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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

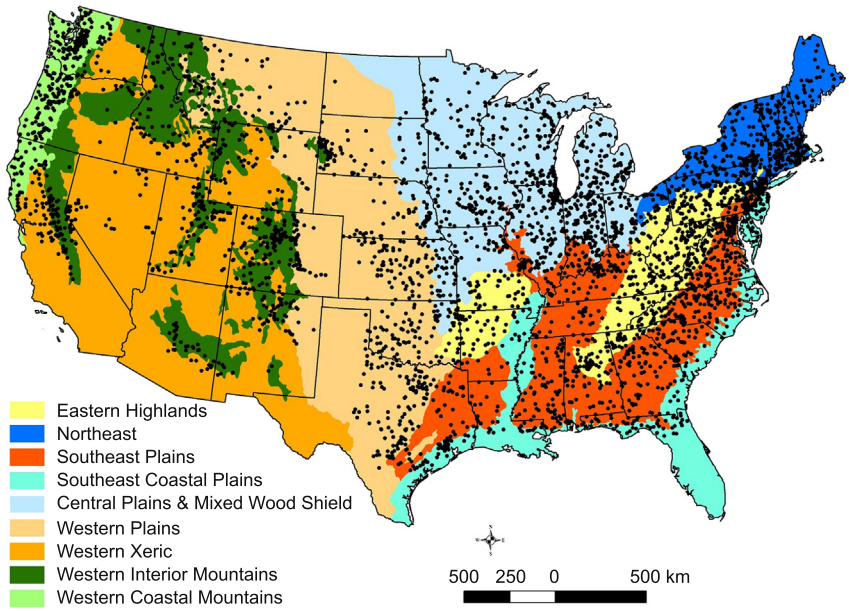

Fig. 1. Black dots represent USGS stream gauges on the 4196 gauged rivers used in this study.

model for natural low flows, which predicted within 15% of observed values. This lower performance was deemed acceptable given the notorious difficulty in predicting low-flow attributes in streams (e.g., Eng and Milly, 2007).

The association between flow changes (i.e., deviation of observed flow from estimated natural conditions) and LWMP variables was explored with RF regression with 500 individual trees using a Matlab application (by Jaiantilal, 2009, available at http://code.google.com/p/randomforest-matlab/). For any pair of LWMP variables with a Spearman rank correlation value greater than |0.5|, one of the variables was excluded from the analysis. The overall performance of RF models was evaluated using the percent of variance explained. A percent variance explained of at least 40% was defined as the threshold for which the RF models would be considered interpretable for this study. This threshold was determined by visual inspection of a histogram of percent variance explained of all 54 models.

The relative importance of LWMP variables (among those considered in this study) was evaluated using the increase in node purity values (Hastie et al., 2009). The increase in node purity was measured by the mean decrease in the mean squared error of the RF model that results when each LWMP variable was, in turn, randomly permuted. The LWMP variables were ranked in descending order, and the

Table 1
List of 13 land and water management practices from Falcone (2011).

Land and water management practice	Units	Description
CHP	%	Percent of land cover in watershed that changed between early 1990s and early 2000s (regardless of type of change), according to NLCD01 "change product".
PC1	%	Percent watershed in Protected Areas Database (PAD) Category 1 (GAP status 1): "most protected lands": Areas managed to maintain a natural state and within which natural disturbance events are allowed to proceed without interference. Primarily: National Park, National Monument, Wilderness Area, Nature Reserve/Preserve, Research Natural Area.
PC2	%	Percent watershed in PAD Category 2 (GAP status 2): (somewhat less protected than Cat 1). Areas generally managed for natural values, but which may receive uses that degrade the quality of existing natural communities. Primarily: State Parks, State Recreation Areas, National Wildlife Refuge, National Recreation Area, Area of Critical Environmental Concern, Wilderness Study Area, Conservation Easement, Private Conservation Land, National Seashore.
AGR	%	Watershed percent "agriculture", 2001 era.
IRR	%	Watershed percent irrigated agriculture.
NPD	No. of sites/100 km^2	Density of NPDES (National Pollutant Discharge Elimination System) "major" point locations in watershed. Major locations are defined by an EPA-assigned major flag. From download of NPDES national database summer 2006.
RDS	km/km^2	Road density from Census 2000 TIGER roads.
NDM	No. of dams	Number of dams in watershed, from our enhanced version of the 2006 National Inventory of Dams (NID).
DDS	No. of dams/100 km^2	Dam density.
MDM	No. of dams	Number of "major" dams in watershed. Major dams defined as being $\geq$ 50 ft in height (15 m) or having storage $\geq$ 5000 acre ft (National Atlas definition).
MDS	No. of dams/100 km^2	Major dam density.
STO	Ml/km^2	Dam storage in watershed (1 Ml = 1,000,000 l = 1000 m^3).
STI	years	Average residence time of annual runoff held in storage behind dams.

