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Implication of remotely sensed data to incorporate land cover effect into a linear reservoir-based rainfall–runoff model

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SUMMARY

This study investigates the effect of land use on the Geomorphological Cascade of Unequal linear Reservoirs (GCUR) model using the Normalized Difference Vegetation Index (NDVI) derived from remotely sensed data as a measure of land use. The proposed modeling has two important aspects: it considers the effects of both watershed geomorphology and land use/cover, and it requires only one parameter to be estimated through the use of observed rainfall–runoff data. Geographic Information System (GIS) tools are employed to determine the parameters associated with watershed geomorphology, and the Vegetation Index parameter is extracted from historical Landsat images.

The modeling is applied via three formulations to a watershed located in Southeastern Arizona, which consists of two gaged sub-watersheds with different land uses. The results show that while all of the formulations generate forecasts of the basin outlet hydrographs with acceptable accuracy, only the two formulations that consider the effects of land cover (using NDVI) provide acceptable results at the outlets of the sub-watersheds.

1. Introduction

1.1. Background

The influence of urbanization, as one important form of land use and land cover changes, on runoff and floods within watersheds has been a major topic of research during the past few decades. Hydrologic response of a watershed indicates its condition, and the overall function of the watershed might be affected by land cover changes (Miller et al., 2002). Urbanization affects the hydrologic processes of a watershed by replacing vegetated land cover with paved surfaces, and by changing the natural drainage network via inclusion of artificial structures. This can have a substantial impact on the hydrological reaction of a watershed to the input, potentially resulting in quick response (Huang et al., 2008), greater river flow volume (Hawley and Bledsoe, 2011), higher recurrence of floods (Hollis, 1975; Braud et al., 2013), and decreased base-flow, and reduced sub-surface recharge (Simmons and Reynolds, 1982).

The direct runoff hydrograph of a watershed indicates the characteristics of the effective rainfall hyetograph and the land surface features which control the runoff generation and overland flow processes. Due to the complexity of the rainfall–runoff relationship, conceptual rainfall–runoff models are commonly employed to analyze and simulate this relationship. Such models are popular because in these models, the transformation of rainfall to runoff is mimicked relying on a simple explanation of physical processes to suggest an integration of ease of development and use, and providing acceptable outcome and transparency (de Vos et al., 2010). In particular, conceptual unit hydrograph (UH)-based models, derived from linear systems theory, have been used to investigate the effects of urbanization on rainfall–runoff process (e.g. see Kang et al., 1998; Cheng and Wang, 2002; Huang et al., 2008). The Nash model, consisting of a cascade of identical linear reservoirs, is

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among the more popular such models as it gives an explicit formula for the Instantaneous Unit Hydrograph (IUH) (Nash, 1957).

To develop the next generation of the IUHs, the overall response of a watershed was characterized as a function of geomorphologic properties of the watershed. The first remarkable suggestion in this field as a geomorphologic IUH (GIUH) was proposed by Rodríguez-Iturbe and Valdés (1979). On the basis of conceptual framework of the Nash's IUH, Chaoqun et al. (2008) proposed a methodology for determining how the mean residence time (storage coefficient) of each reservoir is related to the topography of the watershed. Agirre et al. (2005) and López et al. (2005) introduced unit hydrograph models considering watershed geomorphology and linear reservoirs, applying a fixed calibrated mean residence time for all reservoirs; the watershed morphology was employed just for the determination of linear reservoirs without any consideration of the sub-basin physiographical properties. López et al. (2012) compared the formerly developed one-parameter IUH model with four other IUH models. Nourani and Mano (2007) used TOPMODEL and the kinematic wave approach wherein all model parameters, except one, were linked to the geomorphologic properties. Nourani et al. (2009) developed three linear reservoir based models and compared the results with classic Nash and SCS (Soil Conservation Service) models; their results showed that although the developed models could lead to better performance in rainfall–runoff modeling, the semi-distributed routing ability can help the model to produce more reliable results in compared with fully lumped models. More recently, Saeidifarzad et al. (2014) presented a multi-site calibration for two geomorphologic linear reservoir models via two calibration strategies.

