Severity and Extent of Alterations to Natural Streamflow Regimes Based on Hydrologic Metrics in the Conterminous United States, 1980–2014

Scientific Investigations Report 2019–5001

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey, Reston, Virginia: 2019

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Suggested citation:
Eng, K., Carlisle, D.M., Grantham, T.E., Wolock, D.M., and Eng, R.L., 2019, Severity and extent of alterations to natural streamflow regimes based on hydrologic metrics in the conterminous United States, 1980–2014: U.S. Geological Survey Scientific Investigations Report 2019–5001, 25 p., https://doi.org/10.3133/sir20195001.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)

Abbreviations

EHM	estimated natural hydrologic metric
HM	hydrologic metric
LWM	land and water management
OHM	observed hydrologic metric
P99	99th percentile
P90	90th percentile
P10	10th percentile
P01	1st percentile
RF	random forest
USGS	U.S. Geological Survey

Severity and Extent of Alterations to Natural Streamflow Regimes Based on Hydrologic Metrics in the Conterminous United States, 1980–2014

By Ken Eng,[1] Daren M. Carlisle,[1] Theodore E. Grantham,[2] David M. Wolock,[1] and Rosaly L. Eng[3]

Abstract

Alteration of the natural streamflow regime by land and water management, such as land-cover change and dams, is associated with aquatic ecosystem degradation. The severity and geographic extent of streamflow alteration at regional and national scales, however, remain largely unquantified. The primary goal of this study is to characterize the severity and extent of alterations to natural streamflow regimes for 1980–2014 based on hydrologic metrics at 3,355 U.S. Geological Survey streamgages in the conterminous United States. Twelve hydrologic metrics with known relevance to aquatic ecosystem health were used to characterize the streamflow regime. Alterations to the 12 hydrologic metrics were quantified by taking ratios of the metrics calculated from observed daily streamflow records divided by the same metrics predicted for natural conditions by random forest statistical models. Some level of streamflow alteration (diminishment or inflation of hydrologic metrics) compared to natural conditions was indicated at about 80 percent of the assessed streamgages across the conterminous United States. The severity of alteration differed among ecoregions because of differences in dominant land and water management practices. Finally, when compared over the period 1980–2014, climate variability generally played a minor role in the alteration of streamflows across the United States when compared to the effects of land and water management.

Introduction

Streamflow (hereafter, flow) alteration is a dominant driver of impairment in aquatic ecosystems in the United States and worldwide. Many studies have documented how changes in stream hydrology caused by land and water management (LWM), such as land-cover change and dams, result in fish population decline, ecosystem degradation, and freshwater biodiversity loss (Bunn and Arthington, 2002; Dudgeon and others, 2006; Carlisle and others, 2010). Yet the nature, severity, and geographic extent of flow alteration at regional and national scales remain largely unquantified despite the existence of a large, long-term streamgage network in the United States.

A major obstacle in quantifying flow alteration is the limited availability of hydrologic data from monitoring sites that have not been substantially altered by human influence (commonly referred to as natural conditions). When flow records are collected prior to substantive human influences (for example, before dam construction), comparison with postdisturbance records provides a strong empirical basis for quantifying flow alteration (for example, Poff and others, 2006). Unfortunately, most monitoring sites lack predisturbance data, and comparison of pre- and postdisturbance records can be confounded by climate and other factors (for example, land-use change).

Alternatively, hydrologic models can predict natural, unimpaired flows for direct comparison with observed flow records. Hydrologic models for predicting natural flows can be mechanistic, statistical, or some combination of both. Mechanistic models explicitly represent the dominant hydrologic processes that control watershed runoff and, therefore, flow. Well-known examples include the Variable Infiltration Capacity (VIC) model (Liang and others, 1994), the Precipitation-Runoff Modeling System (PRMS; Markstrom and others, 2015), and the Soil and Water Assessment Tool (SWAT; Arnold and others, 1998). These models require substantial calibration data and typically have been developed for single-river watersheds rather than large geographic regions. Alternatively, a wide range of statistical modeling approaches have been used for predicting flows, including linear regression (Stedinger and Tasker, 1985) and machine-learning methods (Jeong and Kim, 2005; Carlisle and others, 2016; Eng and others, 2017). Rather than predicting daily flows, however, these models attempt to predict statistics (hereafter, hydrologic metrics [HMs]) derived from daily flows, such as monthly averages or annual 7-day minima.