Table 2
Performance of flow-LWMP (land and water management practices) relations. Node impurity values for each LWMP were calculated as percentage of largest node impurity value for each relation. **Bold** text and values indicate interpretable relations (percent variance explained at least 40%). The shading indicates the relative importance among LWMP.

Annual maximum Ecoregion	Percent variance explained (%)	LWMP												
		CPT	PC1	PC2	AGR	IRR	NPD	RDS	NDM	DDS	MDM	MDS	STO	STI
Central Plains & Mixed Wood Shield	**58**	**70**	**18**	**55**	**59**	**62**	**26**	**100**	**60**	**86**	**68**	**77**	**47**	**59**
East Highlands	**47**	**36**	**18**	**20**	**47**	**22**	**23**	**100**	**36**	**34**	**45**	**32**	**64**	**58**
Northeast	**48**	**42**	**17**	**25**	**40**	**25**	**20**	**37**	**50**	**32**	**43**	**57**	**100**	**88**
Southeast Coastal Plains	**61**	**21**	**5**	**32**	**22**	**14**	**62**	**100**	**19**	**9**	**1**	**2**	**9**	**7**
Southeast Plains	**58**	**30**	**22**	**14**	**31**	**16**	**25**	**79**	**100**	**19**	**37**	**33**	**23**	**22**
Western Coastal Mountains	**45**	**50**	**27**	**30**	**22**	**12**	**1**	**56**	**32**	**37**	**33**	**40**	**57**	**100**
Western Interior Mountains	39	75	62	52	81	33	11	100	70	53	60	51	35	61
Western Plains	**55**	**41**	**6**	**16**	**51**	**71**	**12**	**100**	**57**	**60**	**16**	**31**	**38**	**71**
Western Xeric	**40**	**50**	**35**	**68**	**100**	**9**	**8**	**75**	**30**	**31**	**5**	**38**	**35**	**66**

Average May flow Ecoregion	Percent variance explained (%)	LWMP												
		CPT	PC1	PC2	AGR	IRR	NPD	RDS	NDM	DDS	MDM	MDS	STO	STI
Central Plains & Mixed Wood Shield	**47**	**51**	**14**	**17**	**90**	**41**	**36**	**100**	**23**	**49**	**7**	**15**	**26**	**37**
East Highlands	23	36	14	21	43	30	20	100	21	25	9	22	21	20
Northeast	27	81	42	43	81	57	28	83	33	56	13	35	65	100
Southeast Coastal Plains	**51**	**41**	**7**	**7**	**31**	**18**	**100**	**66**	**5**	**6**	**1**	**1**	**7**	**7**
Southeast Plains	25	83	7	14	100	14	18	92	21	16	3	4	20	24
Western Coastal Mountains	14	65	51	32	27	16	5	100	13	43	12	44	37	69
Western Interior Mountains	23	69	46	57	52	23	16	100	46	51	36	35	49	74
Western Plains	**57**	**42**	**10**	**16**	**42**	**40**	**18**	**69**	**27**	**100**	**10**	**42**	**43**	**55**
Western Xeric	33	64	33	81	98	28	7	100	52	36	10	77	53	70

