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Detecting the effects of land use/land cover on mean annual streamflow in the Upper Mississippi River Basin, USA

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SUMMARY

The effects of land use/land cover (LULC) along with other climate and geomorphologic factors on mean annual streamflow in the Upper Mississippi River Basin (UMRB) were explored using a nonlinear model applied to a spatial dataset of more than 180,000 catchments. The model was linearized and solved via a geospatial regression model to deal with spatial dependency in data. Results show that LULC is a very important agent with respect to its impact on mean annual streamflow in UMRB. Compared with other climate and geomorphologic factors, the signature of LULC on streamflow which was shown through various measures in this study is evident and significant. The magnitude of the impact on streamflow varies from one LULC to another. It is not a simple function of a LULC's spatial extent but arguably a result of complex interactions among various LULCs as well as other climate and geomorphologic factors. Our analysis indicates that caution needs to be taken in comparing different studies or in generalization across scales regarding the impact of LULC on streamflow. It is because the result of a study is not only the outcome of the geophysical processes observed at a particular spatial and temporal scales but also a product of the approach, model, variables, and/or measures used in the study. Methodologically the proposed model provided an effective way to utilize an extensive spatial dataset of various climatic, geomorphologic, and LULC variables for a large region like UMRB to assess and compare the impact of various factors on mean annual streamflow at regional scale. Furthermore, the model was able to handle spatial dependency in data while avoiding the common problem of nested input in hydrologic modeling.

1. Introduction

Streamflow is affected by various natural factors, such as precipitation, temperature, and geomorphological characteristics, and by anthropogenic activities, e.g. irrigation, building of dam/reservoir, and changes in land use.[1] The literature in the 1990s and 2000s on the impact of natural factors, e.g., climate change and global warming, on streamflow at regional scale is quite extensive. For example, the International Panel on Climate Change's assessment reports (Watson et al., 1996; McCarthy et al., 2001; Parry et al., 2007) briefly discussed many studies of climate change effects on river flows. Other examples include studies by George (2007), Lu and Jiang (2009), Rossi et al. (2009), Timilsena et al. (2009), Liu and Cui (2011), Zhang et al. (2011), Bell et al. (2012), and Kerstin Verzano et al. (2012) to name a few.

In contrast, studies on the impacts of human factors, in general, and land use/land cover (LULC), in particular, on streamflow at watershed scale are fewer and even less at regional scale. Juckem et al. (2008) studied a small watershed in Wisconsin and found that the timing of hydrologic change coincided with changes in precipitation while the magnitude of the change in baseflow and stormflow was likely amplified by changes in agricultural land management. Tu (2009) used a GIS-based watershed simulation model to study the combined impact of climate and land use changes on streamflow and water quality in watersheds of eastern Massachusetts. Using a similar distributed simulation approach, Cho et al. (2009) explore land use impacts on groundwater levels and streamflow in a Virginia watershed. Tang et al. (2011) detected the effect of land-use change on streamflow, sediment and nutrient losses from a reservoir basin also by a distributed hydrological simulation model. Kustu et al. (2010) explore the influence of long-term, large-scale irrigational pumping during the period of intensive irrigation development (1940–1980) on spatial and seasonal patterns of streamflow regimes in the High Plains region. They found that extensive irrigational pumping had caused streamflow depletion at various degrees across the region. In a robust statistical data analysis Naik and Jay (2011) separated human and climate

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[1] The distinction between natural and anthropogenic factors is relative as a "natural" factor can be influenced by "anthropogenic" factors or vice versa.

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influences on the Columbia River hydrologic cycle and sediment discharge since 1858. Human influences analyzed in this study include water withdrawal for irrigation, flow regulation, reservoir manipulation, mining, and deforestation. Zhang et al. (2011) used a combined statistical and water-balance approach to separate the impact of climate variability on annual streamflow of a river basin from those by human activities.

In the Mississippi River Basin (MRB) increasing streamflow trends since 1940s have been mentioned in several studies (e.g., Lins and Slack, 1999; Raymond and Cole, 2003; Zhang and Schiling; 2006). At the watershed scale, several studies (e.g., Potter, 1991; Gebert and Krug, 1996; Knox, 2001; Schilling and Libra, 2003; Schilling, 2004; Zhang and Schiling, 2006; Schilling et al., 2010) have documented the connection between LULC change/improved land management and changes in streamflow patterns in the Upper Mississippi River Basin (UMRB). Twine et al. (2004) analyzed the effects of land cover change on the energy and water balance of the Mississippi River basin using the Integrated Biosphere Simulator model. In their study, the simulated water balance changes due to land cover change depended on season, crop type and management, as well as the type of natural vegetation that is removed. Note that studies using simulation modeling approach to explore the hydrologic response of large river basins to land cover change (e.g., Vorosmarty et al., 1989; Vorosmarty and Moore, 1991; Costa and Foley, 1997; Matheussen et al., 2000; Twine et al., 2004) often used energy/water balance parameters derived from experimental studies at smaller scales (e.g., field, small watershed).

