow from a specific land use is not uniformly proportional to the area of that land use and depends greatly on the location of that land use within the basin (Warburton et al., 2012). This study further showed that the streamflow response at the basin outlet is influenced by the spatial distribution of various land uses present in the entire catchment and the balancing or cancelling effect of those land uses. For example, where urbanization takes place in the upper sub-catchments, it leads to a disproportionately larger increase in the flood peak downstream (Amini et al. 2011). Human intervention by means of augmentation of channel capacity though improved channel management in the urban areas has been also found to act as a counterbalance to reduce the additional surface runoff generated by expanding urban area or reducing forests (Fox et al., 2012)

The primary application of findings from investigations dealing with LULC change and its effect on downstream flood peaks is in watershed management. Watershed management strategies often aim to identify the source area that generates a significant contribution to the downstream flood peak and implement remedial land use practices to reduce the runoff coefficient from this flood source area. As with the effects of LULC change on catchment hydrology, the effects of land management have been convincingly documented by studies involving small catchments (Bloschl et al., 2007; O'Connell et al., 2007). To be efficient, improvement of land use management practice should be based on a ranking of sub-catchments according to their contribution to downstream flood peaks.

Pattison and Lane (2012) reviewed this topic of possible relation between land-use change and possible downstream flood risk and pointed out that it is not uncommon to find an association between land-use change and streamflow behaviour at field and plot scales but it is quite challenging to upscale this effect to show similar hydrological responses for large catchments. Analysis and identification of the flood source area and its contribution at the cumulative basin outlet has been carried out with hydrologic modelling using the HEC-HMS model (Saghafian and Khosroshahi 2005; Roughani et al., 2007; Saghafian et al. 2008) and with statistical approaches involving rainfall and runoff data at the sub-catchment level (Pattison et al., 2008). Recently, Ewen et al. (2012) attempted to model the causal link between LULC changes at small scale to the flood hydrograph at the basin outlet by using reverse algorithmic differentiation and showed the sources of impact at the scale of small tiles that were used to decompose the model domain.

The statistical approach (Pattison et al., 2008) or the modelling approach (Ewen et al., 2012) are heavily dependent on a dense network of automatic rain and river gauging stations and are not possible to follow in a data scarce environment, which is typical in developing countries. Although a variety of hydrological models are available it is difficult to use them in data scarce environment such as India due to their requirement in terms of soil moisture and channel topography related data. The US Natural Resources Conservation Service (NRCS) curve number (CN) approach for runoff estimation is particularly suitable for applying in data scarce situations and has been widely used to estimate surface runoff in an accurate manner with limited data (Bhaduri et al, 2000; Mishra et al, 2003). The CN is an empirically derived dimensionless number that accounts for the complex relationship of land cover and soil and can be computed with widely available datasets such as satellite-derived LULC maps and small scale soil maps. Easy integration of remotely sensed LULC information has made the NRCS CN a popular choice among the scientific community for runoff estimation from the early days of remote sensing (Jackson et al., 1977; Slack and Welch 1980; Stuebe and Johnston 1990). There are numerous case studies that used remote sensing for deriving CN in order to estimate runoff at catchment scale with sparse data (*e.g.* Tiwari et al., 1991; Sharma and Singh, 1992; Amutha and Porchelvan, 2009). However, the strong seasonal pattern of land-use in monsoon climates has not been highlighted when comparing the hydrologic response of two land use scenarios observed over a period of few decades. Changing canopy cover and the proportion of cultivated land and other land covers may exert considerable control over rainfall-runoff processes.

The investigations to date have mostly dealt with the issue of LULC change across the catchment as a whole. However, as pointed out by Pattison et al. (2008), remedial land management practices are conceived and implemented at the sub-catchment scale. Although the modelling-based approach by Saghafian et al., (2008) and Roughani et al. (2007) attempted to identify the sub-catchments that have serious impact on the flood peak (flood source area) at the main catchment outlet, they did not assess how changes in LULC across the sub-catchment may change the location of the flood source area. There is a need for a systematic evaluation of sub-catchment wise LULC change and resultant changes in priority areas for implementing remedial land-use measures. LULC can change significantly in short periods, and the occurrence of LULC change in different parts of the catchment is likely to affect the flood peak at the catchment outlet in a complex manner.

This study is part of a broad investigation that deals with developing an adequate system for routing flood waves in the lower Damodar River in eastern India with freely available data and minimum ground survey (Sanyal et al., 2013) and modelling widespread floodplain inundation at a frequently flooded reach further downstream using low-cost high resolution terrain data (Sanyal et al., In-Press).

The objective of this study is to investigate (1) the effect of LULC change at sub-catchment level on the peak discharge at the catchment outlet during storm events, and (2) the interplay between sub-catchment position, LULC change and runoff. The findings of this paper have a direct implication on land-use management practices that are undertaken to reduce the peak inflow to reservoirs during storm events. The novel aspect of this investigation lies in the establishment of a direct link between sub-catchment scale LULC changes and their contribution to the flood peak at the basin outlet through semi-distributed rainfall-runoff modelling. In addition, this study also points out the typical challenges of modelling rainfall-runoff processes in data scarce environments and the required adaptations in methods to deal with this constraint.

2 Study Area

The Konar Reservoir is impounded by one of the four major dams in the upper catchment of the Damodar River in eastern India (Fig1). The catchment upstream of the reservoir is a typical example of physiographic, drainage and LULC conditions in the upper Damodar basin. A number of previous authors (e.g. Choudhury, 2011; Ghosh, 2011; Bhattacharyya, 1973) have argued that deforestation in the upper hilly and forested catchments in the upper Damodar basin has increased both the runoff coefficient and flood peak, and has reduced the capacity of the four reservoirs to moderate flood waves downstream. The catchment also exemplifies the scarcity of required data for hydrological modelling, which is a typical scenario in the developing countries. The catchment is drained by the Konar and Siwane Rivers and is 998 km^2 in size. The topography is characterised by a dissected plateau region with occasional hills. Elevation ranges from 402 to 934 m asl. The upland areas in the catchment are mostly under forest cover while paddy cultivation during the monsoon season is the dominant land use in the lower reaches. Rainfall has a strong seasonal pattern which is heavily influenced by the southwest Indian monsoon. Torrential rain for a few hours per day during the monsoon season (mid June to mid October) often leads to high magnitude floods in this part of the Damodar Basin.

3 Materials and Methods

3.1 Generating curve numbers for two LULC scenarios

The NRCS CN model is appropriate for use in data-sparse situations because the primary model inputs are LULC and soil types that are easy to obtain from remote sensing and widely available soil maps. The NRCS method of estimating runoff due to rainfall (NRCS, 1972) is expressed in the following equations:

$$Q = 0 \qquad P \leq 0.2\,S \qquad (1)$$

$$Q = (P - 0.2\,S)^2/(P+0.8S) \qquad P \geq 0.2S \qquad (2)$$

where Q is the direct runoff depth (mm), P is the storm rainfall(mm), and S in the potential maximum retention (mm). S is related to a dimensionless curve number, CN by:

$$S = (254000/CN) - 254 \qquad (3)$$

In this method soil types are classified into four hydrological soil groups (A, B, C, and D) with increasing potential for generating runoff. Hydrological soil groups of any area can be identified by analysing soil texture. The method also considers the antecedent soil moisture condition by providing modified value for dry (AMCI) and wet (AMCIII) condition based on the preceding five days' daily rainfall.

In order to assess the impact of different land-cover scenarios on the peak flood discharge at the entry of the Konar Reservoir, two land-cover maps were generated from satellite imagery. A Landsat MSS image (79 m spatial resolution) from 27th October, 1976 and a Landsat TM image (30 m spatial resolution) from 2nd November, 2004 were used for generating two LULC maps. These two dates were chosen as this is the largest time span that was possible to capture with due considerations to the availability of cloud-free images at the final stage of the southwest monsoon season when the flood events considered took place.

Unsupervised classification was used to classify each image into 30 spectral classes. In the next step, the spectral classes were compared with a high resolution panchromatic Corona satellite image from 21st November, 1973 and a topographic map (1:50,000 scale) from the Survey of India (Map No. 73 E/5) which was surveyed in 1978-79. Similar classes were combined appropriately to create a land-cover map for 1976. High resolution QuickBird images available in GoogleEarth for 15th November, 2004 was utilised for the same purpose in order to classify the Landsat TM image of 2004. Finally we generated two LULC maps with following classes: 1) water body, 2) rocky waste, 3) urban area, 4) paddy field, 5) shrub, 6) open forest, and 7) dense forest. There is a potential problem in comparing LULC changes from pixel to pixel between the two time periods because of the use of different sensors for acquiring the two images. However, Landsat MSS and TM data have been successfully used with unsupervised classification for identifying changes of broad land cover categories in Africa (Brink and Eva, 2009). The spectral resolutions of Landsat MSS and TM for Band 1, 2, 3 and 4 are quite close and we only attempted to identify the broad land cover classes that are identifiable in the coarse resolution Landsat MSS images. Post-classification comparison of the LULC maps for the two time periods is likely to eliminate most of the discrepancies arising from the use of different sensors and spatial resolution. Due to the limitation of the spatial and spectral resolution of the available satellite imagery, identifying land-cover classes for which a CN value is available in standard lookup tables was not always possible and an adjustment of the CN table was necessary to get optimal runoff estimates using the

NRCS-CN approach (Kumar et al., 1991). We used the CN lookup table compiled by Tripathi et al. (2002) for land-use and soil texture classes in the Nagwan sub-catchment, a part of the Konar Reservoir catchment, except that the CN value for paddy fields was taken from Shi et al. (2007); the table in Tripathi et al. (2002) classified the paddy fields as upland and lowland paddy, but it was not possible to distinguish these in our land-cover classification. Hydrologic soil groups of the study area were determined by consulting the composition and texture of the soil types obtained from the soil maps of National Bureau of Soil Survey and Land Use Planning, India (NBSS&LUP). The land-cover maps and hydrologic soil groups map were combined using the lookup table in GIS to create CN maps for 1976 and 2004.