Average July flow Ecoregion	Percent variance explained (%)	LWMP												
		CPT	PC1	PC2	AGR	IRR	NPD	RDS	NDM	DDS	MDM	MDS	STO	STI
Central Plains & Mixed Wood Shield	33	54	22	19	86	51	46	100	53	40	12	21	24	26
East Highlands	37	30	13	15	30	13	45	100	12	18	5	12	29	32
Northeast	13	83	37	40	73	33	40	100	46	72	39	60	77	69
Southeast Coastal Plains	**54**	**41**	**3**	**8**	**35**	**15**	**100**	**62**	**3**	**4**	**1**	**1**	**5**	**6**
Southeast Plains	19	32	1	5	96	6	10	100	8	12	2	4	13	11
Western Coastal Mountains	<10	16	9	5	4	3	1	100	3	5	2	4	8	6
Western Interior Mountains	<10	100	44	37	31	12	7	94	29	30	23	34	73	41
Western Plains	**50**	**58**	**8**	**38**	**48**	**45**	**21**	**100**	**30**	**67**	**17**	**31**	**53**	**59**
Western Xeric	<10	20	20	22	30	12	3	52	12	19	8	100	100	38

Average November flow Ecoregion	Percent variance explained (%)	LWMP												
		CPT	PC1	PC2	AGR	IRR	NPD	RDS	NDM	DDS	MDM	MDS	STO	STI
Central Plains & Mixed Wood Shield	**44**	**39**	**11**	**20**	**37**	**20**	**52**	**100**	**20**	**21**	**6**	**9**	**17**	**19**
East Highlands	27	42	15	35	46	16	48	100	16	35	12	19	20	20
Northeast	23	62	28	51	79	24	17	100	29	38	15	30	65	89
Southeast Coastal Plains	**49**	**33**	**3**	**9**	**24**	**15**	**100**	**47**	**3**	**5**	**1**	**1**	**8**	**8**
Southeast Plains	25	21	2	5	100	10	19	91	22	15	4	5	17	19
Western Coastal Mountains	21	85	72	38	36	26	5	100	20	39	14	32	58	66
Western Interior Mountains	23	72	77	51	51	30	13	100	21	35	27	35	41	57
Western Plains	**52**	**51**	**3**	**19**	**33**	**41**	**17**	**100**	**23**	**57**	**7**	**24**	**32**	**60**
Western Xeric	24	69	55	67	100	30	10	70	46	30	16	70	46	75

Low flow Ecoregion	Percent variance explained (%)	LWMP												
		CPT	PC1	PC2	AGR	IRR	NPD	RDS	NDM	DDS	MDM	MDS	STO	STI
Central Plains & Mixed Wood Shield	20	36	40	35	33	18	99	100	44	23	14	14	17	14
East Highlands	39	31	12	38	44	22	67	100	18	27	10	15	30	27
Northeast	33	84	58	42	81	29	46	100	56	68	97	72	77	63
Southeast Coastal Plains	37	18	1	3	18	12	100	50	3	5	0	1	3	4
Southeast Plains	13	62	6	11	99	14	47	100	21	26	6	18	26	27
Western Coastal Mountains	11	54	36	44	27	19	4	100	20	32	22	41	67	65
Western Interior Mountains	16	89	77	81	49	24	13	100	27	42	22	34	45	48
Western Plains	25	100	9	42	45	50	59	99	57	67	27	39	61	75
Western Xeric	22	21	14	35	25	12	12	41	21	20	15	80	100	41

variables associated with the largest node purity values were considered the most important factors influencing flow changes. The overall performance of the flow-LWMP relations was quantified as the percent of variance explained by the relation. Node purity values were expressed as a percentage of the largest value for each relation, thereby normalizing the numerical scale from 0 to 100 and facilitating comparisons among different flow metrics and ecoregions.

Partial dependency plots (PDPs, Hastie et al., 2009; Cutler et al., 2007; Friedman, 2001) were used to interpret the relation between flow changes and each of the most important LWMP predictors.