One of the roadblocks in studying the LULC impacts on streamflow at regional scale is the lack of time series LULC data. For example, in the United States, the National Land Cover Database (NLCD) developed by the Multi-Resolution Land Characterization (MRLC) consortium has only three releases: NLCD 1992, NLCD 2001, and NLCD 2006. While LULC information can be derived from aerial photos for small watersheds for periods before 1990s, preparing such dataset for a large region is virtually impossible. This study is an attempt to use a geospatial statistical approach to detect the influence of various LULCs on mean annual streamflow at regional scale. We use UMRB as the case-study area to illustrate the approach. The study area and data used in the analysis will be presented in the next section. Then we will discuss the model development in the methodology section. The influences of various LULCs on regional streamflow will be examined in the section of results and discussion.

2. Materials and study area

2.1. Study area

Encompassing an area of roughly 492,000 km^2 (190,000 square miles) in the upper mid-western United States, the UMBR (Fig. 1) covers the headwaters of the Mississippi River in upper Minnesota, extends southward through Minnesota, Wisconsin, Iowa, Illinois, and Missouri, and ends at the confluence with the Ohio River near Cairo, Illinois. In the most southern part of UMRB, the mainstem of the Missouri River enters the Mississippi River just south of Grafton, Illinois. To exclude the flow contribution of the Missouri River Basin, the U.S. Geological Survey (USGS) gauge at Grafton is often considered the effective outlet of the UMRB.

2.2. Land use/land cover (LULC)

Major changes in land cover occurred in the latter part of the 19th century in the UMRB mainly due to the expansion of agriculture and the lumber (Kumar, 2011). We used LULC data from the NLCD 1992 for the analysis in this study. The NLCD 1992 data in 30-m raster format were allocated to National Hydrography Dataset Plus (NHDPlus) catchment level. Nearly half the area of the UMRB is cropland (Table 1), about 16% of the Nation's cropland, which is highly concentrated in northeastern and central Iowa and southern Minnesota. Some counties in Iowa have more than 80% of the land as cropland. Forest which covers about one-fourth of the UMRB, mostly in the north, consists primarily of deciduous trees with conifers and mixed stands in some areas. About 19% of the land cover in the region is pastures and hay land. Urban areas make up about 3% of the UMRB with several major metropolitan areas, e.g., Chicago, IL; Minneapolis-St. Paul, MN; St. Louis, MO; and Des Moines, IA.

2.3. Soil characteristics

Soil permeability is obtained from the USGS "Soils Data for the Conterminous United States" dataset (available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml) which are derived from the NRCS State Soil Geographic (STATSGO) data base. The data contain multi-layered physical soil characteristics in vector format which are rasterized at 30-m resolution to refine data to NHDPlus catchment level.

2.4. Stream network and watershed infrastructure

We used the NHDPlus digital network (version 1) developed by the U.S. Environmental Protection Agency (U.S.EPA) and the USGS (2010) as the model framework of streams, reservoirs, and drainage topology. NHDPlus consists of nine components: the improved 1:100K National Hydrography Dataset (NHD); a set of value-added attributes for stream network navigation, analysis and display; an elevation-based catchment for each flowline in the stream network; catchment characteristics; headwater node areas; cumulative drainage area characteristics; flow direction, flow accumulation and elevation grids; flowline min/max elevations and slopes; and flow volume and velocity estimates for each flowline in the stream network (U.S. EPA and USGS, 2010). The NHDPlus network and dataset are available online at http://www.horizon-systems.com/nhdplus/. The spatial unit used in this study is NHDPlus catchment. There are more than 180,000 catchments in UMRB.

2.5. Mean annual streamflow

We used streamflow data from two sources: the catchment mean annual incremental flow (IncrFlow hereafter) in the NHDPlus dataset and the annual statistics of streamflow from the USGS Water Data for the Nation (http://waterdata.usgs.gov/nwis). IncrFlow in the NHDPlus dataset was as computed by the unit runoff method (UROM) (U.S. EPA and USGS, 2010) using observed data from gauges in the HydroClimatic Data Network (HCDN). UROM computes unit runoff values at 8-digit sub-basin level from selected USGS stream gages in HCDN. IncrFlow then is calculated as a product of catchment area and unit runoff. Details of UROM and the calculation of IncrFlow can be found in the NHDPlus User Guide available online at http://www.horizon-systems.com/nhdplus/.

To have reliable streamflow statistics as well as to maximize the overlap between streamflow and NLCD 1992 data, we chose across the study area 100 USGS sites whose records are longer than ten years and as close to the year 1992 as possible. We obtained the mean and standard deviation of annual streamflow using the standard sample estimators.

2.6. Climate

Precipitation and temperature data were obtained from the NHDPlus dataset which were in turn derived from the PRISM,