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Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems

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Abstract

Using daily discharge data from the USGS, we analyzed how hydrologic regimes vary with land use in four large hydrologic regions that span a gradient of natural land cover and precipitation across the continental United States. In each region we identified small streams (contributing area < 282 km^2) that have continuous daily streamflow data. Using a national database, we characterized the composition of land cover of the watersheds in terms of aggregate measures of agriculture, urbanization, and least disturbed ("natural"). We calculated hydrologic alteration using 10 ecologically-relevant hydrologic metrics that describe magnitude, frequency, and duration of flow for 158 watersheds within the Southeast (SE), Central (CE), Pacific Northwest (NW), and Southwest (SW) hydrologic regions of the United States. Within each watershed, we calculated percent cover for agriculture, urbanized land, and least disturbed land to elucidate how components of the natural flow regime inherent to a hydrologic region is modified by different types and proportions of land cover. We also evaluated how dams in these regions altered the hydrologic regimes of the 43 streams that have pre- and post-dam daily streamflow data. In an analysis of flow alteration along gradients of increasing proportion of the three land cover types, we found many regional differences in hydrologic responses. In response to increasing urban land cover, peak flows increased (SE and CE), minimum flows increased (CE) or decreased (NW), duration of near-bankfull flows declined (SE, NW) and flow variability increased (SE, CE, and NW). Responses to increasing agricultural land cover were less pronounced, as minimum flows decreased (CE), near-bankfull flow durations increased (SE and SW), and flow variability declined (CE). In a second analysis, for three of the regions, we compared the difference between least disturbed watersheds and those having either > 15% urban and > 25% agricultural land cover. Relative to natural land cover in each region, urbanization either increased (SE and NW) or decreased (SW) peak flows, decreased minimum flows (SE, NW, and SW), decreased durations of near-bankfull flows (SE, NW, and SW), and increased flow variability (SE, NW, and SW). Agriculture had similar effects except in the SE, where near-bankfull flow durations increased. Overall, urbanization appeared to induce greater hydrologic responses than similar proportions of agricultural land cover in watersheds. Finally, the effects of dams on hydrologic variation were largely consistent across regions, with a decrease in peak flows, an increase in minimum flows, an increase in near-bankfull flow durations, and a decrease in flow variability. We use this analysis to evaluate the relative degree to which land use has altered flow regimes across regions in the US with naturally varying climate and natural land cover, and we discuss the geomorphic and ecological implications of such flow modification. We end with a consideration of what elements will ultimately be required to conduct a more comprehensive national assessment of the hydrologic responses of streams to land cover types and dams. These include improved tools for modeling hydrologic metrics in ungauged watersheds, incorporation of high-resolution geospatial data

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to map geomorphic and hydrologic drivers of stream response to different types of land cover, and analysis of scale dependence in the distribution of land-use impacts, including mixed land uses. Finally, ecological and geomorphic responses to human alteration of land cover will have to be calibrated to the regional hydroclimatological, geologic, and historical context in which the streams occur, in order to determine the degree to which stream responses are region-specific versus geographically independent and broadly transferable.
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1. Introduction

Freshwater ecosystems are intimately linked to their watersheds or catchments (Hynes, 1975). The rates and temporal variation of delivery of water, sediment, and nutrients from land surfaces to stream channels strongly influence a range of ecosystem processes and the composition of biological communities (Resh et al., 1988). Regimes of water, sediment, and nutrients vary geographically with differences in natural climate, geology, and vegetative cover, and, therefore, generate great spatial heterogeneity in the structure and function of aquatic ecosystems within and among watersheds across the United States (e.g., Poff et al., 1997).

The human transformation of the landscape in the United States over the last three centuries has been extensive and has greatly disrupted the underlying "natural" processes that have shaped aquatic ecosystems. For example, over 50% of wetlands have been lost because of land conversion (Dahl, 1990) and there are now more than 75,000 dams exceeding 2 m in height in the US, thereby severely modifying natural runoff patterns (Graf, 1999; Poff and Hart, 2002). In the 20th century, the US population has shifted from being 60% rural to ca. 80% urban. Currently, about 8000 km^2 (ca. 3000 mi^2) of land in parcels over 0.4 ha (1 acre) in size are converted to residential development each year. Projections suggest that by 2030 the number of residential and commercial structures in the US will be double that of 2000 (Nelson, 2004). On a global scale, over 83% of the land surface has been significantly influenced by the human footprint on "wild lands," and this percentage is even higher in the continental US (Sanderson et al., 2002; http://www.wcs.org/humanfootprint).

The cumulative effect of local transformations on a global scale has been dubbed the geological epoch of the "anthropocene" (Steffen and Tyson, 2001). Certainly, these transformations have dramatically altered fundamental watershed processes that regulate the magnitudes and rates of water, sediment, and nutrient delivery to receiving waters (Vitousek et al., 1997; Jackson et al., 2001). These fundamental changes have, likewise, caused various degrees of ecological degradation in fresh waters (Carpenter et al., 1998; Baron et al., 2002, 2003; Allan, 2004).

A quantitative and predictive understanding of ecological responses to land alteration has proven difficult. Even in the "natural" state, processes influencing stream ecosystems vary within watersheds as a function of channel size (Vannote et al., 1980), network position and spatial variation (Jacobson and Gran, 1999; Benda et al., 2004), and land cover (Allan, 2004) and among watersheds because of geoclimatic variation. Stream ecosystems integrate many upstream processes, and the differential contributions of spatially-distributed controlling factors to the overall ecosystem structure and function is poorly understood. Compounding this, of course, is the overlay of human land-use change, which may have high spatial heterogeneity and temporal lag times in exerting downstream effects (e.g., Trimble, 1977; Harding et al., 1998). And while new tools are being developed to integrate upstream processes in a spatially-explicit (distance-weighted) fashion (e.g., Power et al., 2005), these are not currently well integrated into our understanding of land use change on aquatic ecosystems (Allan, 2004). Consequently, most knowledge about how land use affects fluvial systems comes from evaluating ecological responses to broad categorical types, such as agriculture, urbanization or extent of natural vegetation, with the implicit assumption that these capture important differences in driving factors that regulate the hydrologic, sediment, and nutrient regimes of receiving streams, and, by extension, ecosystem processes and ecological condition.

In this paper, our goal is to provide an overview of the extent to which human modifications of the landscape have altered stream ecosystems across the US. We believe that one of the most tractable ways to approach this problem is to focus on how land use modifies hydrogeomorphic templates, the foundation for many ecological processes in stream ecosystems. Hydrologic regimes vary naturally across gradients of climate, geology, vegetation, and catchment size (Poff and Ward, 1989; Poff et al., 1997), and geomorphic setting varies

geographically in response to geology and physiography (Knighton, 1998; Montgomery and Buffington, 1997; Grant et al., 2003). Although hydrologic variation alone can regulate certain ecological and evolutionary processes (see Poff et al., 1997; Lytle and Poff, 2004), a more complete view of the physical–biological linkage in streams incorporates the interaction between hydrology and geomorphology. Geomorphic setting (e.g., geology and topography) imposes boundary conditions that mediate shorter-term and local-scale hydrologic and geomorphic changes and processes such as erosion, transport, and deposition. Together these create the physical structure and dynamics of the riverine ecosystem (Poff and Ward, 1990; Townsend and Hildrew, 1994). Whereas hydrologic and geomorphic classifications have been independently developed (e.g., Poff and Ward, 1989; Montgomery and Buffington, 1997), the integration of hydrology and geomorphology into a coupled typology has not received much attention, but holds promise (see Poff et al., 2006).

Such an integrated framework is a challenge, however, for several important reasons. First, human-caused variation in hydrologic and sediment regimes is superimposed on underlying natural gradients, and disentangling these two sources of variation has proven difficult (e.g., Allan, 2004). Second, the density of measurements available to quantify fluxes in streamflow and sediment through stream channels is generally low, creating much uncertainty in extrapolation. Third, hydrologic and sediment times series are not necessarily stationary, as climate variation occurs over a range of temporal scales. Indeed, changes in precipitation and runoff have occurred in the US over the 20th Century (Lins and Slack, 1999; McCabe and Wolock, 2002), and this non-stationarity in available streamflow data is confounded with the time frame of land use change. In this paper, our aim is not to develop a comprehensive, integrated hydrogeomorphic framework that takes into account uncertainties in spatial and temporal variation, but rather to make an initial exploration of how human activities (land use and dams) have altered hydrogeomorphic templates in streams across the US. We believe this examination can support the eventual creation of an integrated hydrogeomorphic framework applicable to regional to continental scales.