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Modeled predictions of natural HMs can then be compared to observed HMs calculated from daily flows measured at monitoring stations. This approach avoids the limitations of pre- and postdisturbance flow-alteration studies, but prediction uncertainty can potentially confound estimates of flow alteration and must be considered (Eng and others, 2017).

In this study, we assessed the patterns and degree of flow alteration in rivers and streams across the conterminous United States, focusing on flow regime components that have known relevance to aquatic ecosystem health (Carlisle and others, 2017). We used statistical models to predict the expected natural values of HMs at more than 3,355 streamgages. The predictions were then compared with observed conditions to assess deviation from natural conditions while accounting for model errors by determining if the predictions exceeded the errors (Eng and others, 2017). This assessment extends previous work that used similar methods to quantify flow alteration across the United States (Carlisle and others, 2010; Eng and others, 2017) and to assess the biological relevance of HMs at national and regional scales (Carlisle and others, 2017). Specifically, we assessed alteration of a representative set of HMs that measure distinct attributes of the flow regime (Eng and others, 2017), have known relevance to aquatic ecosystem health (Webb and others, 2013; Carlisle and others, 2017), and are relevant to management and decision making (Kendy and others, 2012).

The purpose of this report is to describe the severity and extent of alterations to natural streamflow regimes for the period 1980–2014 based on hydrologic metrics in the conterminous United States. Specifically, this report (1) describes the degree of flow regime alteration and the geographic distribution at 3,355 streamgages in the conterminous United States, (2) describes associations between flow alteration and types of LWM, and (3) provides a comparison between the relative contributions of climate variability and LWM to flow alteration. A synthesis of results for alterations to natural streamflow regimes also is provided.

Methods

This section of the report describes the methods used assess the severity and extent of alterations to natural streamflow regimes based on hydrologic metrics. The selection and calculation of HMs, quantification of flow alteration for selected streamgages, and quantification of effects of climate variability and LWM are described.

Selection and Calculation of Hydrologic Metrics

Hundreds of HMs have been used to represent the flow regime (for example, Olden and Poff, 2003; Eng and others, 2017), including flow magnitude, variability, frequency, duration, timing, and rate of change. These components can be further partitioned by low- and high-flow dimensions of the flow regime. To identify a comprehensive subset of HMs for this assessment, we considered representation of distinct flow regime components, interpretability, predictability (see Eng and others, 2017), and known empirical associations with indicators of aquatic ecological health (see Carlisle and others, 2017). We identified 12 HMs necessary to quantify flow alteration: 10 are associated with low- and high-flow events (magnitude, variability, frequency, duration, and timing/seasonality), and 2 describe the distributional asymmetry (skewness; hereafter skew) and stochasticity (number of rises) of daily flows (table 1).

Table 1. The 12 hydrologic metrics assessed in this study.

[P01 is the 1st-percentile non-exceedance flow (PNF); that is, 1 percent of daily flows do not exceed this threshold value. Skew is calculated as the third moment of the daily flows. + indicates the hydrologic metric was found to be associated with ecological impairment by Carlisle and others (2017). * indicates the hydrologic metric was not assessed for biological relevance by Carlisle and others (2017). DA, drainage area; CV, coefficient of variation; <, less than; P10, 10th PNF; P99, 99th PNF; >, greater than; P90, 90th PNF]

Hydrologic metric	Description
Low flows	
Magnitude	P01/DA+
Variability	CV of annual minimum daily flows
Frequency	Average annual number of flow pulses < P10+
Duration	Average annual duration of flow pulses < P10
Timing/seasonality	Seasonal distribution of flows < P10*
High flows	
Magnitude	P99/DA+
Variability	CV of annual maximum daily flows+
Frequency	Average annual number of flow pulses > P90
Duration	Average annual duration of flow pulses > P90
Timing/seasonality	Seasonal distribution of flows > P90*
Flow symmetry and stochasticity	
Skew	Average annual skew of daily flows+
Daily rises	Number of days where flow > previous day/total number of days+

