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River flow changes related to land and water management practices across the conterminous United States

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HIGHLIGHTS

- The effects of multiple land and water management practices on flows were examined.
- Roads, dams, agriculture, and wastewater were the main causes of flow changes.
- Roads and dams were widespread drivers of flow changes.

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ABSTRACT

The effects of land and water management practices (LWMP)—such as the construction of dams and roads—on river flows typically have been studied at the scale of single river watersheds or for a single type of LWMP. For the most part, assessments of the relative effects of multiple LWMP within many river watersheds across regional and national scales have been lacking. This study assesses flow alteration—quantified as deviation of several flow metrics from natural conditions—at 4196 gauged rivers affected by a variety of LWMP across the conterminous United States. The most widespread causes of flow changes among the LWMP considered were road density and dams. Agricultural development and wastewater discharges also were associated with flow changes in some regions. Dams generally reduced most attributes of flow, whereas road density, agriculture and wastewater discharges tended to be associated with increased flows compared to their natural condition.

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1. Introduction

Land and water management practices (LWMP), such as the construction of roads and dams, have been associated with changes in the timing and volume of streamflows (henceforth referred to as flow) (e.g., Eng et al., 2012; Steuer et al., 2010; Poff et al., 2007; White and Greer, 2006; Konrad et al., 2005; Burns et al., 2005; Nilsson et al., 2005; Yang et al., 2004; Konrad and Booth, 2002; Hirsch et al., 1990; Sauer et al., 1983). Such human-caused changes to natural flow regimes often have significant negative consequences for aquatic communities and ecosystem functions (Poff and Zimmerman, 2010; Bunn and Arthington, 2002). Understanding how LWMP—singly and in combination—change stream and river flows is key to maintaining and restoring natural flow regimes.

Most previous research on the effects of LWMP on flow changes has focused on small spatial scales (e.g., single river watershed) and/or watersheds with a presumed single dominant practice (e.g., Kustu et al., 2010; Wang and Cai, 2010; Zimmerman et al., 2010; Poff et al., 2006; Zhang and Schilling, 2006; Ye et al., 2003; Rose and Peters, 2001). Most of these studies analyzed gauged rivers that had flow records during pre- and post-LWMP changes or rivers with both upriver and downriver flow records. These studies have provided important insight into LWMP-flow relations, but there are relatively few gauged rivers amenable to isolating the effects of individual LWMP.

Urbanization effects on flows have been widely studied, particularly for high flows. In general, increased urbanization in watersheds

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has been associated with increased frequency, increased magnitudes, and increased return-interval floods (Steuer et al., 2010; Brown et al., 2009; Poff et al., 2006; White and Greer, 2006; Burns et al., 2005; Konrad et al., 2005; Konrad and Booth, 2002; Rose and Peters, 2001; Sauer et al., 1983). The effects of increased urbanization on high flow durations have been inconsistent; some studies report reductions (Steuer et al., 2010; Brown et al., 2009) while others have found increases (Hawley and Bledsoe, 2011; Bledsoe, 2002; MacRae, 1996) in high durations. In addition, the effects of urbanization on low flow have been inconsistent among studies (Poff et al., 2006; Konrad and Booth, 2002; Rose and Peters, 2001). In general most large-scale studies analyzed watersheds that typically had greater than 10% imperviousness. The 10% imperviousness threshold has been found to be associated with large increases in runoff and when river degradation first occurs (Arnold and Gibbons, 1996; Paul and Meyer, 2001).

Large-regional and global studies have examined the effects of dams on flows (Biemans et al., 2011; Poff et al., 2007, 2006; Nilsson et al., 2005). In general, dams have been found to reduce high flow magnitudes and increase monthly flows, particularly in winter seasons (Biemans et al., 2011; Poff et al., 2007, 2006; Ye et al., 2003). Biemans et al. (2011) also found that dams decreased monthly discharges during summer months in North America. In addition, dams have been associated with increased low flow magnitudes (Poff et al., 2007, 2006; Yang et al., 2004; Ye et al., 2003). In all these studies, dams were presumed to be the dominant LWMP changing different aspects of the flow regime.

In addition to urbanization and dam effects on flows, agriculture has been isolated as a dominant effect in watersheds for a few studies. Zhang and Schilling (2006) found that agriculture increased recharge, baseflow, and flow, especially during the spring to summer months (May to July) for the Mississippi River watershed in the United States. Poff et al. (2006) found that high flow magnitudes moderately increased and low flow magnitudes decreased as a result of increasing agriculture. However, Wang and Cai (2010) reported that agricultural watersheds did not have any increasing trends in summer baseflow.