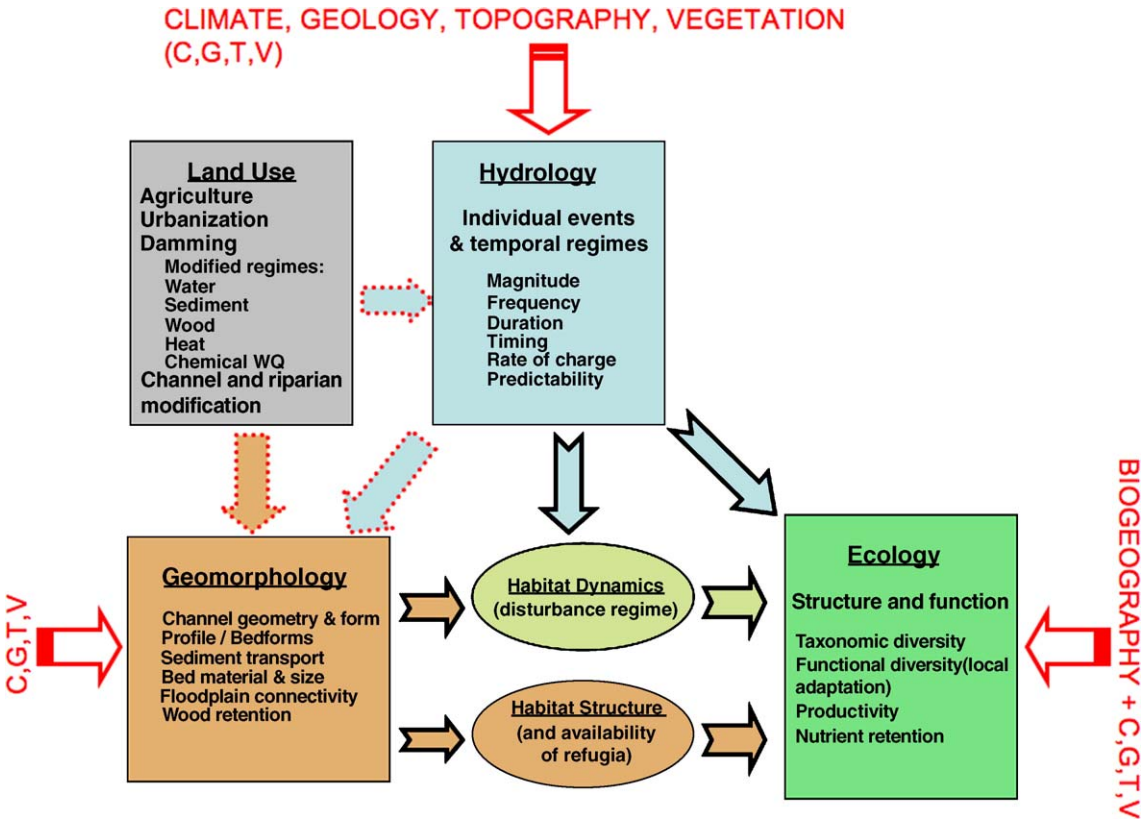

Fig. 1. Conceptual illustration of the relationship between hydrology, geomorphology and ecology of stream and river systems, and how land use modifies hydrologic and geomorphic processes and, thus, induces ecological responses. Terms in red indicate extrinsic controlling factors.

The questions we ask are: 1) Do different classes of land use have consistent hydrologic effects across natural geoclimatic gradients?; 2) How might geomorphic responses to hydrologic alteration vary across these gradients?; and, 3) How might the combined alteration of hydrogeomorphic templates impair stream ecosystems under different types of land use (including dams) across the US? In short, we address the implications of land use change and dams on the hydrogeomorphic integrity of US streams and, by extension, the ecological components. Fig. 1 illustrates the conceptual model for approaching these questions.

We first characterize the spatial pattern and extent of land use alterations (including dams) across US. Second, by selecting four regions that differ in natural hydrogeomorphic templates, we examine how the flow regimes in theses streams have responded to different classes of land use, specifically agriculture, urbanization and dams, and we compare these altered flow regimes to region-specific "reference" conditions, i.e., watersheds with the greatest degree of natural land cover. Using the US Geological Survey stream gauging network (http://water.usgs.gov) to directly assess hydrologic responses to different types and intensities of land use change and to dams, we examine these questions and explore the ecological implications at the national scale.

We focus on small streams with contributing watershed areas less than 282 km^2, which corresponds approximately to a Strahler fourth order stream (1:24 000 map scale) or smaller according to Leopold et al. (1964). Fourth-order and smaller streams represent some 97% of all stream kilometers in the US (Leopold et al., 1964), and they are considered key regulators of water quality at the scale of entire watersheds (Meyer and Wallace, 2001; Lowe and Likens, 2005). Small streams are also most likely to reflect the land-use signature and, thus, allow better inferences on hydrologic–geomorphic–ecological linkages (Knox, 1977; Gomi et al., 2002; Allan, 2004). This is the first attempt at a synthesis using existing USGS gauge data to assess hydrologic alterations along land use gradients. We expect that it will provide the basis for future, more detailed research.

2. Aquatic ecosystems and hydrogeomorphic templates

Ecologists have long viewed stream ecosystems as influenced by hydrologic variation (Resh et al., 1988; Poff et al., 1997) and geomorphic processes (Vannote et al., 1980). In recent years, a consensus has emerged that the geomorphic template interacts with dynamic variation in streamflow to create a disturbance regime that shapes riverine (aquatic and riparian) ecosystems (Pringle et al., 1988; Resh et al., 1988; Poff and Ward, 1989, 1990; Townsend and Hildrew, 1994; Power et al., 1996; Poff et al., 1997; Poole, 2002; Benda et al., 2004). Although hydrologic alteration alone may drive many ecological changes, constraints imposed by a particular geomorphic setting in which hydrologic alteration occurs is critical (e.g. bedrock control on valley and channel morphology, Quaternary geologic deposits available to the stream, etc.), because the hydraulic environment is constrained by interactions among geomorphic processes subject to boundary conditions that act as independent variables over long time frames. For example, flow, channel geometry, bed sediment size, reach slope, and valley morphology interact to dictate stream competence, disturbance regime, and propensity for overbank flows (Parker, 1990; Ferguson, 2003; Dodov and Foufoula-Georgiou, 2005; also see Poff et al., 2006).

The literature on ecological responses to hydrologic alteration has grown tremendously in the last 15 years. The structure and function of stream ecosystems show dependence on the variability of natural flow (Poff and Allan, 1995; Power et al., 1996; Richards et al., 1997). Substantial alteration in flow regimes causes significant changes in ecological organization of aquatic and riparian ecosystems, from changes in the physiology and behavior of individuals to population dynamics to community composition to food web structure (reviewed in Poff et al., 1997; Bunn and Arthington, 2002).

Natural differences occur among streams in components of the flow regimes components (Poff, 1996). In recent years many "ecologically-relevant" hydrologic metrics have been developed to characterize natural (Poff and Ward, 1989; Poff, 1996) and altered flow regimes (Richter et al., 1996; Olden and Poff, 2003). The paradigm of the natural flow regime (Richter et al., 1996; Poff et al., 1997) posits that the magnitude, frequency, duration, timing, and rate-of-change of streamflow are key components of the flow regime and that ecological processes and patterns reflect variation in these specific components along geoclimatic gradients. Thus, every stream has a natural flow regime; however, flow regimes can show important differences within stream systems depending on network position and they can show high similarity across river systems having similar geoclimatic settings (Haines et al., 1988; Puckridge et al., 1998; Poff et al., 2006). Although evidence exists that species can be adapted to the natural flow regime independently of geomorphic constraint (Lytle and Poff, 2004), the *interaction* of the flow regime and geomorphic setting more precisely establishes the disturbance regime that defines the habitat template (Poff

and Ward, 1990; Townsend and Hildrew, 1994) and regulates many ecological and evolutionary processes.

Human-induced land-use change physically modifies land cover, thereby altering fluxes of water and sediment through the networks of stream channels. The subsequent modification of the underlying habitat template in streams induces significant changes in ecological processes and biological communities (Allan, 2004). Whereas different types of human activity have variable hydrogeomorphic effects, a paucity of studies, quantitatively linking hydrologic and geomorphic responses to variation in land-use type across broad natural gradients, leave substantial uncertainty as to the generality of region-specific responses to similar conditions of land-use and potential vulnerability of different types of streams. Agricultural clearing of native vegetation often reduces evapotranspiration and soil infiltration, thereby, increasing runoff and creating more flashy flow conditions (e.g., Sparks, 1995; Peterson and Kwak, 1999; Allan, 2004). Urbanization typically increases watershed runoff because of increased impervious area, which can cause extreme flashiness (Konrad et al., 2005) and low baseflows (Sawyer, 1963; Simmons and Reynolds, 1982) although baseflows may increase when water distribution pipes leak or lawns are heavily watered (Harris and Rantz, 1964; Konrad and Booth, 2002; Lerner, 2002). This creates a so-called urban stream syndrome (Meyer et al., 2005; Walsh et al., 2005) with flashier hydrographs, altered channel morphology and reduced biotic integrity. The rehabilitation of urban streams is argued to be not possible without a restoration of a more natural hydrograph combined with restoration of morphology and geomorphic processes (Booth, 2005). Indeed, increasing effort exists to relate land-use changes to flow regimes with the intent of developing regulatory guidelines on distributed development scenarios that minimize hydrologic degradation of streams in urbanizing landscapes (e.g,. King County Normative Flows Project, http://dnr.metrokc.gov/wlr/BASINS/flows/; State of New Jersey Ecological Flows Project, http://nj.usgs.gov/special/ecological_flow/).