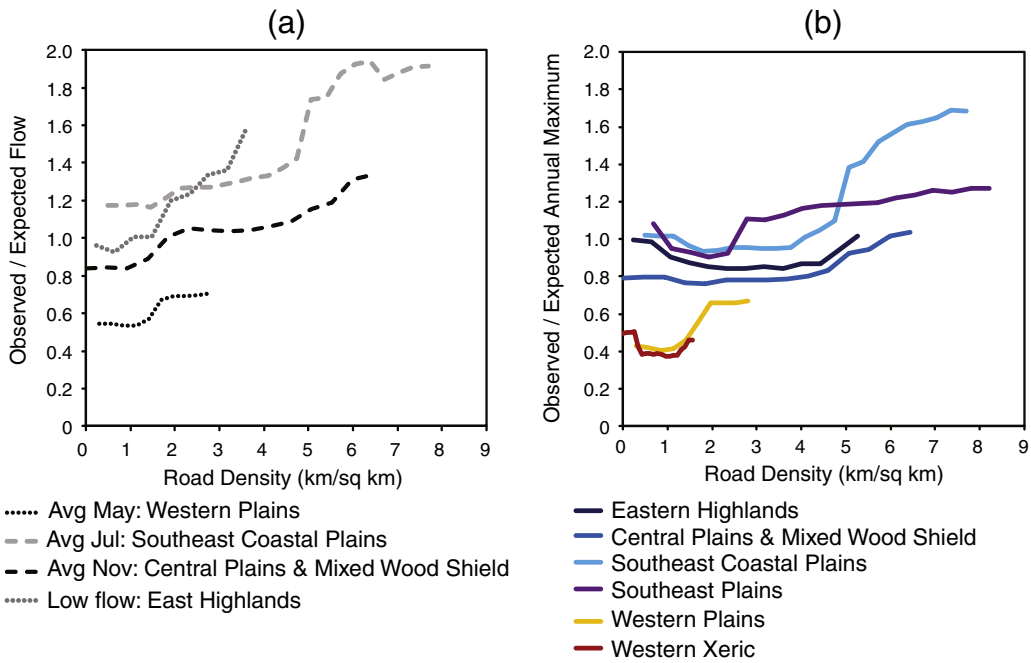

Fig. 2. PDP (partial dependency plot) for road density and flow changes. (a) Average monthly flows and low flow and (b) annual maximums. The vertical axes account for the joint effects of the other LWMP and represent a spatial average over all watersheds within an ecoregion.

PDPs depict the effect of a specific predictor variable (i.e., LWMP) on the dependent variable (i.e., flow change) after accounting for the average joint effects of all other predictor variables. The PDPs were constructed by fixing one LWMP to a single value and then computing the average of the flow-LWMP effects for all combinations of observed values from the remaining LWMP variables. This process was then repeated for other fixed values of the LWMP of interest to include the entire range of the selected LWMP. For PDPs, the LWMP values were plotted on the horizontal axis and the change in the flow metric, expressed as a ratio, was plotted on the vertical axis. Only the interpretable relations (i.e., those from models with explained variance of at least 40%) were interpreted and discussed.

4. Results and discussion

4.1. Performance of models relating flow changes and LWMP

Model performance ranged from <10 to 61% of variance explained, and varied substantially among flow metrics and ecoregions (Table 2). The changes to annual maximum flow were interpretable (i.e., at least 40% explained variance) for all but one ecoregion. Changes to the average monthly flows were interpretable in up to three ecoregions. Changes to low flows were marginally interpretable (percent variance explained = 39%) in the Eastern Highlands, but will be discussed further in order to provide some illustration of the effects of LWMP on low flows. Possible causes of this poor performance were the high uncertainty of predicting a 7-day low flow at natural rivers, and the absence of appropriate climate and geologic predictor variables (Kennard et al., 2010).

An important caveat of the interpretation of the model results was that roughly 50% of variance remained unexplained in many of the models. Ecoregions with the largest number of interpretable models were the Central Plains and Mixed Wood Shield, the Southeast Coastal Plains, and the Western Plains. None of the models were interpretable in the Western Interior Mountains. For the Northeast, Western Coastal Mountains, and Western Xeric ecoregions, only models for changes to the annual maximums were interpretable.

4.2. Road density and flow changes

RDS was the most important predictor of flow change for most flow metrics and ecoregions (Table 2). It was uniformly associated with increases in flow above the natural condition for all types of flow metrics. This result suggests that landscape changes associated with increasing RDS, such as increased impervious area and urban development, were major drivers of flow changes in many different environmental settings. This finding was consistent with prior studies that have investigated land-use effects on flows (Poff et al., 2006; Steuer et al., 2010).