All HMs were calculated from daily flow records at each streamgage for 1980–2014 to summarize annual conditions (complete calendar years). The period 1950–2014 was used to assess the effect of climate variability on magnitude, frequency, and duration low- and high-flow HMs, and these HMs were estimated by using random forest (RF) models; daily streamflow records at streamgages were not used (outlined in the section “Quantification of Effects of Climate Variability”). Missing years and years that did not have complete calendar records of streamflow were excluded in the calculations of all HMs. The low- and high-flow magnitudes were calculated as the 1st-percentile (P01) and 99th-percentile (P99) flow values, respectively, divided by drainage area. Such scaling has been used to normalize flow values when there is large variation in the size of drainage area (Henriksen and others, 2006; Sanborn and Bledsoe, 2006; Tague and others, 2008), and use of this scaling has been shown to improve predictability (Eng and others, 2017). Both percentile values were calculated from all daily flow values for the 1980–2014 period. We quantified the low- and high-flow variability HMs by computing the coefficient of variation of the time series of annual minimum (low flows) and maximum (high flows) daily flows for the 1980–2014 period. For the frequency of low and high flows, we calculated the averages of the annual time series of the number of pulses below the 10th-percentile (P10) and above the 90th-percentile (P90) values, respectively. A pulse was defined as a consecutive *n*-day flow event that either was below the threshold (low flows) or exceeded the percentile threshold (high flows). The annual average length of time in days that the flow was below or above a threshold was used to represent the low- and high-flow duration HMs. The skew was calculated as the average of the annual time series of the skew of the daily-flow values. For the daily rises HM, we computed the number of days where the daily flow was greater than the previous day divided by the total number of days in the period (Henriksen and others, 2006).

HMs related to the timing of extreme (low- and high-) flow events have been shown to be ecologically important (Webb and others, 2013). Most studies, however, have quantified the timing of extreme events by using the Julian date of an event’s first occurrence (Richter and others, 1998; Clausen and Biggs, 2000; Olden and Poff, 2003). This approach is problematic for systems where low- and high-flow events occur in multiple periods during a year (that is, multimodal low- or high-flow seasonality). Examples of multimodality include zero-flow events that commonly occur in both winter and fall in the northern Western and Central Plains and nonseasonal ephemeral streams throughout the United States, where extreme flow events can occur in any season (Eng and others, 2016). Therefore, we developed two new seasonality HMs that measure the frequency distribution of extreme low- and high-flow events on a seasonal basis.

The seasonality metrics we used describe the percentages of high- and low-flow events that have been redistributed in 3-month seasons. Our metrics are different from those based on Julian date determinations, such as the day of maximum or minimum flow (Henriksen and others, 2006) and the day when one-half of the flow volume leaves the watershed (center of volume timing; Stewart and others, 2005). Although timing metrics based on Julian dates are intuitive and easily interpretable, they do not account for multiple high- and (or) low-flow events occurring in different portions of the year. These metrics also suffer from poor predictability at ungaged locations (Eng and others, 2017). The new seasonality metrics used in the current study account for multiple events occurring in different portions of the year and are predictable at ungaged locations (Eng and others, 2017). Wavelet analyses (for example, Zolezzi and others, 2009) and Fourier analyses (for example, Ruhi and others, 2016) are other methods that have been used to characterize temporal changes in flows. These methods are often more esoteric and difficult to interpret than simpler measures, such as those based on Julian dates, and the predictability of these measures at ungaged sites is unknown.