3.2 Setting up the rainfall-runoff model

The HEC-HMS modelling suite was chosen for simulating the rainfall-runoff process, as this package has a host of modelling options for computing the runoff hydrograph for each sub-basin and routing it through river reaches at the basin outlet (Beighley and Moglen, 2003). HEC-HMS has the option of using the NRCS CN method for computing direct runoff volume for a given rainfall event, which is a popular modelling choice for application in the data scarce environment (Olang and Furst, 2011; Candela et al., 2012; Du et al., 2012; Jia and Wan, 2011; Amini et al., 2011). The model has a GIS pre-processor known as HEC-GeoHMS which was used for extracting and integrating GIS data such as DEM, LULC and soil maps into the hydrological model.

A total of 124 sub-catchments were delineated from the SRTM DEM in the Konar catchment during the pre-processing stage in HEC-GeoHMS. The streams were vectorised from the topographic maps of the study area for use as a reference for guiding the automated sub-catchment delineation from the SRTM DEM. Das et al. (1992) used Strahler's stream ordering technique to identify the optimal basin size for NRCS-CN-based estimation of runoff volume for part of the upper Damodar River basin and this principle was used in our study. After filling the sinks a threshold contributing area of 5 km^2 was found suitable to delineate the streams that in general match the 2nd-order streams in the topographic maps. Due to the coarse nature of the SRTM DEM we could not automatically extract the 1st order streams as found in the topographic maps.

Sub-daily rainfall is an essential input for simulating storm runoff, particularly in tropical region where high intensity rainfall for a few hours often leads to flooding. We obtained rainfall data at 1 hour intervals for a storm event lasting from 11 to 12 October, 1973 from an autographic rain gauge located in Hazaribagh Town (Fig1). The data are supplied by the Indian Meteorological Department (IMD). In order to validate the accuracy of the model for the 2004 land cover scenario we used a storm rainfall event from 8-10 October, 2003, which was estimated by the 3B42 V6 product of the Tropical Rainfall Measuring Mission (Huffman et al., 2007). No gauged sub-daily rainfall data was available after 1976 as the autographic rainfall station has been defunct since then. The October, 2003 event was deemed most appropriate as the CN values for 2004 derived from a Landat TM image acquired on 2nd November reflected a land cover that is very similar to the prevailing LULC situation when the storm event of 2003 took place. It has been reported that TRMM data frequently do not match with *in situ* observations. For this reason, the area averaged 3-hourly 3B42 V6 TRMM data for the Konar catchment were summed into daily totals and compared with the daily rainfall product of the Indian Meteorological Department (Rajeevan and Bhate, 2008) which is derived from rain gauges and supplied in 0.5 degree gridded format. We found that the TRMM records for the 3 days (8-10 October, 2003) was only 3.7% higher than the IMD figures. After considering the preceding rainfall of last 5 days for the 1973 and 2003 events from the daily rainfall products of IMD we decided that the antecedent moisture condition was normal (AMCII) (35-53 mm) for the 1973 event but it was dry (AMCI) (> 35 mm) for the 2003 event. Hence, the normal CN values for the 2004 land cover scenario were converted to AMCI using the formula proposed by Mishra et al. (2008):

$$CN_I = CN_{II}/(2.2754 - 0.012754\ CN_{II}) \qquad (4)$$

As four TRMM tiles cut across the Konar catchment, we downloaded and stacked 3-hourly gridded TRMM data for those four tiles for the storm period and extracted the pixel data into a time series. In the next step, four artificial rain gauges were created in HEC-HMS for the NW, NE, SW and SE portions of the Konar catchment and the gauges were populated with the extracted pixel values of the corresponding TRMM grid. In this way we managed to use quasi-distributed rainfall data into HEC-HMS for simulating the 2003 storm event.

The total rainfall received during the 1973 event was 156.7 mm where 132.3 mm was received on 12 October, 1973. The rainfall amount for the 2003 event, as derived from the spatial average of the TRMM data was 176 mm from 07 to 09 October, 2003. 80.63 mm of rainfall was received in 12 hours between 08 to 09 October, 2003.

We have no access to long-term time-series of observed daily discharge data at the model outlet (Inflow to Konar Reservoir) for computing return periods of the two storm events that were considered for the present study. However, Fig 2 provides the general characteristics of the 1973 and 2003 storm events relative to few other major storm events for which daily discharge data at the model outlet is available with us. From this limited available data we may assume that that both events under consideration in this study are average major storm events in the Konar catchment.

The highest temporal resolution of available rainfall data was 1 hour (1973 event). Considering the small lag times of the smaller sub-catchments in the Konar catchment, it was found unrealistic to run the model at 1 or 3 hour time step. A five minute time step was selected for both models and consequently, the rainfall data for 1973 and 2003 were proportionately disaggregated into five minutes interval to match the modelling time step. Since only one functional rain gage (Hazaribagh Town) capable of recording rainfall at a sub-daily interval (1 hour) was available for the 1973 event it was used and we had to assume uniformly distributed rainfall.

TRMM 3-hour interval rainfall estimates are available for a spatial resolution of 0.25 degrees. Konar Basin was almost uniformly subdivided into four such TRMM grids. It was recognised that the 2003 TRMM data is almost certainly of inferior quality than the hourly rain gauge data that was available for the 1973 event . Deriving the mean of four corresponding TRMM grids would further deteriorate the quality of the rainfall input for the 2004 event. In order to avoid this deterioration in the quality of the input rainfall we did not used a spatially uniform rainfall input similar to the 1973 event and this factor should be given due consideration for comparing the results of the two simulations. However, we would like to emphasise that the aim of presenting the rainfall event of 2003 with the LULC condition of 2004 was to only to establish that the model is capable of simulating the rainfall-runoff process in the Konar Basin for different rainfall and LULC conditions with reasonable accuracy.

The NRSC unit hydrograph lag method was used for computing the basin lag which is necessary for transforming the excess rainfall (or direct runoff volume) into runoff into the channels. Finally, the Muskingum-Cunge flow routing model was employed to route the flow through the channels to the outlet. Initially the model was run with the hourly rainfall of 11-12 October, 1973 and the CN values (AMCII) derived from the 1976 land cover map and the results were compared with the available daily runoff volume at the entry point of the Konar Reservoir (basin outlet). In the next step, the model was run with the 3-hourly TRMM rainfall of 8-10 October, 2003 with the CN values (AMCI) of 2004 and the hydrograph in terms of daily runoff volume was compared with the observed data. Following Knebl et al. (2005) and McColl and Agget (2007) it was anticipated that evapotranspiration losses would be negligible as the interest of this study is in high intensity monsoon storms that lead to flooding. Since our model only simulated the direct runoff, we derived the base flow component from the observed daily discharge data graphically by joining the points of infection of the rising and falling limb of the hydrograph and eliminated this flow component in order to make the observed and modelled figures comparable.

The relationship between changing LULC patterns in the sub-catchments of the Konar catchment and the peak rate of discharge at the reservoir inlet was assessed by computing the unit flood response (Saghafian and Khosroshahi, 2005) of each of the 124 sub-catchments for the LULC scenarios of 1976 and 2004. The unit flood response approach can be used to standardise the contributions of sub-catchments to the peak flow. With changing land use, the unit flood response of various sub-catchments within a catchment is likely to change. The storm event of 11-12 October, 1973 was used as the meteorological input in both scenarios. The unit flood response approach ranks each sub-catchment on the basis of their contribution to the flood generation at the basin outlet and is expressed by

$$f = \Delta Q_p / A \qquad (2)$$

where f ($m^3s^{-1}km^{-2}$) is unit area flood index, ΔQ_p is the amount of decrease in peak discharge at the basin outlet due to elimination of a particular sub-catchment (m^3/s), and A is the sub-catchment area (km^2). A version of the HEC-HMS model containing all basin components was saved. In order to compute f for a particular sub-catchment we disabled that sub-catchment while keeping the connectivity of the streams intact for the entire model. In the next step, this model was run (without the contribution of the disabled sub-catchment) and the f value for that particular sub-catchment was derived by subtracting the peak flow of the modified model from the peak flow of the model that incorporates all the sub-catchments.

4 Results

The changes in LULC for the entire Konar catchment from 1976 to 2004 (Fig 3) show considerable increase in rocky waste and decreases in the areas under paddy cultivation and open forest (Table 1).