The association between increases in monthly flows and road density (e.g., Fig. 2a) has been attributed to several causes, including increases in groundwater recharge and baseflow (Wang and Cai, 2010; Garcia-Fresca, 2007; Brandes et al., 2005; Garcia-Fresca and Sharp, 2005; Berg et al., 1996), urban irrigation (Hibbs and Sharp, 2012), leaky water infrastructure (Hibbs and Sharp, 2012; Lerner, 2002), and slow releases of storm-flow from detention ponds (Liu et al., 2013). RDS also may increase flows through the rapid conveyance of water to streams as runoff over roads and through storm sewers during precipitation events. Although prior studies indicate increases in baseflow associated with increases in urbanization, other work has suggested decreases in recharge and baseflow due to urbanization (e.g., Jeppesen et al., 2011; Rose and Peters, 2001; Knipe et al., 1993).

The pattern of increases in annual maximums due to RDS observed in our study (Fig. 2b) was consistent with the relations between urbanization and high flows reported by others (Rose and Peters, 2001; Konrad and Booth, 2002; Poff et al., 2006). The increase in annual maximums was most likely caused by the increased extent and connectedness of impervious areas associated with higher levels of road density.

In many studies, urbanization has been shown to increase flow magnitudes and decrease response time to precipitation events in highly urbanized watersheds (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). In our study, we found that annual maximums decreased in many ecoregions at low RDS values before increasing