We computed the frequency of low flows (daily flows below P10) and high flows (daily flows above P90) for each calendar year by season (defined as consecutive 3-month periods) (fig. 1). To assess high-flow seasonality, winter began in December; for the seasonality of low flows, winter began in November. This shift was done to group August, September, and October as a season for low flows because most low flows occur during those 3 months. The seasonality HMs, which represent the season-to-season variability, were calculated as the sum of the absolute values of the difference between each season’s frequency value and 0.25 (fig. 1). The value of 0.25 represents equal contribution from each season. The annual seasonality metrics for low and high flows were then averaged over the 1980–2014 period to represent the long-term seasonality behavior of the stream. Small values of the seasonality HMs indicate uniform or nonseasonal behavior—that is, low or high flows can occur about equally among the four seasons (fig. 1*B*). Large values indicate a strong seasonal pattern in the occurrence of low or high flows (fig. 1*A*, 1*C*, and 1*D*).

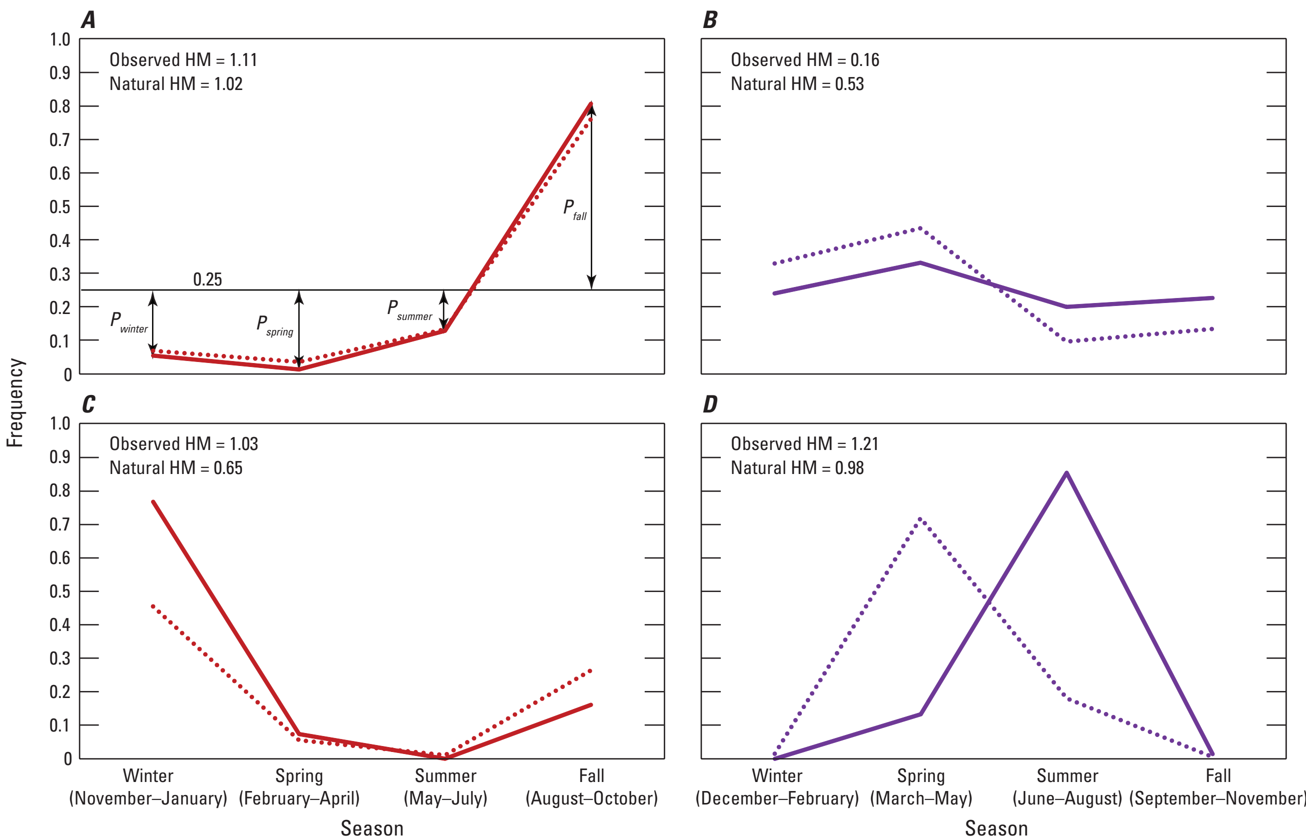

Figure 1. Examples of the observed and predicted natural seasonal frequencies of (*A*) low flows and (*B*) high flows for Accotink Creek near Annandale, Virginia (urban watershed; U.S. Geological Survey streamgage number 01654000), and (*C*) low flows and (*D*) high flows for Weber River at Echo, Utah (dam watershed; U.S. Geological Survey streamgage number 10132000). Solid lines are frequencies computed from observed flows, and dotted lines are natural frequencies predicted by models. The seasonality hydrologic metric (HM) is computed as the sum of the absolute values of the difference between each season's frequency value and 0.25 (|*Pwinter*|+|*Pspring*|+|*Psummer*|+|*Pfall*|). The value of 0.25 