Between 1976 and 2004 a substantial percentage of the total area in the Konar catchment changed in LULC from paddy to rocky waste, paddy to shrub, open forest to shrub and paddy to urban (Fig 4). The comparison of the simulated rainfall runoff event of October 1973 with the LULC situation prevailing in 1976 (Fig 5) reveals a good match between the observed and simulated daily streamflow volume. The association between the modelled and observed daily surface runoff figures for the 2004 LULC situation using the 2003 TRMM rainfall estimates (Fig 6) also shows a good match.

When considering the effect of LULC change in the entire Konar catchment on the peak discharge for the 1973 storm event at the reservoir inlet we found that, for the 1976 LULC scenario the peak discharge was 1023.3 m^3/s occurring on 12th October at 20:10, while for the 2004 LULC scenario the peak discharge increased to 1194.7 m^3/s and the time to peak was decreased by 1 hour and 10 minutes. After ranking the sub-catchments according to the unit flood response computed with the rainfall event of 1973 and LULC scenarios of 1976 and 2004 (Fig 7), we found that in spite of significant LULC change between 1976 and 2004 (Fig 3) there was little change in the ranking.

The spatial patterns of the percentage change in the CN values (Fig 8a), a proxy for the change in the combined effect of the soil and LULC, and the unit flood response between 1976 and 2004 LULC scenario (Fig 8b) did show some degree of agreement; sub-catchments showing a higher percentage change in CN values (i.e. change in LULC) in the predominately forested area in the south and near the main stream of the Konar River tend to show an increase in their unit flood response values between the 1976 and 2004 LULC scenarios. The location of the LULC change in terms of the distance from the outlet may have a negative impact on the intensity of the consequent percentage change in unit flood response. In order to test this, an attempt was made to assess if the distance from the sub-catchment centroid to the outlet, measured along the connecting stream network, had a statistically significant negative relationship with percentage change in unit flood response. However, no statistically significant relationship could be established.

Finally, a weak positive linear correlation was found (Pearson's correlation coefficient (r) of 0.53 ($p < 0.01$) between the sub-catchment percentage change in unit flood response (1976 - 2004) and curve number (CN) values (Fig 9a). Three clusters of sub-catchments showed marked deviations from the overall positive trend between the two variables. Cluster 1 consists of sub-catchments with a large increase in CN values from 1976 to 2004 and a disproportionately large increase in the unit flood response. Cluster 2 consists of sub-catchments with a moderately high percentage increase in the CN values but a negative change in unit flood response values. Cluster 3 includes sub-catchments with small increases in CN values but large increases in unit flood response. In order to reveal any apparent geomorphological reason for these deviations from the overall trend we mapped the sub-catchments falling in the three aforementioned clusters which did not reveal an overall relationship between the location of LULC changes and proximity to higher order streams or the basin outlet (Fig 9b).

As we could not establish a relationship between the proximity of LULC change to the outlet or a higher order trunk stream and the peak discharge at the catchment outlet due to paucity of data, we tested the influence of timing effect of flow convergence at the sub-catchment level following the general argument of Pattison et al. (2008). In HEC-HMS, a single sub-catchment (with identifier W2080) and a junction (identifier J425) were selected as an example of a disproportionate rise in unit flood response (UFR) caused by moderate increase in CN value (LULC change towards more runoff producing LULC). (Fig 9a). On the other hand, sub-catchment W2510 and Junction J328 were chosen as an example of the general positive linear correlation between unit flood response and CN change between 1976 and 2004 LULC conditions (Fig 9a). The location of these sub-catchments can be found in Fig 10.

W2080 demonstrated a 93 percent change in the unit flood response for only 2.03 percent change in the CN values from 1976 to 2004. The simulated hydrographs for W2080 showed little difference in the direct runoff pattern for the LULC conditions of 1976 and 2004 alone

(Fig. 11). Under the LULC conditions of 2004, Junction J425, the confluence of runoff generated from W2080 and the Konar River, experienced a peak discharge of 484.3 m^3/s at 15:35 on 12 October. At that time, the discharge from W2080 was 4.40 m^3/s which was 22.9 % of its peak discharge (19.2 m^3/s) (Fig 11). The contribution of W2080 to the combined discharge at 15:35 on 12th October was thus 0.90 %. Using the LULC conditions of 1976, when the discharge from W2080 merged with the Konar River during the peak outflow at J425 on 12 October, 16:35 (1 hour later than the 2004 LULC scenario) the combined discharge at J425 was 383.8 m^3/s and the contribution from W2080 was 2.1 m^3/s (0.55% of the total) which was only 11.5% of its peak discharge of 18.3 m^3/s (Fig 11). This example illustrates that with only a 2.3 percent increase in the CN value from 1976 to 2004, the contribution of the sub-catchment W2080 to the combined flow of a vast contributing area almost doubled (0.55% to 0.90%).

Sub-catchment W2510 revealed a different picture at Junction J328, where the runoff from the sub-catchment converged with the Konar River. Under the 2004 LULC conditions J328 experienced a combined peak discharge of 280.7 m^3/s at 15:15 on 12th October. At that time the discharge from W2510 was 7.8 m^3/s, which was 2.77% of the combined discharge and 65.54 % of the peak discharge of W2510 (11.9 m^3/s) (Fig 12). For the LULC conditions of 1976, the runoff from W2510 merged with the peak discharge at J328 on 15:45 (30 minutes later than 2004 LULC case) at a rate of 6.1 m^3/s, which was 2.42 % of the combined peak flow of 251.7 m^3/s. The runoff from W2510 at that time was 70.11% of its peak discharge (8.7 m^3/s) (Fig 12). This test case illustrated that for a moderate 11% increase in the CN value from 1976 to 2004 LULC conditions the contribution of W2510 during the peak flow at Junction J328 increased from only 2.42% to 2.77%, which is in line with the overall trend in Fig 6.8.

5 Discussion

If we consider the effect of overall LULC changes in the Konar catchment to the flood peak at the catchment outlet, it becomes evident that a general increase in the higher runoff producing LULC classes resulted in higher peak discharge and shortened the time to peak. However, when investigating the sub-catchment-wise local LULC change and its influence over the peak discharge at the catchment outlet a complex relationship began to emerge.

When the location of the sub-catchments showing marked deviation from the overall trend was mapped (Fig 9) we could not find a convincing reason for their unusual hydrologic response, For example, two of the predominantly deforested sub-catchments in cluster 1 (see Fig 3 and 9b) were found to be near the trunk stream, which may explain their rapid reaction in terms of increase in percentage unit flood response; however, the other two sub-catchments in the same cluster that are located at the farthest point from the outlet did not have any apparent physical explanation based on the distance from the outlet or proximity to a stream of very high stream order. Nothing could be established about the negative reaction of the sub-catchments in cluster 2 to their contribution to the peak discharge at the outlet. The sub-catchments in cluster 3 were found to be adjacent to each other and located at a consistent position near the main stream (Fig 9) which may partially explain the spike in their percentage increase in the unit flood response caused by moderate positive percentage change in CN values.

Although an overall statistically significant positive relationship was found between the changes in LULC at the sub-catchment scale and their impact on the basin flood peak, the pattern was altered by other factors. Increments of 2.03% and 11% in the CN values of sub-catchment W2080 and W2510 between 1976 and 2004 resulted in expected changes in their surface runoff hydrographs (Fig 11 and 12). However, during the peak discharge at the junctions where the runoff from these two sub-catchments flows into the Konar River, their contribution to the combined flow differed markedly. Pattison and Lane (2012) highlighted the important role played by the timing of extreme rainfall events at different parts of the catchment and the consequent hydrological response. In addition, they also pointed out that the structure of the basin also determines the convergence of hillslope and channel flow which changes with distance and influences the magnitude and timing of the flood peak downstream. For example, W2080 has little difference in the shape of hydrograph (not surprising because of small change in CN) for the two LULC conditions, but its apparent change in UFR is very high because the time of the peak at its outlet is very different (big spread between the vertical lines in Fig 6.10). On the other hand, W2510 has a very different hydrograph, but because the peak at the outlet comes on the falling limb, and because there's a fairly small change in the time of the peak, the change in UFR is modest. Thus the effect of time matters more than the effect of changes in CN.

The characteristics of individual sub-catchments such as shape and slope may also play a vital role in the causal relationship between sub-catchment wise LULC changes and the flood peak at the basin outlet. These factors may partially explain why similar amounts of LULC change in different sub-catchments have varying impacts on the flood peak at the catchment outlets. It is likely that more than one of these factors are simultaneously playing a role in influencing the peak discharge at the catchment outlet. Thus, correcting the land use practice in one of the priority flood generating sub-catchments may not always result in reducing the flood peak. Hence, it is not surprising that this study did not find any pattern similar to one reported by Roughani et al. (2007), in which the sub-catchments located at the centroid of the catchment were found to be more likely to exert an influence to the peak discharge at the catchment outlet.