In contrast to spatially-diffuse land-use changes like agriculture and urbanization, dams represent "point" sources of flow and sediment alteration. These structures have very large effects on flow and sediment regimes, scaled in some proportion to the size of the dam and/or reservoir (which determine hydraulic retention time) relative to the stream (Poff and Hart, 2002). Dams have been shown to cause dramatic changes in flow that are relatively easy to detect (e.g., Collier et al., 1996; Graf, 1999; Magilligan et al., 2003; Magilligan and Nislow, 2005). In recent years the ecological importance of flow has been recognized in many restoration schemes broadly associated with managing dams for ecological sustainability (e.g., Stanford et al., 1996; Poff et al., 1997, 2003; Bunn and Arthington, 2002; Richter et al., 2003).

Although the critical ecological importance of flow regime is now established, growing recognition exists that the geomorphic context of the alteration of flow is equally important to predicting how ecosystems will respond to hydrologic alteration, because geomorphic features and processes influence the ecological response and disturbance regime (Montgomery, 1999; Power et al., 2005; Poff et al., 2006). By diminishing watershed storage, infiltration, and vegetative cover, land-use alterations associated with urbanization and agriculture often intensify the potential for erosion and sedimentation through increases in runoff volumes and rates. Changes in the magnitude, relative proportions, and timing of sediment and water delivery induce channel adjustments and modify physical habitat and ecological potential via a wide variety of mechanisms. Possible responses to imbalances in sediment supply and transport capacity include alteration of channel morphology and bed material, hydraulic environments, and substantive changes in the magnitude, frequency, and timing of sediment transport events relative to aquatic life cycles (Waters, 1995; Trimble, 1997; Merritt and Cooper, 2000; Konrad et al., 2005). The effects of these modified runoff and sediment yields are often further exacerbated by direct channel disturbances that increase energy of flow, decrease channel roughness, and reduce erosional resistance (Jacobson et al., 2001).

Although qualitative response models, based on water and sediment supply, are useful for predicting the general direction of geomorphic responses (Lane, 1955; Schumm, 1969; Grant et al., 2003), predicting the *magnitude* of morphologic adjustments and physical habitat changes is extremely challenging because of historical contingencies, the large number of interrelated variables that can simultaneously respond to natural or imposed perturbations, and the continual evolution of fluvial forms and response with changing water and sediment discharges (Schumm, 1977; Hey, 1997; Richards and Lane, 1997; Brewer and Lewin, 1998).

Further complications arise in attempting to generalize impacts associated with broad, simplistic categories of land use, such as urbanization or agriculture, as changes in water and sediment flows depend on the spatial pattern, sequence, and "style" of impacts (Trimble, 1983; Potter, 1991; Fitzpatrick and Knox, 2000). In urban watersheds, for example, the styles of development (including extent of development, connectivity and conveyance of man-made surfaces, compacted area, and stormwater practices), the sequencing of construction, and the net departure from

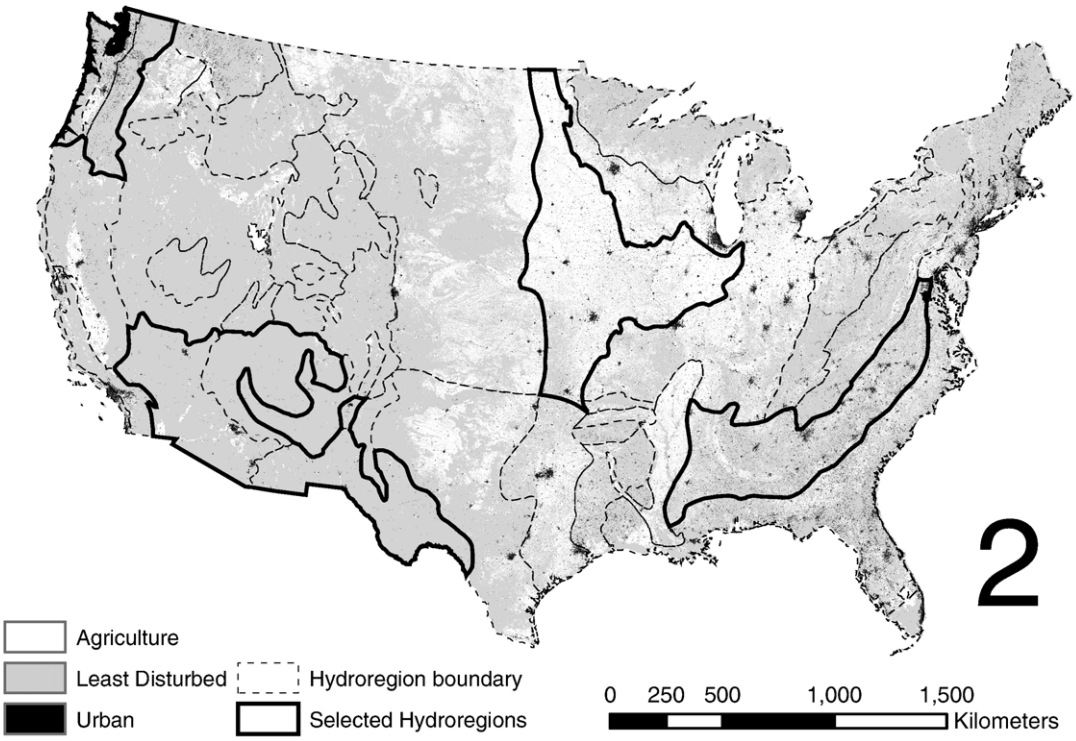

Fig. 2. Land use map of the conterminous United States, indicating locations of four study regions used in this paper.

natural hydrologic processes, influence the nature and extent of impacts on receiving streams (Wolman, 1967; Roberts, 1989; Booth and Jackson, 1997; Roesner and Bledsoe, 2002). Given the interplay of these factors, geomorphic responses to land use are often highly context-specific, within and among physiographic regions.

In short, significant changes in the water and sediment regimes induced by the extensive and intensive changes in land use and by damming have induced complex changes in fluvial processes and in aquatic ecosystem structure and function across the US. In this paper we examine the relative importance of these types of human intervention within and among regions and whether similar types of human intervention have similar effects in different geoclimatic settings.

3. Materials and methods

3.1. Region selection

A goal of this paper is to explore national trends in the relationships between land cover and hydrologic indices. Because over 2 million 4th order and smaller streams exist in the US (Leopold et al., 1964), we did not attempt to conduct a final nationwide analysis, which would entail an exhaustive characterization of the land cover attributes of each small stream watershed. To make this study feasible, the number of watersheds to delineate and evaluate had to be reduced. Therefore, we selected four large regions that span a precipitation gradient across the US to evaluate hydrologic–geomorphic–ecological linkages at the national scale. Each of these regions was constructed by combining one to several ecoregional provinces (Bailey, 1983) that are broadly indicative of differences in natural vegetation, climate, geology and physiography that are important to geomorphic and hydrologic features of streams. Indeed, relatively unimpaired streams in these four regions vary markedly in daily and seasonal flow regimes (see Poff, 1996). Because they occur along a pronounced precipitation gradient, they should represent much of the range of hydrologic response to human-modified land cover across the US.

The Pacific Northwest region (hereafter referred to as NW) combines the Pacific Lowland Mixed Forest and Cascade Mixed Forest–Coniferous Forest–Alpine Meadow provinces. The Southwest region (SW) is a combination of three provinces: the Colorado Semi Arid Plateau, the American Semi-Desert and Desert, and the Chihuahuan Semi-Desert. The Central region (CE)

Table 1
Summary statistics for the three classes of watersheds in each of four regions

Land use type	Region			
	SE	CE	NW	SW
Agriculture				
# gauges	14	43	3	None
Watershed area				
Mean	105	137	52	NA
Range	17–242	14–277	16–69	NA
Period of record				
Mean	15	15	16	NA
Range	10–20	6–20	10–20	NA
% ag in watershed				
Mean	40	75	37	NA
Range	26–65	28–97	26–38	NA
Urban				
# gauges	14	15	14	2
Watershed area				
Mean	92	75	99	236
Range	17–239	12–211	6–218	212–260
Period of record				
Mean	15	15	15.5	12
Range	10–20	6–20	10–20	12
% urban in watershed				
Mean	44	58	27	41
Range	15 – 68	21 – 97	15–55	36–46
Least disturbed				
# gauges	32	1	5	15
Watershed area				
Mean	127	4.09	101	97
Range	16–280	4.09	59–204	2.2–264
Period of record				
Mean	15	20	18	16
Range	10–20	20	10–20	6–20
% Least in watershed				
Mean	83	80	99.3	99
Range	71–98	80	98.5–99.8	92.8–100
Dams				
# gauges	14	15	12	2
Watershed area				
Mean	2005	70 517	1856	146 109
Range	57–11 395	95–723 901	157–18 855	2657–29 000
Pre-dam period of record				
Mean	28.5	27.5	32	45
Range	15–62	20–46	15–55	41–49
Post-dam period of record				
Mean	35	35	31	30
Range	15–62	13–47	17–46	22–38

"Watershed area" in km^2. "Period of record" is the number of years of daily streamflow records. Each watershed was classified as "least disturbed" if at least 70% (SE and CE) or 90% (NW and SW) of the land use within the watershed was some "natural" cover; "agricultural" if greater than 25% was agricultural; and "urban" if greater than 15% of the land area was urbanized. In the NW region, only watersheds averaging 940–1300 mm precipitation per year are included.