represents equal contribution from each season. The graphs show (*A*) little change from natural conditions, (*B*) diminished seasonality indicated by the flattening of the distribution, (*C*) inflated seasonality because of more events occurring in winter, and (*D*) mode shift from spring to summer.

Quantification of Flow Alteration for Selected Streamgages

Our approach to quantifying flow alteration relied on comparison of an observed HM (O_{HM}) to a natural, or unaltered, HM (E_{HM}) predicted by models. Deviation from predicted values was assumed to result from LWM, that is, anthropogenic modifications to watershed hydrology from dams, diversions, and land-cover change (Eng, Carlisle, and others, 2013). Our assessment considered flow alteration patterns between 1980 and 2014. This period is after the development of most major water projects and reflects contemporary patterns in LWM. O_{HM} values of the 12 HMs (table 1) were calculated from daily flows measured at 3,355 U.S. Geological Survey (USGS) streamgages in human-modified watersheds from 1980 to 2014 (fig. 2); the calculated HM values are available in an associated data release (Eng, 2018). The 3,355 streamgages used in this study are a subset of the approximately 9,000 streamgages compiled by Falcone (2011). We selected streamgages that had concurrent flow data for at least 70 percent (24 years) of the 1980–2014 period and had data on corresponding natural watershed characteristics, such as elevation, climate (that is, precipitation and temperature), and soils. The selected streamgages were assigned to one of eight ecoregions based on aggregated Level II ecoregion boundaries (Falcone, 2011). Daily flow records from each streamgage were batch downloaded from the USGS National Water Information System (https://doi.org/10.5066/F7P55KJN; U.S. Geological Survey, 2015) using a program by Granato (2008).