In order to implement remedial land management practices for controlling the flood peak at the reservoir inlet and reducing soil erosion, authorities like the DVC generally try to identify the sub-catchments that require urgent attention. If only a single LULC condition is of interest then the unit flood response approach (Saghafian and Khosroshahi, 2005) can be considered as an ideal solution to identify the priority target area for land-use planning. However, LULC conditions across sub-catchments change with time and the nature of this transformation from one LULC class to other LULC classes varies considerably from one sub-catchment to another. This factor tends to have a complex influence on the hydrologic response of the entire catchment over the years. Hence, the relevance of this study comes from testing whether local changes in LULC, at which scale the remedial measures are likely to be implemented, actually have a straight forward mitigating effect on the flood peak at the basin outlet. Pattison and Lane (2012) recommended that any empirical association found between local LULC change and downstream flood peak is valid only for that particular catchment and storm event. We suggest that, after identifying the major flood source areas for a storm event of approximately five year return period, further simulations should be carried out to evaluate the effect of possible remedial land-use planning in those sub-catchments over the flood peak at the cumulative basin outlet of interest. Undertaking remedial land-use measures in a few sub-catchments, especially in the upper catchment, may alter the tributary flow convergence timing in an adverse manner, nullifying the effects of corrective land management measures at the local scale.

Our study has emphasised the challenges faced in data scarce areas such as developing countries for modelling the impact of LULC changes on basin hydrology. The LULC maps were derived from freely available satellite data that varied in spatial and spectral resolution. In our study area, we had severe constraints in the availability of high-frequency (~hourly) rainfall data and historic ground truth data in terms of topographic maps, as well as low-cost, high resolution imagery such as Corona or GoogleEarth images. The reasonable match between the simulated and observed daily hydrographs for two rainfall events and LULC conditions demonstrated that the HEC-HMS model in conjunction with the NRSC CN method is capable of accurately reproducing rainfall-runoff processes with broad LULC classes and moderate resolution topography. Fig 5 and 6 illustrated that the HEC-HMS model setup in our study can accurately reproduce rainfall-runoff processes under two LULC conditions resulting from two different storm events. It established that the model can perform well independently of the nature of the storm event and LULC scenarios, and this provided an element of confidence when we applied the same storm event of 1973 for the LULC situations of 1976 and 2004 to address the core purpose of this research. Lower-frequency discharge data at the inlet of the Konar Reservoir might have hidden some mismatch between the observed and simulated surface runoff patterns. Availability of a more disaggregated observed streamflow record would have revealed some element of inaccuracies in the simulated hydrograph, possibly arising from the non-uniform distribution of actual rainfall depth, measurement errors in rainfall depth, coarse soil map and the low resolution of Landat MSS image (in terms of LULC and CN) or the SRTM DEM (in terms of delineation of channels, sub-catchments and channel configuration parameters for routing). In this context, we would like to highlight that availability of higher resolution LULC data would not make much difference in demonstrating the influence of LULC on the hydrological response, as Wang and Kalin (2011) reported that the selection of model parameters (derived from coarse quality inputs) had little influence on modelling the impact of changing LULC scenario on surface runoff with the NRSC CN method.

6 Conclusion

We have illustrated a systematic approach of analysing the effect of LULC changes in the sub-catchment level and their varying impact on the flood peak at the catchment outlet. An overall positive relationship was found between the two factors. However, our findings indicated that varying timing of flow convergence between hillslope and streams at the sub-catchments caused by localised LULC changes is the key factor behind the frequent deviation from this overall trend. While unit flood response (Saghafian and Khosroshahi, 2005) is an innovative means of identifying the sub-catchments that need urgent attention in terms of land management to reduce flood peak, we argue that the complex interaction between changing LULC in sub-catchments, especially in large basins with heterogeneous LULC, is likely to be dependent on other factors which are not within the scope of this study. These factors may include soil types and nature and duration of the precipitation event. This study also demonstrated ways of utilising free or low-cost spatial and meteorological data, typically available in developing countries, to set up a widely used hydrological model that is capable of reproducing event scale rainfall-runoff processes with reasonable accuracy. The described methodology and the key findings will be beneficial for mitigating flooding through non-structural measures, particularly in the developing world.

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List of Tables:

Table 1 Percentage coverage of different LULC categories for 1976 and 2004 and the changes between the two time periods.

	LULC Classes	Percentage Cover 1976	Percentage Cover 2004	Difference in Percentage Cover (2004 - 1976)
1.	Water body	5.4	5.9	0.5
2.	Rocky wasteland	9.7	24.2	14.5
3.	Urban	0.1	8.2	8.1
4.	Paddy Field	42.3	20.9	-21.4
5.	Shrub	9.6	23.2	13.6
6.	Open Forest	26.5	14.5	-12
7.	Dense Forest	11.3	8.2	-3.1

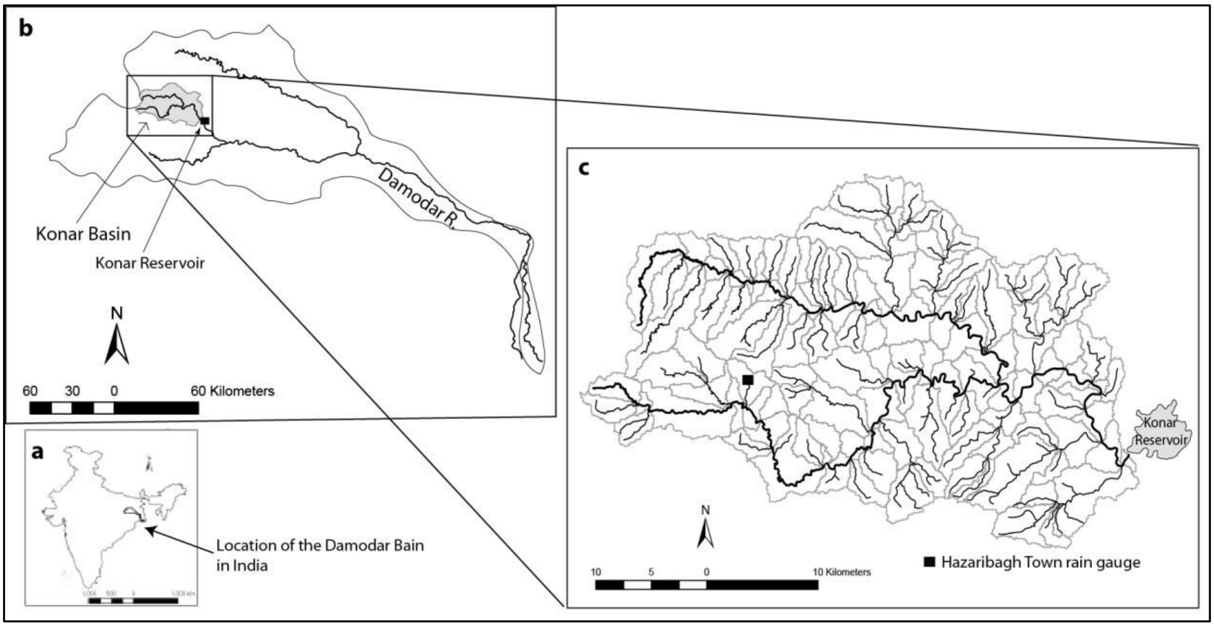

Fig 1 The Study area; a: Location of the Damodar Basin In India, b: Location of the Konar River catchment in the Upper Damodar River Basin, c: The sub-catchments of the Konar River derived from the SRTM DEM with dark lines showing the streams vectorised from topographic maps. Automatically extracted drainage networks (derived from the SRTM DEM with a threshold contributing area of 5 km^2) that approximately correspond with the 2nd order streams from the topographic maps were used to delineate the 124 sub-catchments.

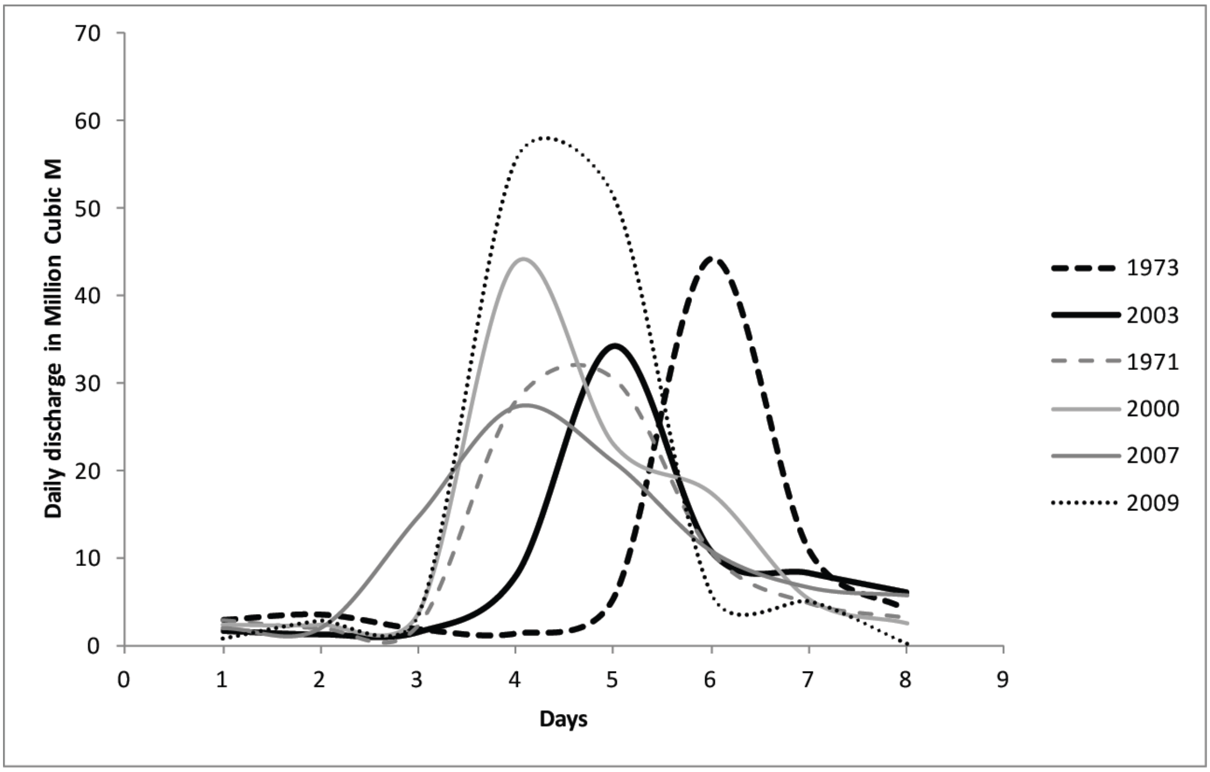

Fig 2 Some major observed storm hydrographs in last four decades at the entry of Konar Reservoir. The storm events under consideration in this study (1973 and 2003) are shown in thick lines.