Unlike lumped models, semi-distributed geomorphologic models need large amount of spatial information in which a combination of remote sensing, Geographic Information Systems (GIS), and simulation modeling can provide and manage spatial data at landscape to global scales (Pickup, 1995). NASA Earth Observing System efforts offer exciting possibilities to couple hydrologic models and directly incorporate remotely sensed data (Goodrich and Woolhiser, 1991). Remote sensing provides various hydro-geomorphologic measurements of variables which are used in hydrologic and environmental modeling. The digital remote sensing data are typically in pixel format and this makes them suitable to be merged with GIS. Estimation of vegetation conditions by remotely sensed data has also been successful (Qi et al., 2000). The classified land cover maps obtained from remote sensing data are used as input parameters of a wide range of hydro-environmental models (Miller et al., 2007); therefore as an implication, a watershed's land use/cover changes can be detected and monitored by remotely sensed data.

Changes in land use include surface characteristics such as impervious cover and vegetation, which can affect the resulting runoff index and speed of runoff travel in the drainage area (Ferguson, 1998). Research into the impacts of vegetation change on water budget at watershed scale has been subject of extensive observation and modeling (e.g., McGulloch and Robinson, 1993). There is evidence that changes in land use can significantly influence the hydrological behavior of a basin (Jones and Grant, 1996).

Coincident with the progress in remote sensing and GIS, it has been shown that in hydrological modeling, the use of remote sensing data to detect spatially consistent values for imperviousness is more appropriate and efficient (e.g., Chormanski et al., 2008; Canters et al., 2011). Widely available earth observation data such as Landsat images for detecting land cover changes via Normalized Difference Vegetation Index (NDVI) have demonstrated to be very beneficial for the successful evaluation, monitoring and depiction of landscape situations in many areas (Ma and Frank, 2006). NDVI is functionally correlated with the leaf area index (LAI) and vegetation coverage (Baret and Guyot, 1991); the higher the NDVI, the larger the LAI, and the higher the vegetation coverage. Therefore, NDVI can reflect the growth status of surface vegetation and act as an effective index for monitoring vegetation variations (Tucker et al., 1985). There are some studies which considered the effect of vegetation cover using NDVI on different hydrologic properties such as inflow into the reservoirs (Wang et al., 2012), runoff coefficient (Sriwongsiatnon and Taesombat, 2011), runoff and sediment yield (Braud et al., 2001), rainfall and temperature (Wang et al., 2003; Udelhoven et al., 2009) and evapotranspiration (Sun et al., 2004); but to the best of authors' knowledge, incorporating NDVI vegetation cover into conceptual rainfall–runoff models has rarely (if ever) been done. In some of the formerly proposed IUH models (e.g., Agirre et al., 2005; Chaoqun et al. (2008); Huang et al., 2008; Nourani et al., 2009; Cheng and Wang, 2002; López et al., 2012) the effects of land cover variation over the watershed have not been incorporated into the model formulation, explicitly. Therefore, such models although may appropriately predict the output hydrographs in watersheds with roughly uniform land uses; they will be unable to reliably estimate interior sub-watershed's outlet hydrographs in a watershed with extremely heterogeneous land uses.

1.2. Scope

This study proposes an integration of remote sensing and GIS tools for monitoring the land-cover and urbanization condition of a watershed to determine the effects of changes on the watershed responses predicted from a geomorphology-based semi-distributed rainfall–runoff model.

The approach is used to investigate land cover impacts for a small, well instrumented pair of watershed in the city of Sierra Vista, Cochise County, Southeastern Arizona through three steps of: (i) Determining the land cover changes in two sub-watersheds of study area with different land uses using the Landsat 4–5 TM (Thematic Mapper) satellite images, (ii) Developing a Geomorphological Cascade of Unequal linear Reservoirs (GCUR) model integrated with the NDVIs of different land cover types, and (iii) Demonstrating model performance and suitability through three different formulations using available hydro-geomorphological data.

In the next sections of the paper, the study area and data sources including field measurements and satellite data, and the methodology for remote sensing analysis and the concept of NDVI are described. Subsequent sections present the hydrologic model considering three different formulations, and the performance criteria. The results obtained via the proposed modeling framework are then presented and discussed, followed by concluding remarks.

2. Study area and data

2.1. Study area

The study watershed consists of a 32-ha mesquite grassland and a 13-ha residential area (mentioned respectively as the '*grassland*' and '*urban*' sub-watersheds, in this study) in the City of Sierra Vista, Cochise County, in Southeastern Arizona (Fig. 1). The study area is at ~1300 m elevation, in the transition zone between the Sonoran Desert to the west and the Chihuahuan Desert to the south and east. Average annual precipitation is roughly 370 mm with approximately 65% originating from localized convective air mass thunderstorms from June to September during the Mexican monsoon, roughly 5% from late summer tropical depression and the remainder from low-intensity frontal systems during the winter (Goodrich et al., 2008). The elevation