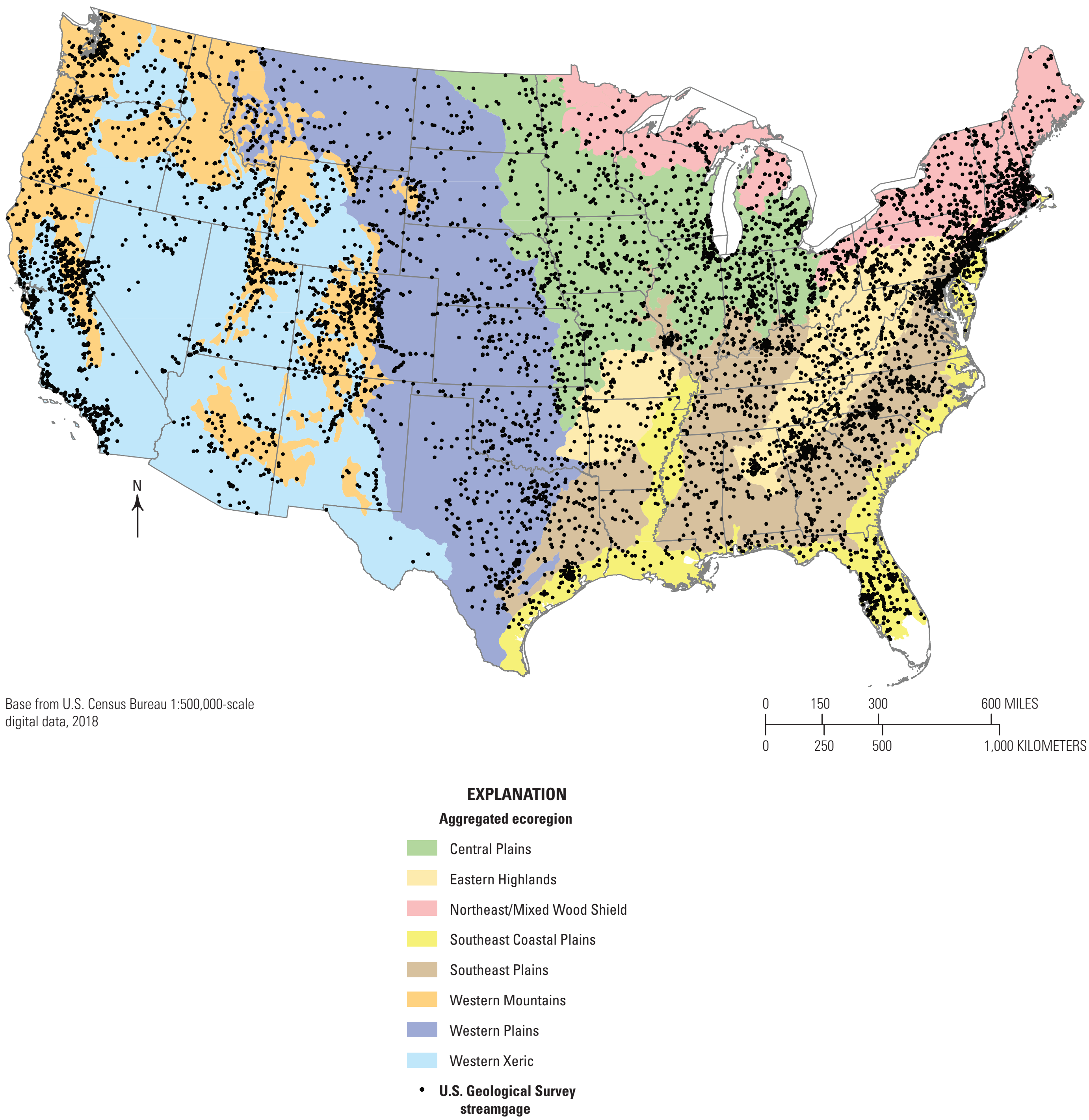

Figure 2. Locations of the 3,355 U.S. Geological Survey streamgages selected for assessing severity and extent of alterations to natural streamflow regimes. Streamgage locations and ecoregions are from Falcone (2011). Ecoregions are modified from Omernik (1987).

Following methods described in Eng and others (2017), we predicted the E_{HM} of each HM for the 3,355 USGS streamgages (Eng, 2018) by using RF models (Prasad and others, 2006; Cutler and others, 2007) trained with data from 848 USGS streamgages in natural watersheds (Falcone, 2011) (fig. 3) with a minimum of 24 years of record for the 1980–2014 period. Briefly, RF models predicted the HMs by using natural physical characteristics of watersheds, such as elevation, climate, and soils, as predictors. A total of 176 geographic information system-derived watershed predictor variables (Falcone, 2011; Eng and others, 2017) were evaluated, and the 20 most influential predictors based on importance values (Friedman, 2001) were used to develop the final models for each HM. Model performance was assessed by 100 bootstraps of different subsets of the data using a composite performance metric. The final models for application at the 3,355 selected gage locations used all 848 streamgages in natural watersheds. The error distributions from RF models were not normally distributed. Eng and others (2017) provided a method to characterize the model error by using the P10 and P90 from the distribution of errors. However, their method (Eng and others, 2017) characterizes the model error across all sites instead of providing a local estimate of error at a single site. As a solution, we used an inverse weighted distance function (Shepard, 1968) to obtain a local estimate of error for each site (streamgage), which weighted the errors closest to the model's predicted value more heavily than those further away.