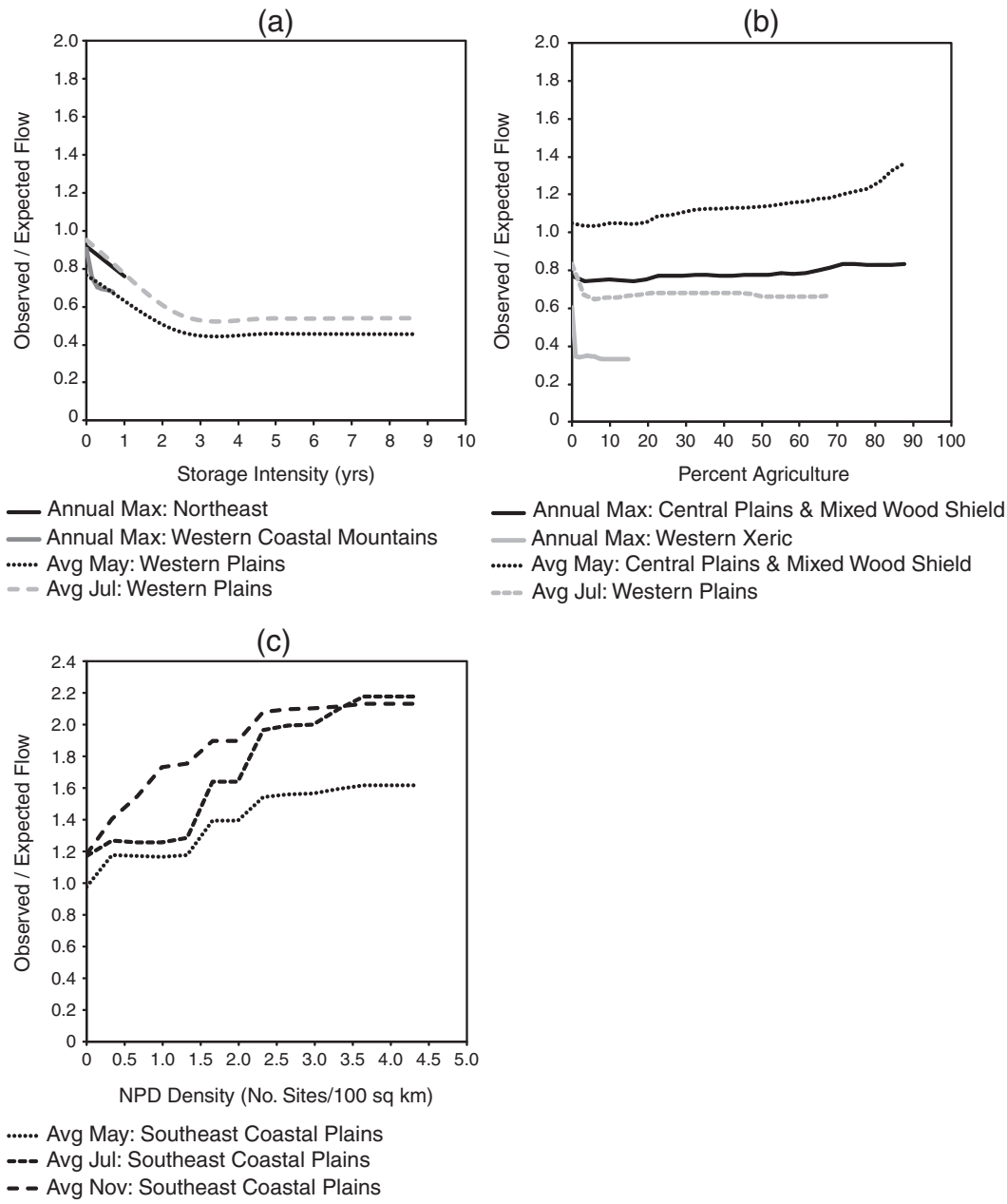

Fig. 3. PDP (partial dependency plot) for different flow change LWMP relations (land and water management practices). (a) Dams (storage intensity) and flow change, (b) agriculture and flow change, and (c) NPD and flow change (the density of National Pollutant Discharge Elimination System point locations in a watershed). The vertical axes account for the joint effects of the other LWMP and represent a spatial average over all watersheds within an ecoregion.

at higher RDS values (Fig. 2b). Decreases in 2-year floods were also found in 12% of watersheds analyzed by Sauer et al. (1983). The watersheds in the Sauer et al. (1983) study were identified as having detention storage; however, it was unclear if the decreases in 2-year floods were occurring at an increasing rate in less developed watersheds compared to the more developed ones. Our study suggests that in low RDS watersheds, some type of widespread storage/flow detention mechanisms may be responsible for the observed decreases in the annual maximums in some ecoregions, such as culverts with insufficient capacity, storm-water inlets, parking lots, on streets, on rooftops, and in basements, and/or a difference in urbanization in different portions in the watershed (Paul and Meyer, 2001; Hirsch et al., 1990).

The low-flow models generally were poor, so caution should be taken in interpreting the relations between RDS and low flows. These results (Fig. 2a) indicated that RDS was related to increases in low flow. This outcome was consistent with several other studies that found that increases in baseflows were due to leaky infrastructure, urban irrigation, or releases from storm-water detention ponds (Wang and Cai, 2010; Garcia-Fresca, 2007; Brandes et al., 2005; Garcia-Fresca and Sharp, 2005; Berg et al., 1996; White and Greer, 2006) but contrary to findings in other research (Konrad and Booth, 2002; Poff et al., 2006).

The prominence of RDS as a predictor of flow changes in all ecoregions was somewhat surprising because the extent of land development was minimal within some of the regions. For example, the 95th percentile values of highly developed land in the Western Plains and Eastern Highlands regions were only 1.1 and 1.5%, respectively. These regions as well as others would be considered mostly rural areas, yet the effects of RDS on flows were clear.

4.3. Dams and flow changes

Indicators representing dams and reservoirs were important predictors of flow changes in 6 of 9 regions (Table 2). Dams were most commonly associated with changes to annual maximums and were among the most important predictors of flow changes in the Northeast, Western Coastal Mountains, Western Plains, Southeast Plains, and Central Plains & Mixed Wood Shield. Dams were also associated with changes in the May and November flows in the Western Plains. The prevalence of flow changes associated with dams has been shown in many previous studies (e.g., Biemans et al., 2011; Zimmerman et al., 2010; Pyron and Neumann, 2008; Poff et al., 2007, 2006; Nilsson et al., 2005; Yang et al., 2004; Ye et al., 2003).

In general, increasing density of dams or reservoir storage was associated with reductions in flows relative to natural conditions (Fig. 3a). This was consistent with other studies that reported reduced annual maximums related to dams (Poff et al., 2006, 2007). The decrease in average May and July flows observed in the Western Plains was consistent with the findings for North America by Biemans et al. (2011), and suggests that flow during spring and fall was being retained in reservoirs or used consumptively (or both) in this region. Watersheds in the Western Plains also have the highest cumulative reservoir storage—relative to average flows—compared to all other regions (Table 3), which may explain why associations between dams and reduced monthly flows were so apparent in this region.