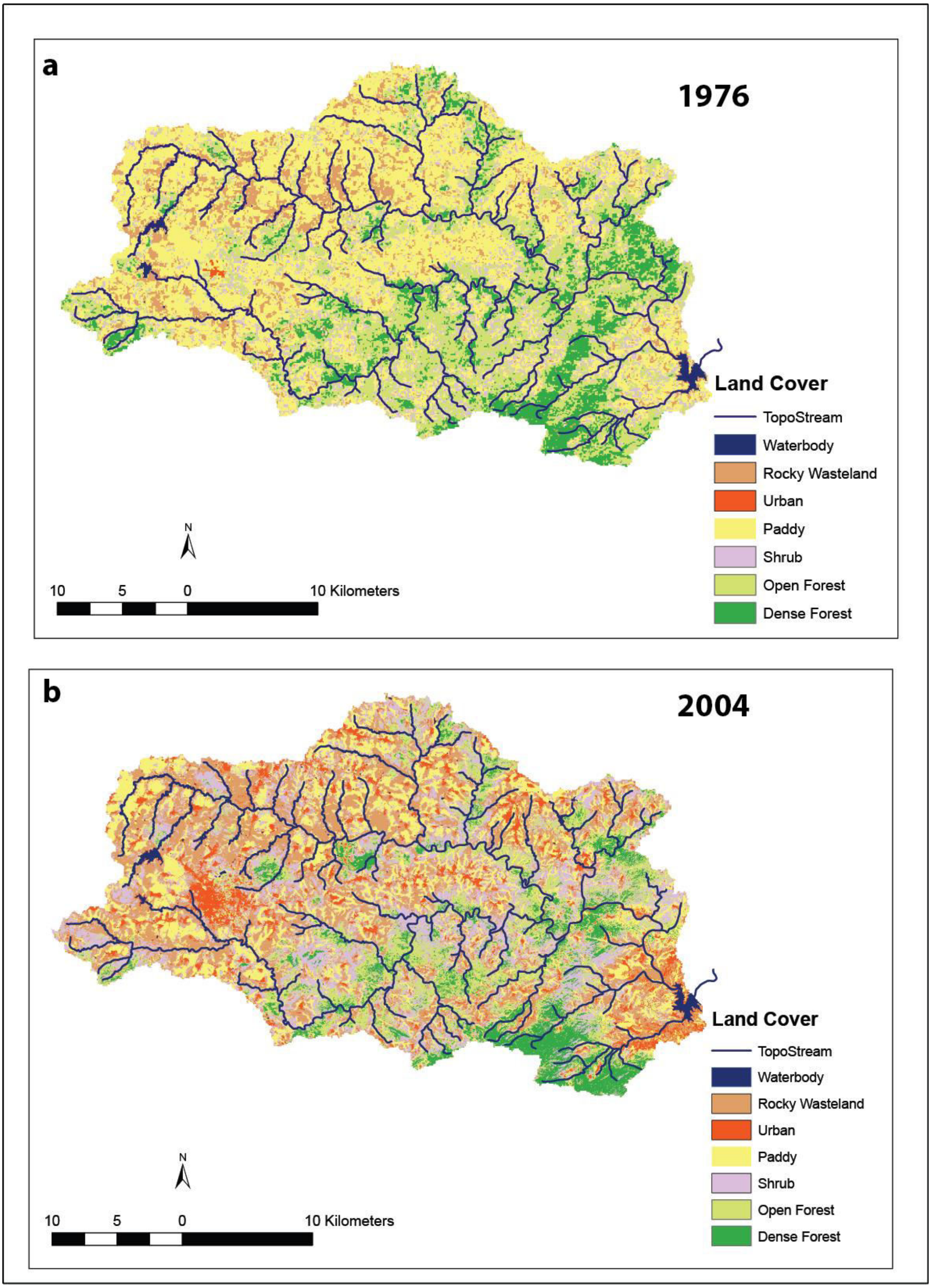

Fig 3 Land cover classification of (a) 1976 and (b) 2004. Maps were derived from Landsat MSS (a) and Landsat TM (b) in the early post-monsoon season in late October to early November.

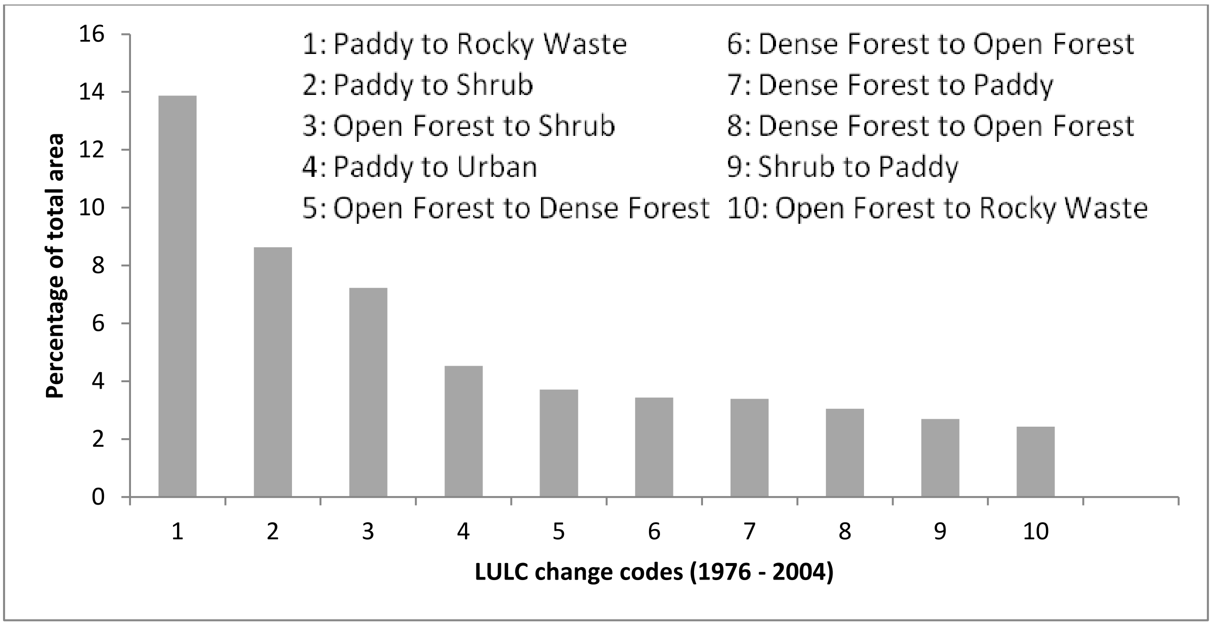

Fig 4 Percentage of land in the Konar basin that had undergone substantial transformation from one LULC category to another between 1976 to 2004. These LULC scenarios are valid for the early post-monsoon season in late October to early November.