We quantified flow alteration at each streamgage as the ratio of the observed to estimated HM values (O_{HM}/E_{HM}) for all HMs except for the two seasonality HMs, which were quantified as the difference between the O_{HM} and E_{HM} values. The O_{HM} and the two E_{HM} values for the 1950–2014 and 1980–2014 periods are published in Eng (2018). Several studies have used O_{HM}/E_{HM} values to quantify diminished or inflated HMs (for example, Carlisle and others, 2017). Use of the $O_{HM}-E_{HM}$ values was necessary to characterize the temporal shift of low-flow events (less than P10) and high-flow events (greater than P90). Values of O_{HM}/E_{HM} close to 1 would indicate little change from the expected natural HM. For the two seasonality HMs, the $O_{HM}-E_{HM}$ values describe the redistribution of low- and high-flow events throughout the year, with values near 0 indicating no change. Positive $O_{HM}-E_{HM}$ values indicate inflated conditions where flow events were concentrated into fewer seasons, and negative values represent diminished conditions where flow events were dispersed among the seasons. For both seasonality metrics in this report, the terms "concentrated" and "dispersed" were used in place of "inflated" and "diminished," respectively, to ease interpretation. Negative $O_{HM}-E_{HM}$ values were associated with dispersal, and positive $O_{HM}-E_{HM}$ values were associated with concentration of flow events. In addition, the $O_{HM}-E_{HM}$ values in Eng (2018) were converted into percentages to make the changes more intuitive. A change of 0.1 in the absolute value of $O_{HM}-E_{HM}$ corresponds to a redistribution of 5 percent of flow events. For example, an $O_{HM}-E_{HM}$ value equal to −0.1 would be interpreted as a dispersal of 5 percent of flow events to other seasons. Shifts away from the season that had the largest frequency under natural conditions were also reported (for example, fig. 1*D*). Streamgages were grouped into the following classes according to the degree to which the seasonality of flow events was either concentrated or dispersed ($|O_{HM}-E_{HM}|$): 0 to 9 percent of flow events, 10 to 24 percent, 25 to 50 percent, and greater than 50 percent. For all other HMs, streamgages were classified by O_{HM}/E_{HM} values in increments of 0.25 ranging from 0 to greater than 2. Streamgages with O_{HM}/E_{HM} or $O_{HM}-E_{HM}$ values equal to or less than the local prediction error from the RF model were designated as "indeterminant" because the range of deviation from expected values did not exceed model prediction error.

To describe the associations between streamflow alteration and LWM, we classified all streamgages as influenced by row-crop agriculture, irrigation, dams, urbanization, or a mix of these modifications on the basis of threshold criteria for the streamgage's watershed (table 2). Each streamgage was assigned to one class only; the classification for each streamgage is provided in Eng (2018). The threshold for dams (reservoir storage greater than 100 megaliters per square kilometer) was two times the P99 value among 1,944 streamgages in the United States considered hydrologically undisturbed (Falcone and others, 2011). Thresholds for urbanization (watershed impervious cover greater than 10 percent) and row-crop agriculture (watershed row-crop cover greater than 50 percent) were based on previous studies (Carlisle and others, 2013). Streamgages classified as influenced by irrigation did not meet threshold criteria for the dam, urbanization, or row-crop categories; had watershed irrigated land cover greater than 1 percent for arid and semiarid streamgages (that is, areas west of the 100th meridian); and were deemed influenced by irrigation on the basis of local expert knowledge. Streamgages that met none of the above criteria were classified as "mix," indicating the influence of multiple LWM activities. We then summarized for each of the 12 HMs the degree of change and percentage of streamgages associated with each category of LWM.