Table 2
Description of the 10 hydrologic metrics (in four categories) used in the analysis

Peak flows
- Mx1d [m^3/km^2] — average annual 1-day maximum daily streamflow

Low flows
- Mn3d [m^3/km^2] — average annual 3-day minimum daily streamflow
- ZeroD [days] – the average number of days per year with a daily streamflow value of zero.

Flow durations
- $D_{Q1.5}$ [days] — average number of days flows equal or exceed the 1.5-year return period maximum based on annual maxima of average daily flows
- $D_{50\%Q1.5}$ [days] — average number of days flows equal or exceed 50% of the 1.5-year return period maximum based on annual maxima of average daily flows
- $D_{75\%Q1.5}$ [days] — average number of days flows equal or exceed 75% of the 1.5-year return period maximum based on annual maxima of average daily flows

Flow variability
- CV_Day [–] — the average annual coefficient of variation in daily flow values (standard deviation divided by mean flow)
- Skew [–] — the statistical measure of asymmetry in the distribution of daily flow values; the third statistical moment of the distribution.
- Flash [–] — the flashiness index of Sanborn and Bledsoe (2006) which represents the average daily change in streamflow divided by the mean streamflow over the period of record.
- T_{Qmean} [–] — the mean fraction of time that streamflow exceeds the mean annual streamflow. T_{Qmean} provides a measure of the asymmetry of the frequency distribution of daily streamflow but with less sensitivity than the skew coefficient Konrad et al. (2005). T_{Qmean} is inversely related to flow flashiness.

Units for each metric are given in brackets.

consists only of the Prairie Parkland Temperate province. The Southeast region (SE) consists only of the South Eastern Mixed Forest province (with two disconnected and smaller areas excluded).

3.2. Definition and derivation of land use types

Grids with statewide National Land Cover Data (NLCD, Stehman et al., 2003; USGS, 2005) were merged and clipped to the four study regions. The 21 classes comprising the grids were then reclassified using ArcInfo into three classes: Least Disturbed ("natural" cover types such as forests, grasslands, wetlands, open water, or bare rock); Agriculture (e.g., orchards, pasture, croplands, fallow lands); and Urban (e.g., low/high intensity residential, mines, recreational grasses). We calculated the percent land cover in each region by summing the total number of cells in each class and the total number of cells in the region. USGS gauged watersheds, created using 30-m DEMs, were used to clip the reclassified landcover grids to determine the percentages of the three classes in the

same manner. Fig. 2 shows the distribution of the types of land cover across the entire US and the locations of the four study regions.

3.3. Selection of gauges for examining hydrologic responses to types of land cover

We focused on small streams for this analysis to maintain a strong association between land use and hydrologic signal. We determined *a priori* that only gauged watersheds <282 km^2 would be included as this area approximates Strahler 4th order and smaller watersheds and represents more than 93% and 99% of the US stream length and numbers, respectively (Leopold et al., 1964). The contributing watershed area for each gauge was determined using data provided by the USGS with the gauge records.

In each region we initially identified USGS gauges with flow records of at least 20 years. Because the NLCD data were for the year 1992, only stream gauges spanning water years 1983–2002 were selected. Because watersheds <282 km^2 are not proportionately represented in the gauge network, we subsequently included less than 20-yr records to increase sample size, even though we recognize the limitations associated with using short periods of record. In the SE regions, where more data were available, we used a minimum 10 yr record. Elsewhere, we used a minimum 6-yr record. A statistical summary of the selected gauges and associated watersheds is presented in Table 1.

Land cover within each watershed was determined as above. Each watershed was classified into one of the three types of land use using the following criteria which were based on examination of available data: "least disturbed" if at least 70% (SE and CE) or 90% (NW and SW) of the land use within the watershed was some "natural" cover; "agricultural" if greater than 25% of the land cover was agricultural; and "urban" if greater than 15% of the basis was urbanized (Table 1). For all watersheds, we examined the USGS "Summary Comments" pages to check for the presence of upstream dams or other major water infrastructure that might alter the flow regime in the watershed (e.g., diversion structures).

In the NW region, we screened sites for strong precipitation gradients and limited our inclusion of gauges to those having 940–1300 mm average precipitation per year to ensure no discrepancies between "least disturbed" watersheds (typically at higher, wetter elevations) and agricultural or urban watersheds (typically at lower, drier elevations).

3.4. Selection of gauges for examining hydrologic responses to dams

To examine the effects of dams on flow regimes in each of the four regions, we used the National Inventory of Dams (NID; http://crunch.tec.army.mil/nid/webpages/nid.cfm), which gives the location all dam structures > 2 m in height in the US. Using GIS, we matched dam structures to the first downstream USGS gauges that had at least 15 years of continuous daily streamflow data during the pre-dam period and after the date of dam completion. We also only included gauges where no other mainstem dam occurred between the gauge and the target dam and where any tributaries joining the mainstem river between the target dam and the gauge lacked any major

Table 3
Correlation coefficients (Pearson r) for 10 flow metrics along increasing proportions of watershed area comprised by three types of land use for each of four regions

Region	Land use	Metric									
		Peak flows	Low flows		Flow durations			Flow variability			
		Mx1d	Mn3d	ZeroD	$D_{Q1.5}$	D_{50Q1}	$D_{75Q1.5}$	CVD	Skew	Flash	T_{Qmean}
SE	Urban	0.35*	−0.06	−0.18	−0.28*	−0.17	−0.24	0.20	−0.12	0.49*	−0.46*
	Agriculture	−0.02	−0.18	0.25*	0.30*	0.15	0.25	0.22	0.23	−0.01	−0.05
	Least disturbed	−0.25*	0.10	0.01	0.00	0.00	0.00	−0.28*	−0.04	−0.38*	0.40*
CE	Urban	0.51*	0.38*	−0.12	−0.12	−0.12	−0.13	0.08	−0.01	0.44*	−0.34*
	Agriculture	−0.45*	−0.30*	−0.19	0.08	0.06	0.08	−0.17	−0.13	−0.45*	0.33*
	Least disturbed	0.10	−0.25	0.41*	−0.03	−0.03	−0.04	0.42*	0.38*	0.40*	−0.28*
NW	Urban	−0.05	−0.51*	0.19	−0.36	−0.46*	−0.41	0.61*	0.18	0.78*	−0.73*
	Agriculture	−0.17	−0.32	0.33	−0.18	−0.25	−0.23	0.35	0.24	0.08	−0.18
	Least disturbed	0.12	0.60*	−0.33	0.40	0.52*	0.47*	−0.70*	−0.27	−0.72*	0.73*
SW	Urban	−0.16	−0.15	0.48*	−0.24	−0.17	−0.16	0.36	0.30	0.04	−0.39
	Agriculture	−0.24	0.09	−0.05	0.14	0.73*	0.77*	−0.16	−0.35	−0.10	0.35
	Least disturbed	0.21	−0.64*	0.17	−0.50*	−0.28	−0.20	0.32	0.31	0.15	−0.43*

Values denoted by * are statistically significant from zero at $p<0.05$. Units for metrics are provided in Table 2.

dams. Although the NID typically reports the operational "purpose" of dams (e.g., recreation, hydropower), we did not use this information in our analysis. Characteristics of the dammed watersheds are given in Table 1. For this analysis, we report the effect of dams on flow metrics relative to the historical (before-dam) conditions, although we do not control for type of land cover in the watershed above the dam.

3.5. Hydrologic variables and analytical approaches

Our selection of hydrologic variables was guided by the dual need to select those that are ecologically meaningful and those that are sensitive to type of land cover. We followed the literature to select a small number of variables (e.g., Poff and Ward, 1989; Richter et al., 1996; Olden and Poff, 2003; Konrad et al., 2005; Sanborn and Bledsoe, 2006) that are described in Table 2.