The effects of dams and reservoirs on changes to flows were probably underestimated in this study. Dams and reservoirs are known to influence many components of the flow regime (e.g., Poff et al., 2007, 2006), only some of which were detected in this study. Dams and reservoirs operate in diverse ways (Poff and Hart, 2002) that are not well represented in the nationally consistent databases (such as the National Inventory of Dams) that are available. Variability in dam operation goals, and lack of predictor variables to quantify the effects of dam operation strategies, likely resulted in unexplained variation in flow changes and the inability of models to detect some effects of dams and reservoirs.

4.4. Agriculture and flow changes

Indicators of agriculture were associated with flow changes in some regions (Table 2). The percent of watershed in agricultural land was the leading predictor of changes in the annual maximum in the Western Xeric ecoregion, and it was a secondary predictor of change in the May flow in the Central Plains and Mixed Wood Shield. The percent of watershed in irrigated agriculture was among the most important predictors of changes in the annual maximum in the Western Plains.

Agricultural land use and associated water-management practices are known to have major influences on flows in many regions (Wang and Cai, 2010; Zhang and Schilling, 2006), but discerning those effects was complicated by several factors. First, current estimates of water uses such as irrigation were crude and rarely differentiate between consumptive (e.g., evaporation) and non-consumptive (e.g. irrigation return flows) uses. Flows in agricultural settings were therefore often composed of natural flows that have been depleted by upstream diversions, but also augmented by irrigation return flows. Second, agricultural-based water management such as storage reservoirs and diversions were often geographically distinct—but connected—from the regions where the water was used. This phenomenon was especially common in the western U.S., where much of the irrigation water used in the arable Xeric lowlands was stored, diverted, and delivered from mountainous areas where snow packs can accumulate. In these situations, flow changes in Xeric regions would be more strongly associated with water management in the adjacent mountainous regions than in the Xeric regions themselves.

Table 3
Predictor ranges used in the random forests. CPT was the percent of land cover change, PC1 was the percent of watershed in the Protected Areas Database Category 1, PC2 was the percent of watershed in the Protected Areas Database Category 2, AGR was the percent agriculture in the watershed, IRR was the percent irrigation in the watershed, NPD was the density of National Pollutant Discharge Elimination system point locations in a watershed, RDS was the road density, NDM was the number of dams in a watershed, DDS was the dam density, MDM was the number of major dams in a watershed, MDS was the major dam density, STO was the dam storage in a watershed, and STI was the storage intensity.

Ecoregion	No. of USGS stream gauges	Land and water management practice																							
		CPT		PC1		PC2		AGR		IRR		NPD		RDS		NDM		DDS		MDM		MDS		STO		STI	
		Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%	Min	95%
Central Plains & Mixed Wood Shield	800	0.0	7.6	0.0	1.4	0.0	6.9	0.0	88.3	0.0	6.8	0.0	0.6	0.0	6.5	0.0	170.0	0.0	5.4	0.0	21.0	0.0	0.4	0.0	275.0	0.0	1.2
East Highlands	529	0.0	6.6	0.0	12.5	0.0	15.9	0.0	55.5	0.0	0.6	0.0	0.7	0.2	5.2	0.0	133.0	0.0	5.4	0.0	31.0	0.0	1.6	0.0	429.3	0.0	0.9
Northeast	492	0.0	5.1	0.0	20.9	0.0	34.5	0.0	45.8	0.0	0.6	0.0	0.9	0.0	4.6	0.0	129.0	0.0	11.6	0.0	23.0	0.0	1.3	0.0	591.0	0.0	1.0
Southeast Coastal Plains	108	0.1	17.6	0.0	10.3	0.0	12.8	0.0	82.4	0.0	50.1	0.0	4.3	0.5	7.6	0.0	15.0	0.0	5.3	0.0	2.0	0.0	0.6	0.0	199.5	0.0	0.3
Southeast Plains	766	0.0	13.7	0.0	3.3	0.0	4.3	0.0	65.5	0.0	2.5	0.0	0.8	0.7	8.2	0.0	356.0	0.0	8.6	0.0	23.0	0.0	0.7	0.0	532.5	0.0	1.4
Western Coastal Mountains	253	0.0	7.9	0.0	73.2	0.0	41.6	0.0	11.2	0.0	4.1	0.0	0.1	0.0	2.5	0.0	23.0	0.0	1.3	0.0	8.0	0.0	0.7	0.0	712.0	0.0	0.7
Western Interior Mountains	720	0.0	8.2	0.0	82.5	0.0	53.1	0.0	9.4	0.0	10.7	0.0	0.2	0.0	1.9	0.0	73.0	0.0	2.8	0.0	22.0	0.0	1.3	0.0	635.0	0.0	3.5
Western Plains	401	0.0	9.5	0.0	1.5	0.0	5.1	0.0	66.6	0.0	16.9	0.0	0.1	0.3	2.8	0.0	431.0	0.0	7.3	0.0	35.0	0.0	0.9	0.0	638.0	0.0	8.6
Western Xeric	127	0.0	4.3	0.0	23.5	0.0	62.0	0.0	15.2	0.0	17.4	0.0	0.1	0.0	1.5	0.0	123.0	0.0	1.4	0.0	23.0	0.0	0.4	0.0	370.0	0.0	2.8
Total no.	4196																										