In an effort to expand the number of gauged rivers and geographic extent of LWMP-flow studies, we present an analysis method that is less restrictive in the types of gauged rivers that can be included. The only requirements for gauged rivers in this analysis are perennial flow, a minimum period of record, and characterization of the gauged river drainage watershed in terms of the natural and human factors that commonly affect flow metrics. This study relies on a method that quantifies flow deviations from natural conditions in watersheds that can experience any number of LWMP. The objectives of the study were to (1) identify some of the common LWMP causing flow changes, (2) determine how spatially prevalent these drivers and flow changes were among different regions, and (3) improve understanding of how specific LWMP influence flows. Five flow metrics were selected in this study to represent several important aspects of the perennial flow regime. This study was not intended to be an exhaustive evaluation of all LWMP and all possible attributes of the flow regime. Instead, the study illustrates an approach for assessing how LWMP are associated with flows in heterogeneous watersheds across broad spatial scales using a tractable number of metrics that represent contrasting flow attributes.

2. Study area, flows, and LWMP variables

The 4196 gauged rivers (hereafter streams) used in this study are located throughout the conterminous United States (Fig. 1) and represent a wide range of climatic conditions and LWMP (Falcone et al., 2010). Site selection was primarily determined by the availability of a daily flow record at least ten years in length during the period 1990–2009. In addition, only streams that had perennial flows were included in the analysis. Associations between flow changes and LWMP were determined in the nine aggregated ecoregions identified in Falcone (2011). Ecoregions were defined by geographic contiguous areas having similar topography, climate, and natural vegetation (Bryce et al., 1999) where the ecosystem functions and responds in a similar manner to stressors, such as LWMP.

Five attributes of flow were examined: the average of the annual 1-day maximum flow (hereafter annual maximum), average of the annual 7-day minimum flow (low flow), and average May, July, and November flows. This selection was subjective and based on a review of flow metrics used in other studies of LWMP effects on the flow regime (e.g., Eng et al., 2012), as well as our desire to maintain a tractable yet illustrative analysis. All flows were calculated from observed daily flow values from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website (http://waterdata.usgs.gov/nwis) using software that allows batch-mode retrieval and data formatting (GNWISQ version 1.0) (Granato, 2008).

Thirteen LWMP were selected as potential predictors of flow changes (Table 1); these variables were described in detail by Falcone (2011) and available at http://water.usgs.gov/lookup/getgislist. These LWMP include watershed land use and land-use change, irrigation, the impacts of dams (reservoir storage and dam density) as quantified in the National Inventory of Dams (NID), road density, and wastewater discharge locations identified in the National Pollutant Discharge Elimination System (NPDES) by the United States Environmental Protection Agency (http://cfpub.epa.gov/npdes/). In addition, a simple reservoir storage index (STI, total reservoir storage volume divided by estimated annual runoff, in volume/year) was calculated to express the NID-based reservoir capacity in terms of years of available water storage. It should be noted that the NID database represents only the approximately 70,000 largest impoundments and does not include the millions of small water bodies found throughout the landscape such as agricultural and urban detention ponds.

Four LWMP variables were initially considered to represent the general effects of infrastructure associated with land development: road density (RDS), population density, percent impervious surfaces, and percent urban land cover in the watershed. These measures were highly redundant (pair-wise Pearson correlation values > 0.9) and only a single infrastructure development metric was used in the study. RDS was selected to represent land development because RDS has been used in several previous studies examining the effects of land development on stream ecosystems (e.g., Kaufmann and Hughes, 2006; Trombulak and Frissell, 2000; Forman and Alexander, 1998; Rieman et al., 1997). In addition, RDS quantifies a gradient of land development that spans all classes of land use (e.g., agriculture and urbanization).

3. Associations of LWMP and flow changes

Relations between flow changes and LWMP were evaluated using random forest (RF) regressions (e.g., Cutler et al., 2007; Prasad et al., 2006) for each flow metric ($n = 5$) within each of the nine ecoregions (i.e., 45 RF models). The key steps were: (1) quantifying the deviation of each flow metric from its estimated natural condition at each stream, (2) relating these flow changes to LWMP, and (3) identifying the statistically significant LWMP.

For each flow metric, the change from natural conditions was quantified as a ratio of the observed (1990–2009) flow value divided by its expected natural value. The natural value was estimated with statistical models (Eng et al., 2012) previously developed from flow measured at 1035 gauged and relatively undisturbed rivers across the conterminous US. These models use a large number of natural features such as climate and topography to make predictions of natural flow values. Cross validation was used to evaluate model performance for each flow metric. On average, predictions were within 10% of observed conditions, which indicates that the models used to estimate natural conditions performed well. One exception was the