We evaluated hydrologic responses to the type of land cover in two ways. First, we examined correlations for flow metrics along increasing proportions of watershed area comprised by three types of land cover (natural, agricultural, urban) for each of four regions. Second, we classified each watershed as agricultural, urban, or least disturbed (Table 1), then examined percent *departures* of the flow regime variables relative to the least disturbed watersheds. To examine the relationship between the degree of hydrologic alteration and the extent of land cover type, we assigned gauged watersheds to one of two land cover types and arbitrary cutoffs or "threshold" levels of land cover type. Watersheds having >30% urban land cover type were labeled "high urban" and those having >15% (including those in the high urban category) were labeled simply "urban." Likewise, watersheds having >50% agricultural land cover were labeled "high agriculture" and those having >25% were labeled "agriculture." We conducted this analysis in the SE, NW, and SW regions, because they had at least two gauged watersheds characterized as least disturbed (see Table 1). In this second analysis we implicitly assumed that watersheds with the most natural land cover are "controls" against which the "impact" of anthropogenic land cover can be evaluated.

4. Results

In the following sections, we report hydrologic changes associated with different types of land cover across the four study regions. Flow responses are grouped into four categories: peak flows, low flows, flow duration, and flow variability.

Table 4
Effects of dams on 10 flow metrics for each of four regions

Region		Metric									
		Peak flows	Low flows		Flow durations			Flow variability			
		Mx1d	Mn3d	ZeroD	$D_{Q1.5}$	$D_{50Q1.5}$	$D_{75Q1.5}$	CVD	Skew	Flash	T_{Qmean}
SE	Pre Mean (sd)	1.768	0.015	2.18	3.14	11.22	5.54	1.95	10.58	0.44	0.27
		(0.942)	(0.010)	(8.15)	(3.73)	(13.07)	(6.69)	(0.67)	(4.47)	(0.20)	(0.03)
	Post Mean (sd)	1.632	0.016	0.23	3.07	12.40	5.74	1.76	8.61	0.42	0.28
		(0.879)	(0.011)	(0.86)	(3.35)	(13.1)	(6.79)	(0.47)	(2.59)	(0.18)	(0.04)
	Departure (%)	−8	5	−89	−2	10	4	−9	−19	−6	6
CE	Pre Mean (sd)	0.757	0.001	13.66	7.96	23.24	12.83	2.85	9.93	0.42	0.23
		(1.006)	(0.001)	(25.29)	(6.3)	(17.74)	(9.58)	(1.54)	(7.83)	(0.38)	(0.08)
	Post Mean (sd)	0.625	0.002	4.86	12.67	43.17	26.76	2.06	5.92	0.30	0.27
		(0.687)	(0.001)	(16.07)	(19.21)	(68.16)	(48.46)	(0.77)	(2.9)	(0.21)	(0.1)
	Departure (%)	−18	73	−64	59	86	109	−28	−40	−30	19
NW	Pre Mean (sd)	1.923	0.045	11.94	4.25	29.20	11.34	1.34	4.89	0.20	0.33
		(0.837)	(0.053)	(40.66)	(4.17)	(26.43)	(12.55)	(0.53)	(2.65)	(0.1)	(0.03)
	Post Mean (sd)	1.261	0.047	4.96	9.54	49.10	20.75	1.18	3.71	0.15	0.36
		(0.685)	(0.047)	(10.63)	(9.17)	(33.95)	(16.42)	(0.5)	(3.09)	(0.09)	(0.06)
	Departure (%)	−34	5	−58	125	68	83	−12	−24	−26	7
SW	Pre Mean (sd)	0.153	0.001	14.18	10.36	31.05	18.67	4.46	13.29	0.50	0.21
		(0.146)	(0.001)	(20.05)	(10.33)	(35.28)	(20.43)	(5.65)	(15.53)	(0.62)	(0.11)
	Post Mean (sd)	0.131	0.002	13.96	26.91	138.93	66.87	3.45	11.79	0.42	0.33
		(0.161)	(0.003)	(19.74)	(31.85)	(185.35)	(85.77)	(4.17)	(13.11)	(0.44)	(0.2)
	Departure (%)	−15	130	−2	160	347	258	−23	−11	−16	55

"Pre" refers to pre-dam flow regime, and "post" to period after damming; and, "departure" is the percentage change in the pre vs. post. Units for metrics are provided in Table 2.

Table 5
Departures (%) relative to least disturbed gauged watersheds for different categories of land use and intensity for three regions

Region	Land use	Metric										
		n	Peak flows		Low flows	Flow durations				Flow variability		
			Mx1d	Mn3d	Zero D	$D_{Q1.5}$	$D_{50Q1.5}$	$D_{75Q1.5}$	CVD	Skew	Flash	T_{Qmean}
SE	All urban	14	25	1	−93	−28	−24	−26	12	−13	46	−19
	High urban	10	42	−22	−94	−33	−27	−30	24	−8	54	−28
	All ag	14	8	−14	77	22	14	19	16	14	22	−9
	High ag	3	33	−65	455	59	50	55	46	57	33	−18
NW	All urban	14	84	−64	–	−21	−51	−34	59	13	267	−13
	High urban	6	22	−79	–	−52	−71	−62	85	19	564	−24
	All ag	3	21	−84	–	−43	−70	−58	93	27	263	−16
SW	High urban	2	−62	−100	116	−70	−72	−71	47	22	−44	−68

The CE region is excluded because it has only one gauged "reference" (i.e. least disturbed) stream (Table 1). "n" is the number of gauges per category. Units for metrics are provided in Table 2. Urban land cover classes are all (>15%) and high (>30%), and agricultural land cover classes are all (>25%) and high (>50%).

4.1. Hydrologic change along land-use gradients

Table 3 summarizes the correlation between 10 hydrologic variables and the proportion of contributing watershed area that is least disturbed, agricultural, and urban for each of the four study regions. Some consistencies and interesting differences were revealed across regions.

Hydrologic responses were variable along a gradient of least disturbed land use. Generally maximum flow (Mx1d) was not correlated significantly with proportion of land in the least disturbed class with the exception of a negative correlation in the SE region. Minimum flows (Mn3d) increased in the NW and decreased in the SW with increasing proportion of area in the least disturbed class, whereas CE streams showed increased ZeroD with increasing area in the least disturbed class. For the duration statistics, NW streams showed increases in $D_{50\%Q1.5}$ and $D_{75\%Q1.5}$, and SW streams showed a decline in $D_{Q1.5}$ with increasing natural land in the least-disturbed class.

Measures of daily variation of flow differed among regions. For example, CVD and Flash declined with increasing watershed "naturalness" in the SE and NW, but increased in the CE. CE streams also showed increased Skew with increasing least disturbed area. The metric T_{Qmean} was highly inversely correlated with Flash for all four regions, increasing in the SE and NW, but decreasing in the CE and SW with increasing proportions of least disturbed area. Thus, it appears that along natural gradients, the more mesic SE and NW are similar to each other, as are the more arid CE and SW.

With an increasing proportion of agricultural land use, maximum and minimum flows decreased in the CE, and an increase in ZeroD occurred in the SE. For duration, $D_{Q1.5}$ increased in SE, while $D_{50\%Q1.5}$ and $D_{75\%Q1.5}$ increased in SW. Flow variability responded to increasing proportions of agricultural land only in the CE, with a decrease in Flash and an increase in T_{Qmean}.

With increasing urbanization, maximum flows increased in the SE and CE. Minimum flows increased in the CE, but decreased in the NW. Durations of moderately high flows, approximating bankfull, consistently decreased with urbanization across all regions, but were significant only for the SE ($D_{Q1.5}$) and the NW ($D_{50\%Q1.5}$). Measures of flow variability were reasonably consistent across regions, with SE, CE, and NW showing increased flashiness and reduced T_{Qmean} with increases in urban cover. SW streams trended similarly, while also showing an increase in ZeroD.

4.2. Hydrologic alteration caused by dams

Table 4 shows the effects of dams on streams in the four regions for each of the 10 flow metrics. Dams imposed fairly consistent hydrologic changes across all regions. Peak flows declined in all regions, especially the NW, and minimum flows increased substantially in the CE and SW. Measures of the duration of flows increased greatly in all regions except the SE, which showed little alteration. All regions showed decreases in measures of variability, especially Flash and T_{Qmean} in the CE and SW. In short, dams act to reduce peaks, increase minima, raise durations of moderate flows and generally stabilize the flow regime relative to unimpaired pre-dam flows.

4.3. Hydrologic departures relative to "reference" gauges for types of land cover

Table 5 shows the relative change in hydrologic metrics for land cover type and intensity versus the least disturbed watersheds. In agricultural watersheds, peak flows increased in the SE and NW. Minimum flows

declined in both regions and ZeroD increased in the SE, which reflects the sensitivity of these small streams (with lower specific yield) to intermittency. Durations increased in the SE but declined in the NW. Flow variability increased in the SE and NW, with a particularly large increase in Flash in the NW.

Peak flows in urban watersheds increased relative to least disturbed streams in the SE and NW, but declined in the SW. In the NW a surprising greater increase in peak flow was indicated. Minimum flows generally declined in all three regions, especially in the NW and SW. Durations decreased in all three regions with urbanization, again more severely in the NW compared to the SE. Finally, flow variability generally increased substantially (positive CVD, negative T_{Qmean}) with urbanization in the SE, NW and SW, although skew decreased in the SE. Increases in variability with urbanization were more dramatic in the NW, especially for Flash.