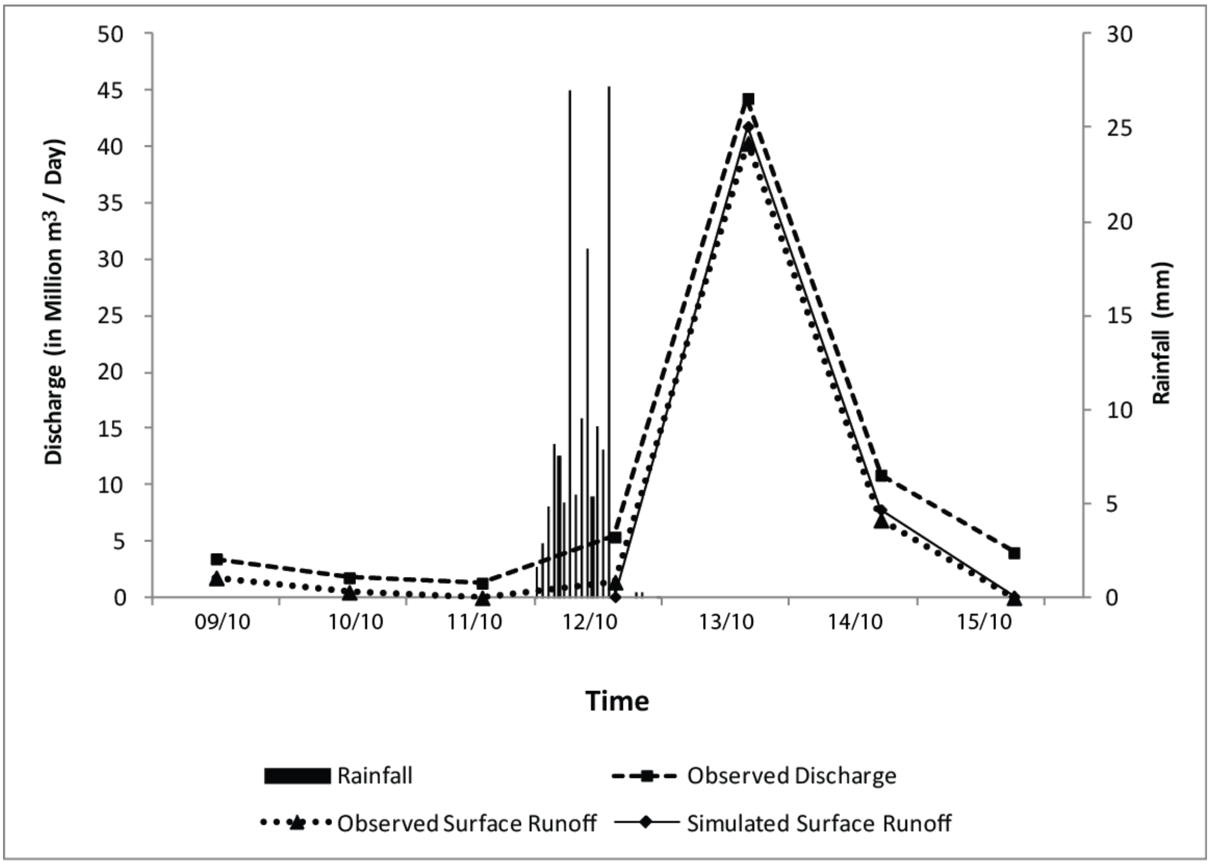

Fig 5 Simulated surface runoff with gauged hourly rainfall input of October 1973 and land cover of 27th October, 1976. The observed surface runoff (depicted as dotted line) was derived from the observed discharge figure by means of base flow separation.

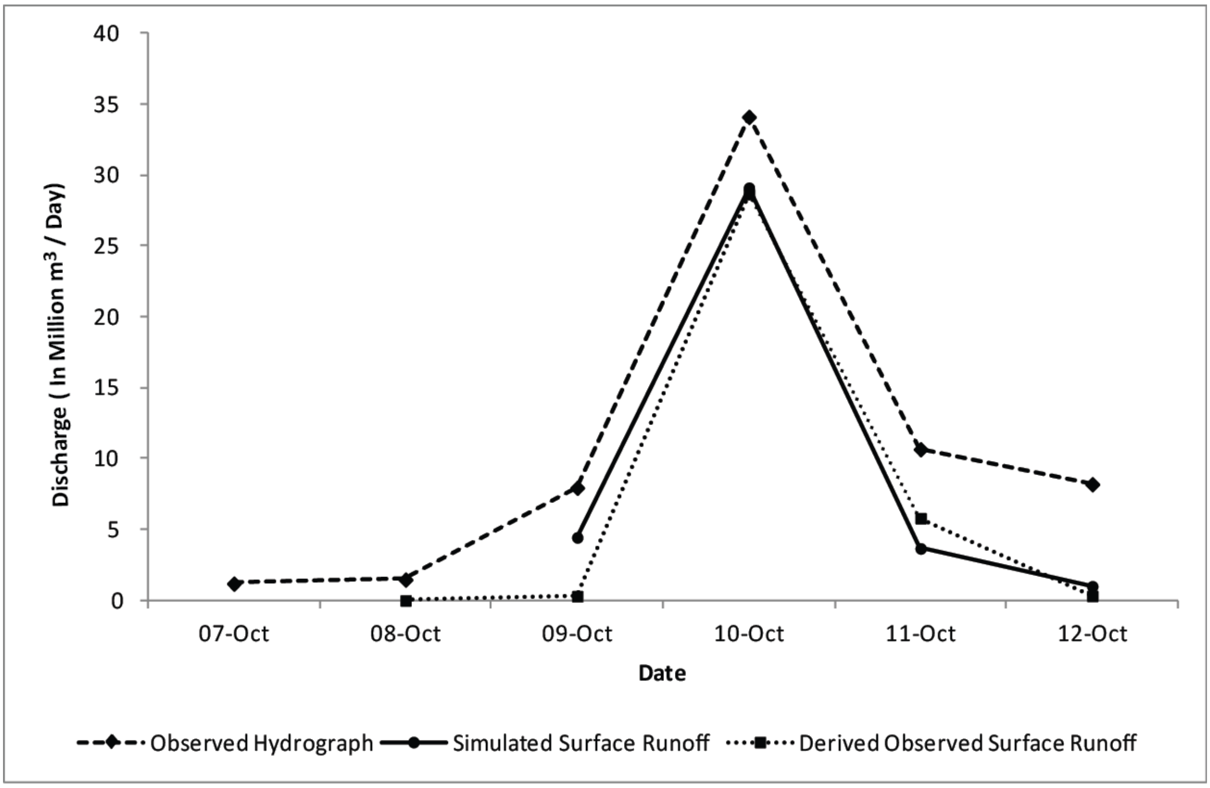

Fig 6 Simulated surface runoff with TRMM 3-hourly rainfall input of October, 2003 and land cover of 2nd November, 2004.

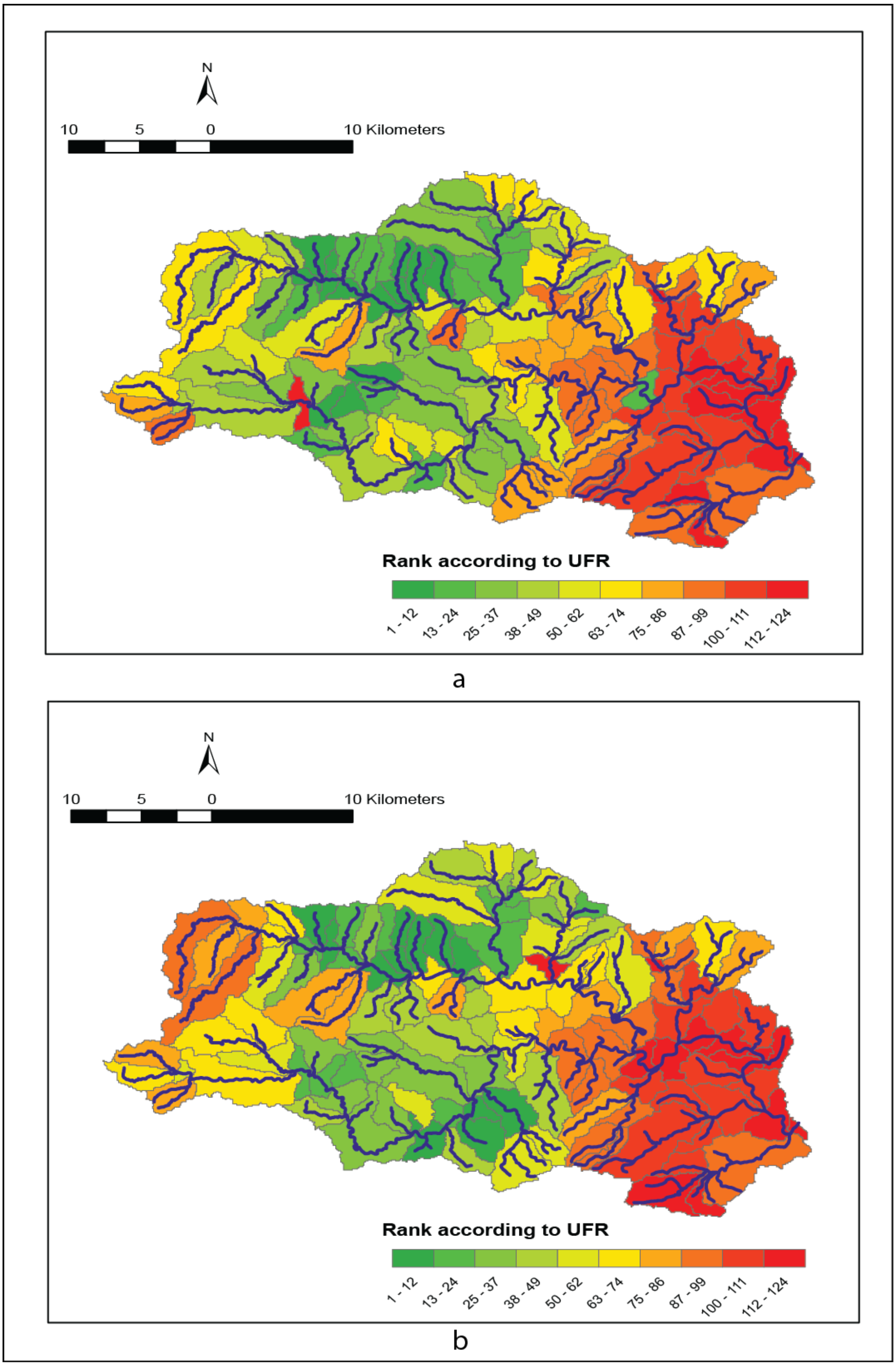

Fig 7 Rank of the sub-catchments according to the unit flood response (UFR) values derived with the land cover of 1976 (a) and 2004 (b). The gauged hourly storm rainfall event of October, 1973 was used as the meteorological input in both models.

