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

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ABSTRACT

This paper aims to evaluate how varying degrees of land-use/cover (LULC) changes across sub-catchments affect a flood peak at the catchment outlet. The study site was the Konar catchment, a part of the upper Damodar Basin in eastern India. A HEC-HMS model was set up to simulate rainfall–runoff processes for two LULC scenarios three decades apart. Because of sparse data availability 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 of the catchment. Although a weak ($r = 0.53$) but statistically significant positive linear correlation was found between sub-catchment wise LULC changes and the magnitude of the 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 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.

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 (Amini et al., 2011; Chen et al., 2009; 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 further 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 has been 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 (Andréassian, 2004; Beschta et al., 2000) while others have even observed 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 a 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. Finally, Shi et al. (2007) reported that high antecedent moisture conditions outweighed the effect of increased urbanisation 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 (Ali et al., 2011; Chen et al., 2009; 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 increases 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. This type of study has generally been restricted to small urban catchments, partly due to the easy availability of

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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 contributes to the flood peak. It is not surprising that the finding of these studies support the intuitive conclusion that reduction in forest or increase in paved surfaces leads directly to increased runoff. An overemphasis on the effects of afforestation and urbanisation and lack of interest in examining the LULC changes in river basins with diverse LULC types have thus characterised much recent research on the effect of land cover change in flooding (Wan and Yang, 2007).

The contribution of streamflow from a specific land-use type 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). These authors 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 urbanisation 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 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 effects of LULC change on downstream flood peaks is of primary importance in watershed management strategies, which 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 possible relationships between land-use change and downstream flood risk, and pointed out that while it is not uncommon to find an association between land-use change and streamflow behaviour at field and plot scales, 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 (Roughani et al., 2007; Saghafian and Khosroshahi, 2005; 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) and the modelling approach (Ewen et al., 2012) are both heavily dependent on a dense network of automatic rain and river gauging stations, and neither is applicable in the data-sparse environments that are common in developing countries. Although a variety of hydrological models are available, it is difficult to use them in data-sparse environment such as India due to their requirements, particularly in terms of soil moisture and channel topographic data. The US Natural Resources Conservation Service (NRCS) curve number (CN) approach for runoff estimation is particularly suitable for application in data-sparse situations and has been widely used to estimate surface runoff in an accurate manner with limited data (Bhaduri et al., 2000; Mishra and Singh, 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 such case studies in Indian context (*e.g.* Amutha and Porchelvan, 2009; Sharma and Singh, 1992; Tiwari et al., 1991) where paucity of data is a major obstacle for rainfall–runoff modelling. However, the strongly seasonal pattern of land-use in monsoon climates has not been investigated 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.

Also, most investigations to date have 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 approaches of 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-catchments may change the location of the flood source area. There is thus 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.

The objective of this study is to investigate (1) the effect of LULC change at sub-catchment scales 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 direct implications for 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 (Fig. 1). The catchment upstream of the reservoir is a typical example of physiographic, drainage and LULC conditions in the upper Damodar basin. The catchment is drained by the Konar and Siwane Rivers and is 998 km^2 in area. 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. A number of previous authors (*e.g.* Bhattacharya, 1973; Choudhury, 2011; Ghosh, 2011) 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 developing countries.

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