When comparing the joint hydrologic changes in agricultural and urban streams, we observed differences between the SE and NW streams. In the SE and NW streams peak flows in urban streams (>15% land cover) were 3–4 times those in agricultural streams (>25%). For the duration indices, however, the SE streams showed an opposing trend between agricultural (increased duration) and urban (decreased), whereas the NW streams showed a consistent trend with agriculture and urbanization decreasing duration.

In general, we did not see large or consistent differences between streams having a "high" level of urban or agricultural land cover versus those defined by a lower threshold. This finding may reflect a number of factors, such as small sample size or the inclusion of the "high" land cover watersheds in the "all" category.

5. Discussion

In this section we discuss some of the more likely geomorphic and ecological responses of streams to the hydrologic alterations associated with land cover and dams for each of the four regions. These responses are based on a large, diverse literature and represent broad hypotheses about how different regional contexts can produce variable responses to similar levels of anthropogenic land use change.

5.1. Geomorphic consequences of hydrologic alterations

5.1.1. General considerations

The time scales we focus on here are intermediate (decadal) in that water and sediment discharge are both primary independent variables on such time scales (Schumm and Lichty, 1965; Schumm, 1991). Channel responses to changes in these variables occur at spatial scales that range from drainage networks to reaches to streambed patches. We focus primarily on the reach scale, where geomorphic adjustments to altered water and sediment regimes have immediate consequences for stream ecosystems via changes in habitat structure and dynamics (disturbance).

Geomorphic responses to hydrologic change are difficult to evaluate in a precise or quantitative manner for several reasons. For instance, geologic and human disturbances histories can vary markedly within and among hydroclimatic regions and they may impose a specific context in which a channel responds to contemporary hydrologic change (Knox, 1977; Fitzpatrick and Knox, 2000). Examples include the massive forest clearing and sediment erosion in the 19th Century that have modified channel morphology in the SE Piedmont (Trimble, 1974; Costa, 1975), the extensive channelization and drainage of channels in the CE (Rhoads and Herricks, 1996), tie drives and removal of debris dams in the NW (Sedell and Froggatt, 1984; Collins and Montgomery, 2001; Montgomery et al., 2003), and the episodic arroyo cutting and extended "memory" of fluvial systems in the SW (Graf, 1983; Yu and Wolman, 1987).

Many stream channels are still adjusting to historical legacies that produce ongoing, lagged geomorphic responses (Trimble, 1977, 1995). Moreover, any ongoing or present day geomorphic responses to contemporaneous imbalances in sediment and water budgets are subject to thresholds and non-linearities. Several other factors also influence channel response to recent land alteration. For example, whether a channel incises or widens can depend on local variations in boundary materials, as with contrasts in cemented till and weakly consolidated outwash in the NW (Bledsoe and Watson, 2001), and riparian vegetation may constrain channel adjustment and migration (Thorne, 1990; Dunaway et al., 1994; Friedman et al., 1998). Because these and other factors exhibit heterogeneity across the landscape, the response of a local channel to watershed-scale hydrologic alteration can be complex and difficult to predict (Richards and Lane, 1997; Jacobson et al., 2001).

5.1.2. Potential geomorphic responses based on past studies

5.1.2.1. Magnitudes of maximum and minimum flows. Channel enlargement, bank instability, degradation of physical habitat, and numerous other geomorphic responses have been associated with increases in peak

flow in various hydroclimatic regions (Hammer, 1972; Arnold et al., 1982; Booth, 1990; Booth and Henshaw, 2001; Jacobson et al., 2001). Sediments produced via bank instability can initiate formation of a central bar and braiding, as well as alter substrate size, embeddedness, and bed stability (Jackson and Beschta, 1984; Carson, 1986; Waters, 1995; Wilcock and Kenworthy, 2002). Our exploratory analysis indicates that streams, affected by urbanization and agriculture in the SE and NW regions, have annual flood peaks (based on the daily average series) that are magnified 8–33% for agricultural watersheds and 22–84% for urbanized watersheds relative to least disturbed conditions (Table 5). These increases could be more pronounced had we examined 15-minute flow data and used instantaneous peaks in a partial duration flow series. Urban peak flows in these two regions are magnified three to four times than those in agricultural regions. Thus, urban land cover exceeding 15% of the total watershed appears to have potential for initiating greater impacts than total agricultural land cover of 25% in the SE and NW regions.

In the CE region, the significant inverse relationships between agricultural land cover and the 1-day maxima and 3-day minima (Table 3) appear to be an artifact of the high correlation between agricultural and urban land covers in this region ($r=-0.75$), where relatively sparse natural land cover occurs. Thus, as agricultural land cover goes up, percent urban cover goes down, reducing the peak flows and low flow discharges associated with urban landscapes. From a geomorphic perspective, increases in sediment supply associated with agriculture create a potential for sediment deposition and aggradation in the low gradient, capacity-limited channels prevalent in this region (Rhoads and Urban, 1997).

By contrast, the correlation between urban and agricultural land cover is much lower in the SE ($r=-0.30$), NW ($r=0.20$) and SW ($r=0.23$) and percent agricultural cover does not have a significant effect on maximum or minimum flows, with the exception of ZeroD in the SE (Table 3). Although past research has clearly shown that agricultural conversion tends to increase peak flows, this increase with increasingly agricultural cover is probably obscured in our correlation analysis by spatial variations in topography, geology, soils, climate, and farm practices.

While urban construction and agriculture can create parallel increases in water and sediment supplies, the eventual build-out of urban watersheds with imperviousness, compacted surfaces, landscaping, and flow detention and storage facilities ultimately tends to diminish sediment supply from uplands, concomitantly with a magnification in peak flows. The simultaneous increase during build-out in sediment transport capacity and in a shifting sediment supply from external (upland) to internal (channel) sources should lead to accelerated erosion and geomorphic activity that are severe in urban watersheds.

Geomorphic responses to the reduction of peak flow by damming vary widely with distinctive changes in sediment transport capacity and supply, as well geologic context (Petts, 1982; Williams and Wolman, 1984; Brandt, 2000; Grams and Schmidt, 2002; Grant et al., 2003). Our results indicate that, at least within a few kilometers below dams, decreases in peak discharges occur across the four focus regions despite marked climatic differences. The potential for morphologic responses in the early stages of a departure from quasi-equilibrium conditions fundamentally depends on the cumulative excess of specific stream power relative to the resistance of erodible channel boundaries (Rhoads, 1995; MacRae, 1997; Bledsoe, 2002; Grant et al., 2003). Thus, without context-specific information on the erodibility of boundary materials, critical discharges for entrainment of boundary materials, sediment replenishment, and channel "lability", it is impossible to generalize if cumulative sediment transport capacity has shifted below dams on this regional scale.

Alteration of low flows may affect the dynamics of riparian groundwater and the viability of streambank vegetation. Low flow reductions generally increase deposition of available fine sediments and, thereby, alter habitat quality and bed mobility (Waters, 1995; Wilcock and Kenworthy, 2002; Suttle et al., 2004). This may be most pronounced in regions where high intensity convective storms produce large sediment loads from tributary basins during low flows.

5.1.2.2. Flow durations. Measures of flow duration increased for dammed streams in all regions except for the duration of $Q_{1.5}$ in the SE, which is virtually unchanged (Table 4). CE, NW, and SW streams had duration increases of 5–350% across a range of flows spanning roughly mid-bankfull to annual flood magnitudes. Durations of moderate flows also influence the stability of bank toes, bank drainage, and vegetative influences on bank stability and near-bank hydraulics (Thorne, 1990; Simon and Collison, 2002; Keane and Smith, 2004). Moderate flow may potentially initiate bed and bank erosion, particularly in live bed channels where the threshold for bed material entrainment is exceeded for virtually all flows. Bed coarsening, armoring, and increased bed stability may result from increased durations as finer material is winnowed from gravel-cobble beds (Gessler, 1970; Parker and Sutherland, 1990; Reid and Laronne, 1995; Almedeij and Diplas, 2005).

Flow durations in agricultural and urban watersheds generally declined relative to least disturbed reference gauges in the SE, NW, and SW, with the exception of agricultural watersheds in the SE, where flow durations increased (Table 5). In urban streams that lack effective controls on stormwater runoff, increased peaks, reduced durations, and rapid rates of recession may increase the frequency of high flows more than the cumulative duration of those same flows (Konrad et al., 2005). Gravel bed surfaces that are only briefly exposed to high flows in urban streams with at least modest sediment supplies may be less armored and more unstable given insufficient time to exhaust the in-channel sediment supply (Reid and Laronne, 1995; Konrad et al., 2005).

5.1.2.3. Flow variability. Existing literature indicates that the increases in flow variability and flashiness, consistently observed for urban and agricultural watersheds in the CE, SE, and NW regions (Table 3), are likely associated with decreased bank stability. Amplified flow variability can significantly increase the risk of bank instability via rapid wetting and drawdown (Thorne et al., 1998), and relatively small but frequent flows can promote prolonged periods of bank retreat, channel migration and high yields of fine-grained sediment (Simon et al., 2000). These bank-destabilizing processes could also occur in association with hydropeaking projects that are not resolved by the daily dataset. Conversely, the lateral stability of dammed streams could potentially be increased by the effects of reduced flow variability on bank drainage (Simon and Collison, 2002) and vegetative encroachment (Graf, 1978).