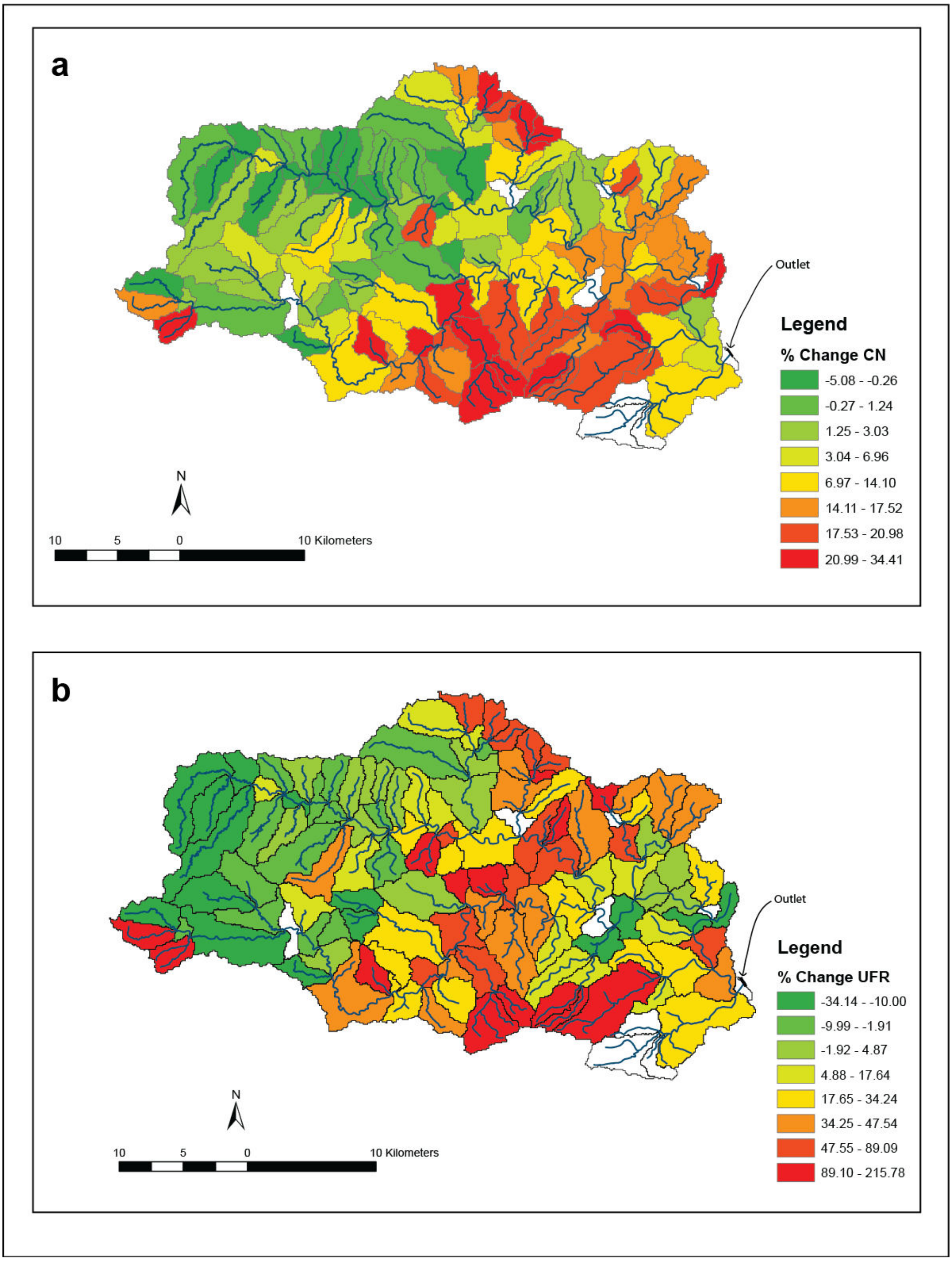

Fig 8 a, percentage change in NRCS Curve Number (CN) values (1976 - 2004); b, percentage change in unit flood response (UFR) values (1976 land cover to 2004 land cover). In both panels, negative values indicate that the CN or UFR was higher in 1976 than 2004, and positive values show the opposite. The sub-catchments shown in white experienced negligible change. The class intervals of the data represented in Panel a and b have been derived from eight quantiles of the respective series.

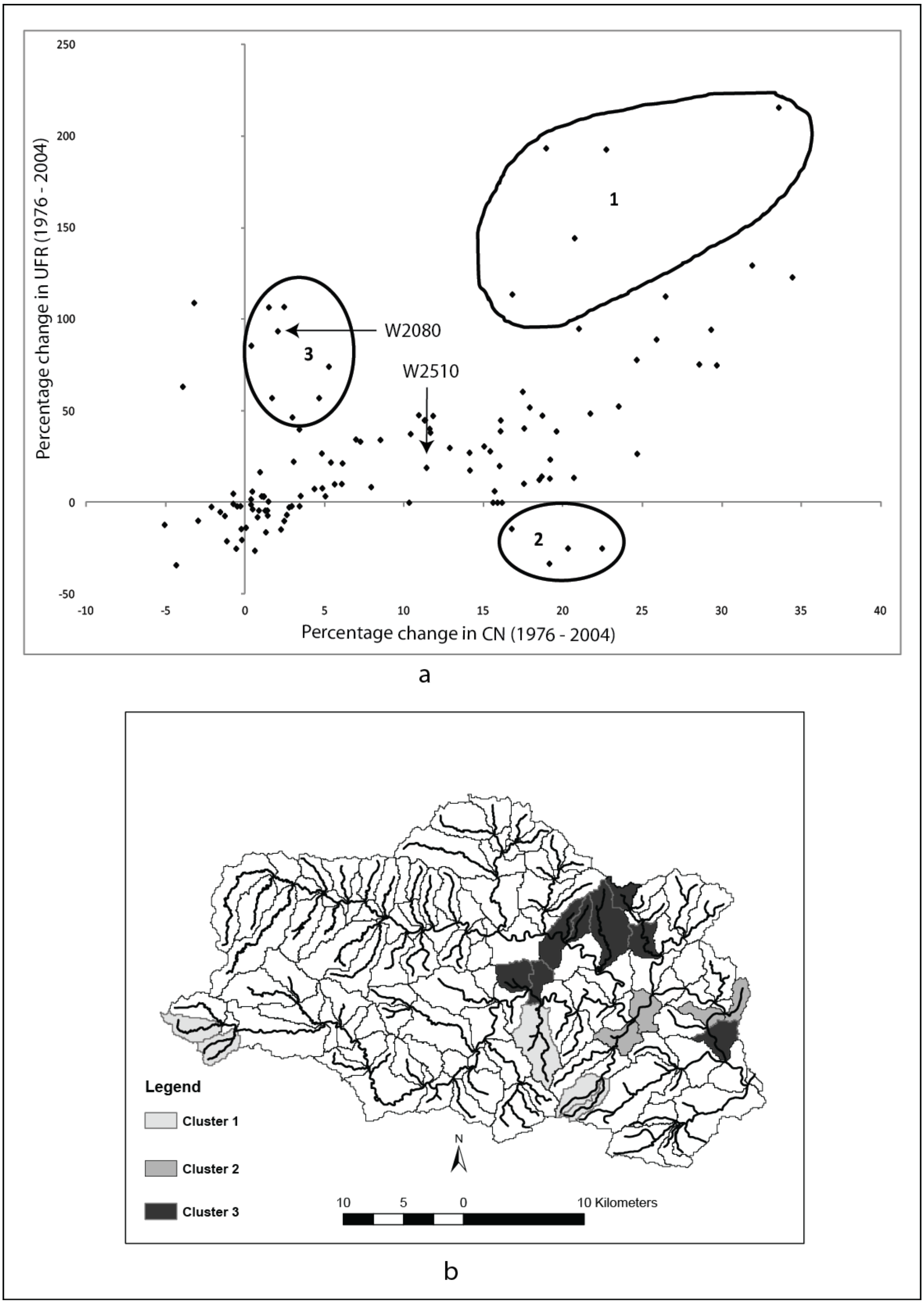

Fig 9 a, Scatter diagram of the sub-catchment wise percentage changes in the unit flood response (1976 - 2004) and curve number (CN) values. Sub-catchments that did not fit into the overall linear positive correlation pattern were separated into 3 clusters. Sub-catchments W2080 and W2510 were selected as representative of extreme and typical cases, respectively, of UFR change in relation to changing LULC conditions. b, Location of the sub-catchments identified as 3 clusters in panel a.