The relationships between agricultural indicators and flow changes were intuitive and consistent (Fig. 3b). Increasing agricultural land cover in watersheds was associated with increased average May flow in the Central Plains and Mixed Wood Shield ecoregions, which were areas of extensive row crop production (Fig. 3b). Increases in the average May flow were also found by Zhang and Schilling (2006), who hypothesized that conversion of perennial vegetation to seasonal row crops decreased evapotranspiration and surface runoff, which increased recharge, baseflow, and thus flow during the early growing season. In the Western Xeric region, there was a sharp decrease in the annual maximum as agriculture increased (Fig. 3b). This result could be due to the substantial amounts of groundwater pumping and diversions used for irrigation in agricultural areas close to rivers (e.g., Webb and Leake, 2006; Pitt, 2001).

4.5. Wastewater discharge and flow changes

Wastewater discharges (NPD) were unrelated to flow changes in most regions (Table 2), but they were the primary predictor of monthly flow changes in the Southeast Coastal Plains and among the important predictors of changes to low flows in the Eastern Highlands. In the Southeast Coastal Plains, increases in the density of NPD were associated with inflated (relative to natural conditions) monthly flows (Fig. 3c). This result suggests that wastewater discharge comprises a significant portion of monthly flows in the Southeast Coastal Plains. This supposition was evaluated using a data set of wastewater discharges compiled by US Environmental Protection Agency permit compliance system (PCS) database (USEPA, 2006). Monthly PCS discharge values were arithmetically averaged for watersheds above all stream sites within the Southeast Coastal Plains ecoregion and subsequently compared to the observed monthly flows. Wastewater discharges comprised 10 to 40% of the total observed flows, which is consistent with Glassmeyer et al. (2005) who found that wastewater discharges comprised a large portion of flow in some watersheds in this region.

The effect of wastewater discharge on flow can be complicated by storm-water management practices. The NPD does not distinguish contributions from wastewater discharges, storm-water additions due to combined sewer overflows, and slow-released flows from storm-water detention ponds. In addition, a river can have the appearance of increasing flows due to natural flows being depleted upstream then augmented downstream by wastewater and/or storm-water discharges.

5. Conclusions

There has been extensive literature examining the independent effects of LWMP on flow changes, but there have been few, if any, studies examining the net effect of multiple LWMP on flow changes across a wide spatial scale. The analysis presented herein was made possible by using a nationally consistent method to characterize flow changes. This study has identified major causes of flow changes among different competing LWMP in watersheds and identified those that were regional causes of the flow changes, such as roads and dams, and those that were more localized, such as agriculture, and wastewater discharges. It also was found that the changes to flows were prevalent even at low levels of road densities. However, often more than half of the variation in the models was unexplained by the LWMP variables used in this study, indicating that much more research is required to fully understand how LWMP affect flows. However, our results on LWMP-flow relations were consistent with the findings in several studies that presumed the dominant LWMP in watersheds.

Conflict of Interest

None of the authors have a conflict of interest.

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