The variability, flashiness, and magnitude of flow also drive instream disturbance regimes. Temporal patterns in shear stress relative to substrate size are directly related to the depth of scour (Haschenburger, 1999; Bigelow, 2005) and the prevalence of unstable bed patches (Lisle et al., 2000; Haschenburger and Wilcock, 2003). The tendency for geomorphic complexity to diminish with channel enlargement and instability (Pizzuto et al., 2000; Henshaw and Booth, 2001) suggests the potential for additive or synergistic impacts on disturbance in streams where the magnification of peak flow is accompanied by increased variability.

5.1.3. Comparing potential geomorphic responses of the four focus regions

Streams within and among the four focus regions are very diverse in terms of historical legacies, ratios of transport capacity and supply, lateral versus vertical adjustability, and vulnerability to hydrologic change. In this section, we use the literature-based assessment of potential geomorphic responses and the regional hydrologic analysis to speculate on regional stream adjustments to land use.

Within the constraints set by extreme antecedent events, SW streams are perhaps most vulnerable to morphologic adjustment because of the prevalence of live bed channels, historical incision, and lack of woody riparian vegetation. The results suggest that, of the four focus regions, these streams could be most affected by damming as they tend to experience the largest net change in formative discharges of water and, at least proximate to the dam, sediment supply. Although we lacked sufficient gauges for assessing urbanization impacts in the SW, it is well known that streams in arid regions can exhibit radical morphologic responses to urbanization (Trimble, 1997). Adjustments can also be relatively subtle and spatially discontinuous, however, because of the influence of urban infrastructure (e.g. culverts and pipelines acting as grade control; Chin and Gregory, 2001) and undoubtedly depend on stormwater controls, vegetation colonization, and many other extrinsic factors. Recent studies of the management of stormwater suggest that urban streams in the southwestern US detectably enlarge at lower levels of watershed urbanization than streams in the eastern US (Coleman et al., 2005). In general, the effects of urbanization on perennial streams in humid regions have received much more attention than impacts to dryland systems (Rhoads, 1986; Chin and Gregory, 2001). Findings from perennial streams cannot be directly extrapolated to arid systems where extreme events tend to be more geomorphically effective in ephemeral channels because of the extended memory and long recovery times (Wolman and Gerson, 1978), sporadic movement and storage of sediment (Graf, 1982), and discontinuous adjustments between form and process (Rhoads, 1988).

CE streams are highly vulnerable to flow magnitude, duration, and variability increases because of a prevalence of relatively erodible boundary materials and the 175-year history of intensive drainage and channelization in the region (Urban and Rhoads, 2003). These streams are frequently low gradient, incised, and fine-grained, especially in glaciated portions of the region where boundaries are composed of till and outwash, lacustrine deposits, and/or loess. The ubiquitous practice of channelization generally increases flood energy and may both increase susceptibility to enlargement and sensitivity to urbanization (Graf, 1977). Departures from the well known channel evolution model of incisional adjustments (e.g. Schumm et al., 1984; Simon, 1989) have been noted in channelized streams in this region where extreme overwidening overshadows the influence

of slope increases and results in a depositional response (Landwehr and Rhoads, 2003).

Streams in both forested regions (SE and NW) are highly variable in terms of channel boundary materials, transport capacity, and vegetative influences. In the SE, for example, the dominant boundary materials range from bedrock to fines, even in similar lithotopographic contexts (T. Cuffney, USGS NAWQA Program, written comm.). This tremendous spatial variability in geology probably influences the low correlations (0.00 to 0.10) between percent least disturbed cover and both low flow and flow duration indices in the SE (Table 3). SE streams also tend to have relatively densely vegetated and/or cohesive banks and may have armoring potential and bedrock control. Hydrologic impacts associated with urbanization are likely less pronounced relative to pre-development conditions in areas with relatively shallow and dense soils (e.g., shale-dominated Triassic basins), resulting in less net change in geomorphic processes driven by the magnitudes and variability of flow. This region also contains extensive areas of Paleozoic schists and meta-igneous rock with thick, extremely permeable saprolite. Substantial spatial heterogeneity in the response characteristics of runoff (as mediated by geology) also occurs in the NW and SW, and again underscores the difficulty of making generalizations about slopes, drainage network structures, and net hydrologic changes within and among regions.

Despite this heterogeneity, NW streams are arguably more vulnerable to land-use change because of differences in hydrologic processes. Relatively large departures from natural patterns of flow occur when forest cover is cleared for suburban development and hillslope storage may be diminished fourfold (Burges et al., 1998; Konrad et al., 2005). Geomorphic responses also depend greatly on the influence of wood, which may act as a stabilizing or destabilizing agent, as well as the resistance and armoring potential of bed materials that can include heterogeneous glacial sediments. Because we screened out sites with high precipitation, these results predominantly reflect flows in capacity-limited segments with gradients less than 2–3% which are relatively vulnerable to land use impacts (Booth, 1990; Montgomery and Buffington, 1998; Montgomery and MacDonald, 2002).

5.2. Ecological implications of hydrologic alteration associated with land use

Ecological responses to hydrologic alteration have been increasingly documented in the literature over the last decade, particularly with respect to dams (see reviews in Poff et al., 1997; Bunn and Arthington, 2002; Graf, 2006-this issue). Here, we provide a brief overview of some likely ecological responses to land-use types and dams, specifically in terms of flow alteration and change in physical disturbance regimes.

Peak flows help maintain the channel form and provide important lateral connection of the channel to the riparian zone and floodplains, maintaining healthy riparian communities (Naiman et al., 2005) and access to favorable backwater habitats for juvenile fish (Sommer et al., 2001). Higher shear stresses associated with increased peaks move more sediment, and they can directly displace benthic invertebrates (e.g., Poff and Ward, 1991) and small fishes (Harvey, 1987). Streams that differ naturally in characteristics of peak flows can have differences in the types of species present (Poff and Allan, 1995; Richards et al., 1997). From a biological standpoint, the magnitude and timing of peak flows and low flows are especially critical for aquatic and riparian species, and over evolutionary time they provide strong selective forces for the biota (Lytle and Poff, 2004). Differences in timing of peak flows can explain failures in the spread of non-native species, such as rainbow trout, which have not established in rivers where high flows occur during the period of emergence of young from the gravel (Fausch et al., 2001).

Modifications of the magnitudes and timing of peak flows, therefore, can alter many ecological processes and communities (e.g., Poff et al., 1997). In agricultural and urbanizing watersheds peak flows generally increase, although the timing is unlikely to be modified. Higher peaks can increase sediment transport and, thus, increase disturbance intensity by increasing depth of scour of bed sediments and inducing greater mortality of benthic invertebrates (Palmer et al., 1992; Townsend et al., 1997) and fish (Montgomery et al., 1999) within the substrate.

By contrast, dams typically reduce peak flows. Such stabilization of high flows in particular seasons can facilitate invasion by otherwise maladapted non-native species (Meffe, 1984) or modify stream food webs by eliminating seasonal disturbance (Wootton et al., 1996). Capture of peak flows behind dams also impairs downstream riparian communities by reducing lateral connectivity (Scott et al., 1996; Magilligan et al., 2003) and by preventing the downstream transport of water-borne seeds (Merritt and Wohl, 2006). Loss of high flows can reduce cleansing of gravel interstices and, thus, diminish the quality of habitat for benthic invertebrates and smother fish eggs (Waters, 1995). Even small dams may have large effects. For example, navigation dams on the Illinois River reduce peak flows that provide nursery grounds for native fishes and create non-seasonal

summer flows that reduce success of native fishes (Koel and Sparks, 2002).

Low flows create ecological "bottlenecks" that reduce available habitat and buffering from atmospheric processes, such as heat transfer. Accordingly, water quality conditions are strongly associated with low flow conditions, and elevated mortality among aquatic species is common during extremely low flows (Lake, 2000). Many streams, however, naturally have prolonged low flow periods to which native species are adapted (Lake, 2000), e.g., in terms of reproductive timing (King et al., 2003). Alteration of natural low flows can create conditions unfavorable to native species but favorable to non-natives. For example, dams typically elevate low flows and may provide the perennial flows needed by non-native fishes in arid lands (Marchetti and Moyle, 2001), and may raise alluvial water tables under floodplains to modify riparian vegetation (Sparks, 1995). Reduced flows resulting from groundwater pumping in agricultural and urban watersheds in the SW can lead to a conversion of hydric plant species to mesic species (Stromberg et al., 2005) or loss of cottonwood gallery forests (Scott et al., 1998).