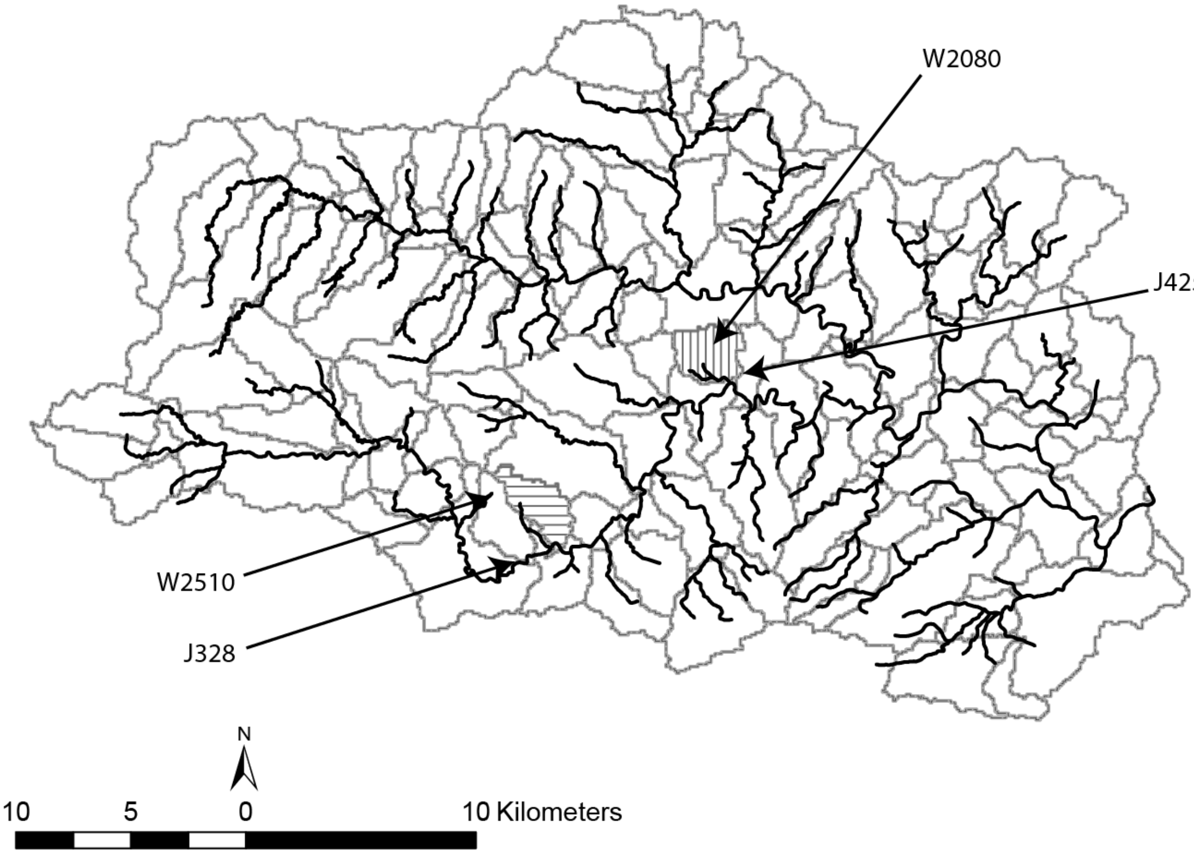

Fig 10 Location of the sub-catchments and flow junctions that were selected for testing the influence of timing effects of flow convergence on the relationship of local LULC changes and downstream flood peak.

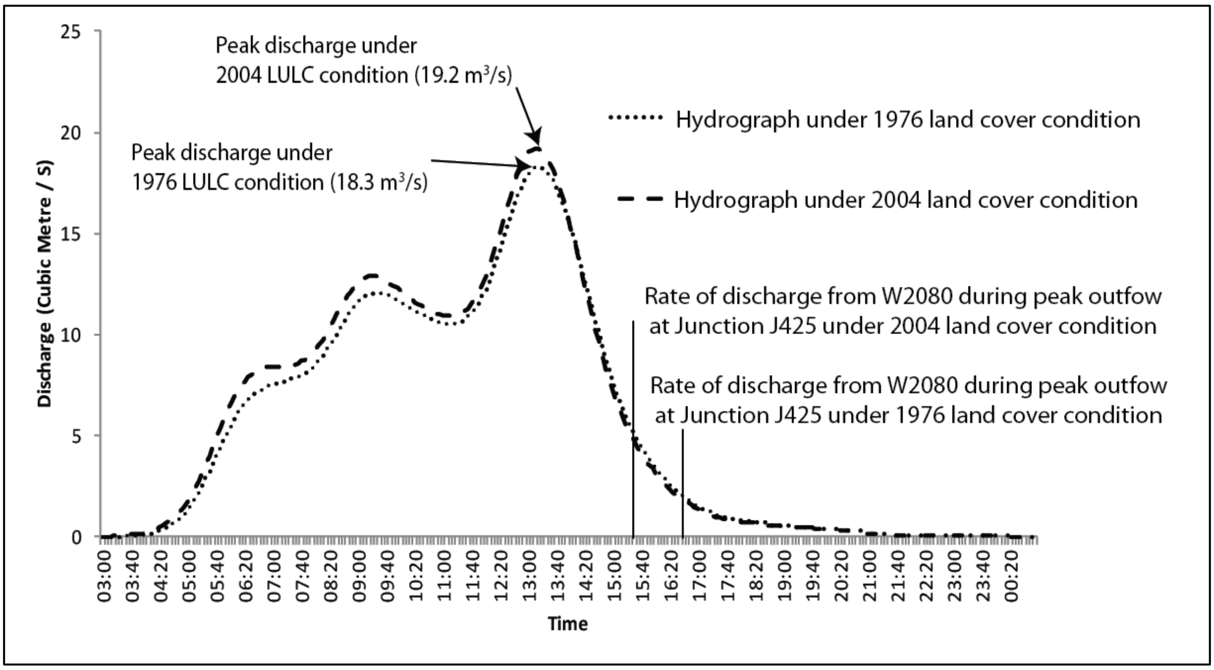

Fig11 Hydrographs of sub-catchment W2080 for 1976 and 2004 LULC scenarios. Vertical lines show the timing of the combined peak flow at J425 for the 1976 and 2004 LULC.

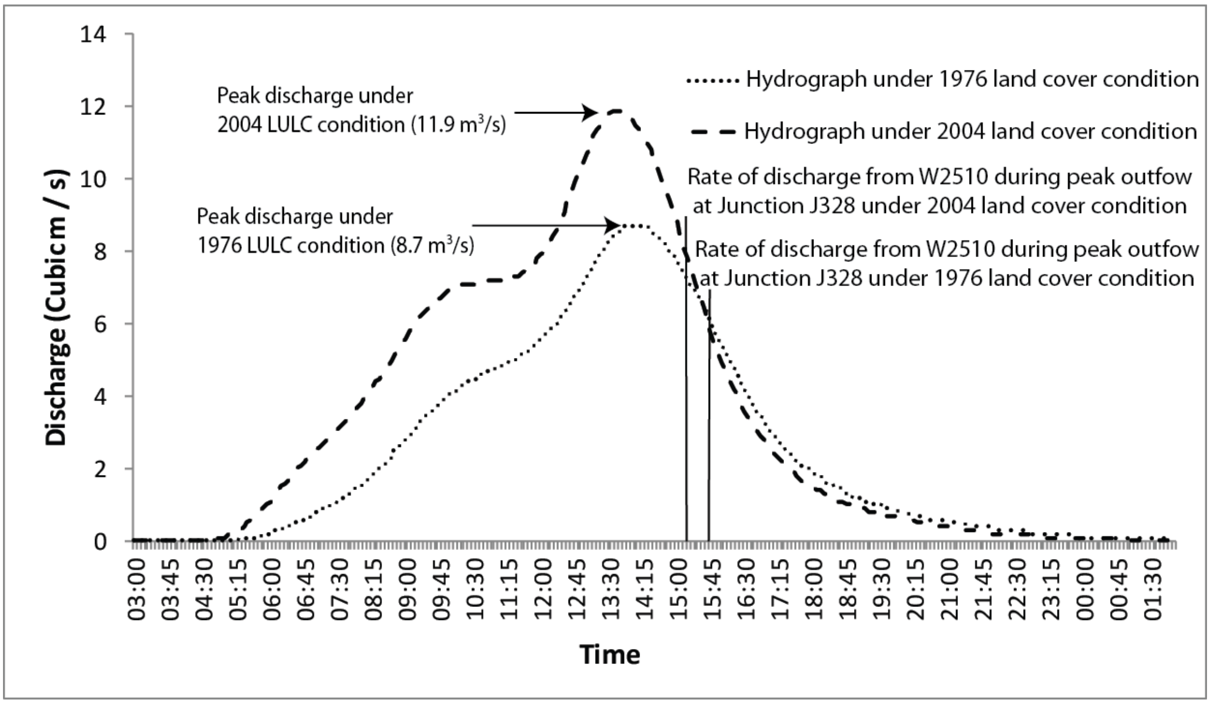

Fig12 Hydrographs of sub-catchment W2510 for 1976 and 2004 LULC scenario, Vertical lines show the timing of the combined peak flow at J328 for the 1976 and 2004 LULC.