Interestingly, dams show a strong increase in flow durations for all regions except in the SE (Table 4). Such increases in sub-bankfull flows can increase the cumulative transport of available fine materials, but because of reduced peak flows can decrease the transport of larger sediment. This could lead to bed armoring, which often has negative ecological consequences for invertebrates and fish (Allan, 1995).

In this analysis, flow variability represents daily changes in stream stage, which is an indicator of the disturbance regime, a key organizer of stream ecosystem structure and function. Flow variability increases relatively consistent in agricultural and urbanizing streams relative to regional references (see CVD and T_{Qmean} in Table 5). Increased disturbance selects for shorter-lived, more weedy invertebrates in both non-urban (Scarsbrook and Townsend, 1993; Richards et al., 1997; Robinson and Minshall, 1998) and urban (Kennen, 1999; Paul and Meyer, 2001) settings. Similarly, more variable streams are characterized by more generalist and tolerant fish in agricultural (Poff and Allan, 1995) and urban (Morgan and Cushman, 2005; Roy et al., 2005) settings.

Flashiness in urban streams is also associated with decreased retention of organic matter and nutrients (Meyer et al., 2005). Where stream morphology is simplified, transient storage zones in the channel may be lost, thereby reducing the capacity of the stream to metabolize and transform dissolved nutrients (e.g., Haggard et al., 2002). The term "urban stream syndrome" has emerged (Meyer et al., 2005; Walsh et al., 2005) to describe the suite of hydrologic, geomorphic, and biological degradations associated with these highly disturbed systems.

Dams, by contrast, generally reduce flow variability and stabilize flow regimes. Some dams, however, clearly do increase flow variation, particularly storage hydroelectric dams that modify downstream river stage rapidly in response to electrical demand on an hourly basis. Such dams, although not analyzed in this study, would appear to create conditions similar to highly flashy urban streams, and they have many significant ecological effects (see Poff et al., 1997).

Overall, the hydrologic (and likely the geomorphic) effects of >15% imperviousness exceed those associated with a >25% agricultural land cover, but this observation obviously requires additional research. Agricultural development clearly leads to extensive habitat degradation and biotic impairment (Roth et al., 1996; Allan, 2004). Of course, in many watersheds, a mixture of types of land cover occurs and the specific "cause" of biological impairment is not clear (Allan, 2004). Some researchers have recently suggested, however, that urban streams, with headwaters in non-urban settings (mix of agriculture and forest), have a higher potential for rehabilitation than urban streams lacking headwater areas (Moore and Palmer, 2005).

6. Prospectus for a national assessment of land-use effects on stream hydrology, geomorphology and ecology

Clearly, hydrologic alteration is ubiquitous across the United States in response to human land use practices, including dams. These changes, in conjunction with associated alteration of sediment budgets, imply extensive and significant modifications of the physical structure and dynamics of stream channels, and by direct extension, profound ecological "adjustments" to new (and evolving) fluvial environments. This exploratory analysis of the variability of the four focus regions underscores the importance of interpreting the effects of land use types in the context of region-specific histories, hydrologic processes, and channel sensitivities.

At present, developing an even rudimentary understanding of the implications of variations in land use on hydrogeomorphic processes and ecological functions is a daunting challenge in an area with greater than 2,000,000 km^2 of agricultural land (28% of the conterminous US), combined impervious areas equaling the size of Ohio (Elvidge et al., 2004), and over 75,000 dams exceeding 2 m in height (Graf, 1999). Developing such an understanding will require region-specific mixes of

historical, associative, and process studies (Jacobson et al., 2001). Based on our experiences in this study, we believe that fundamental barriers and exciting opportunities exist for innovation toward this end.

First, basic limitations in existing monitoring networks must be overcome before significant progress can occur towards assessing the scope of impacts from land use on US streams. Continuous streamflow gauges are heavily biased toward relatively large streams and rivers: 95% of streams have less than 3% of the gauges and over 93% of stream length is represented with less than 1/3 of gauges (Fig. 3). The growing recognition of the ecological and water quality functions of headwater streams (Brinson, 1993; Meyer and Wallace, 2001; Peterson et al., 2001) suggests that the dearth of gauges in these systems is fundamentally limiting our capacity to understand and mitigate the effects of land use change. Greater representation of small streams in gauging networks could also accelerate development of improved models for prediction in ungauged basins. In the absence of more gauging on numerous small streams, more effective modeling tools need to be developed (National Research Council, 2004) to simulate streamflow under a range of land covers in different hydroclimatic and geologic contexts.

Second, understanding the geomorphic and ecological implications of land-use changes will require analysis of the scale-dependent dispersion of land-use impacts. As a simple example, we analyzed land cover in 18,979 watersheds of two sizes throughout the study regions using flow accumulation grids generated from 30-m DEMs. 5-km^2 watersheds were delineated to roughly approximate 1st to 2nd order streams (Leopold et al., 1964), and 85 km^2 watersheds were delineated to represent the median size of watersheds for all USGS gauges less than 282 km^2. We found that each of the four regions has a unique distribution signature for land cover in watersheds of different scales (Table 6). For example, urbanization tends to be focused in broad valley floors and floodplains in the SW (Graf, 1988) and is, therefore, seven times less prevalent in 4th order and smaller watersheds than it is in the region as a whole. In contrast, urban land cover is 2.3 times higher in headwater catchments of the SE compared to the entire region. Although we did not evaluate the scale sensitivity of different hydrologic metrics in this study, doing so would be necessary to more accurately characterize the effects of land use at broad scales.

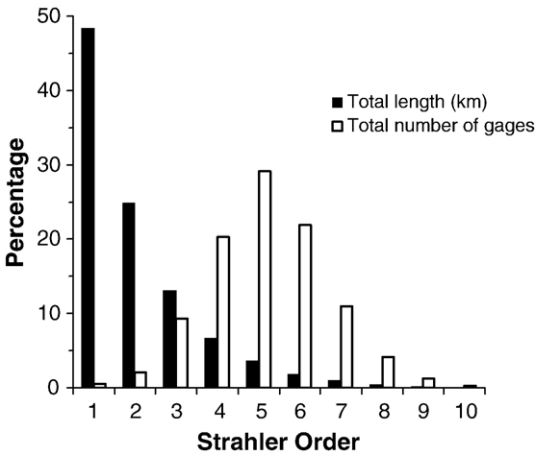

Fig. 3. Histogram showing contribution of streams of different size to percentage of total stream length and total number of USGS gauges in the conterminous United States. Stream size is approximated from a drainage area to Strahler Order relationship (1: 24,000 map scale) from Leopold et al. (1964).

Table 6
Summary of GIS analysis to determine land use cover at three spatial scales in each of four geographic regions in the U.S.

Region	Land use	Spatial scale		
		% of 5 km^2 watersheds	% of 85 km^2 watersheds	% land cover hydroregion
SE	Urban	13.6	5.7	6.1
	Agriculture	35.7	39.9	21.9
	Least disturbed	50.7	54.4	72.0
CE	Urban	2.9	2.5	2.3
	Agriculture	92.6	88.7	76.3
	Least disturbed	4.5	8.8	21.5
NW	Urban	10.1	15.5	7.5
	Agriculture	11.6	10.3	7.4
	Least disturbed	78.3	74.1	85.1
SW	Urban	1.0	1.1	6.6
	Agriculture	2.0	3.2	1.9
	Least disturbed	97.0	95.8	91.5

Values reported for the 5 km^2 and 85 km^2 scales are based on random selection of ca. 20% of all possible watersheds in each region (total # watersheds analyzed were 18 335 for 5 km^2 and 644 for 85 km^2).

Third, we restricted our analysis to watersheds primarily of a single type of land use; however, most watersheds have mixed land uses, and varying human controls of flow. For example, approximately 2.6 million ponds exist in the conterminous US that represent a major sediment sink in many mixed land use basins (Renwick et al., 2005). Key questions include: how do these different sources of alteration interact? Can synergistic effects be identified, diminished or even reversed? How can the effects of individual land uses be aggregated at the scale of a whole basin with mixed land use? How do we assess the downstream and upstream extent of dam impacts across large geographic regions? Such questions may be best addressed through long-term studies or observatories in basins with nested watersheds of mixed land use and with ample streamflow gauges throughout, including in the headwaters.

Fourth, we believe that the associative relationships between gross measures of land use and ecological metrics that are frequently used in management must be carefully calibrated to different hydrogeomorphic settings. For example, imperviousness of a watershed on the order of 5–20% clearly has the potential to severely destabilize streams, but changes in stream power and sediment delivery associated with suburban and urban development are highly context-specific. It is clear why a simple, quantitative delineation of a threshold between healthy and unhealthy streams is very desirable from a management perspective, but we should avoid "one size fits all" thresholds that may jeopardize more sensitive streams (Booth, 2005).

Finally, we believe rapid improvements in the availability of high-resolution geospatial data will facilitate mapping of geomorphic drivers and contexts (e.g., channel types, instream and riparian habitats, wood recruitment potential) across large regions (Marcus et al., 2003; Flores et al., 2006) and, thereby, improve understanding of regional vulnerability to land use change and potential for restoration.

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