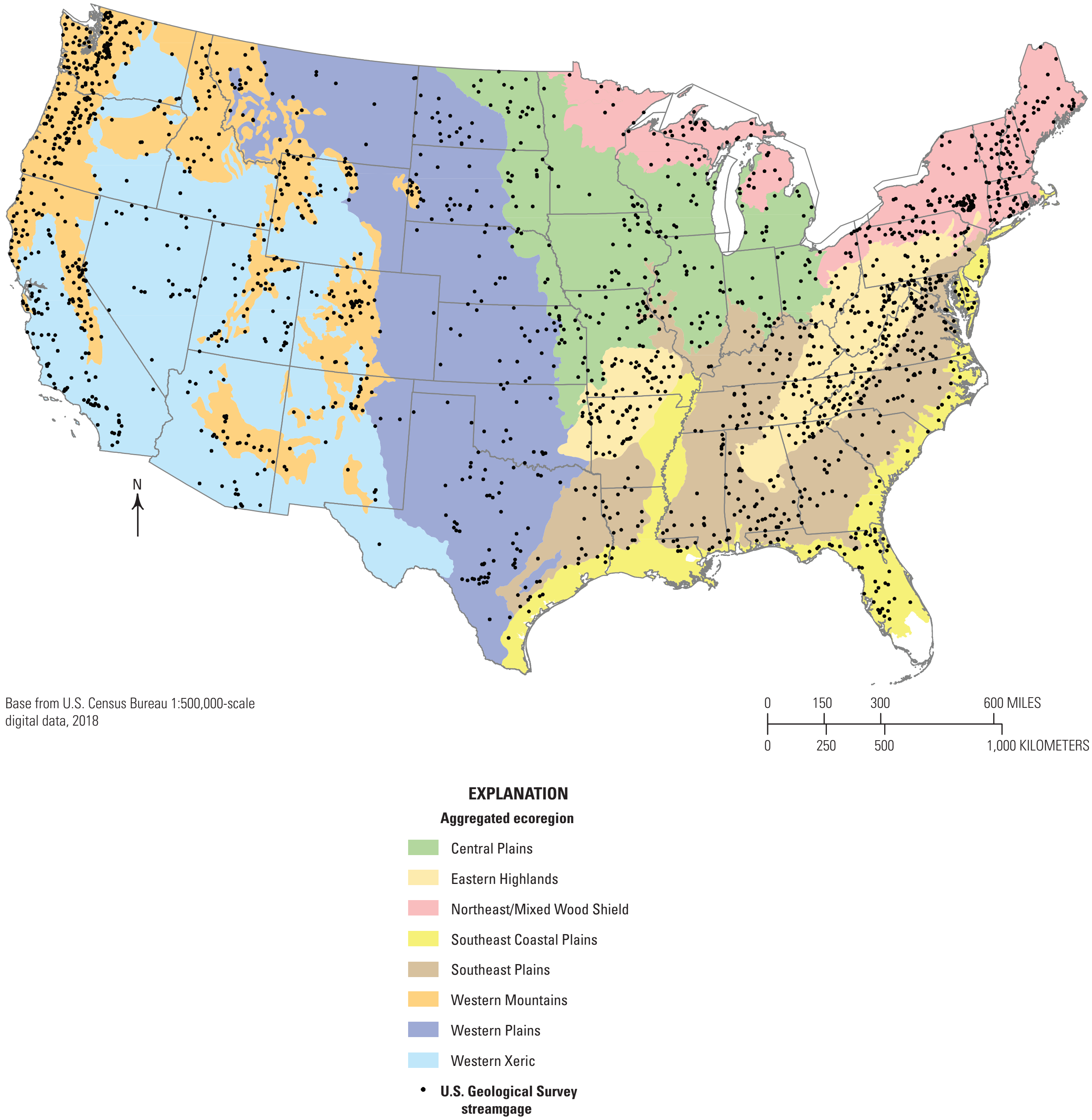

Figure 3. Locations of the 848 U.S. Geological Survey streamgages selected for modeling natural conditions. Streamgage locations and ecoregions are from Falcone (2011). Ecoregions are modified from Omernik (1987).

Table 2. Criteria for defining classes of land and water management for watersheds of 3,355 U.S. Geological Survey streamgages.

[<, less than; >, greater than]

Class	Criteria
Row-crop agriculture	Reservoir storage <100 megaliters per square kilometer; impervious cover <10 percent; row-crop cover >50 percent.
Irrigation	Irrigated agriculture >1 percent in regions west of the 100th meridian; irrigation mentioned in the annual data report.
Dams	Reservoir storage >100 megaliters per square kilometer; proximal reservoir or dam.
Urban	Reservoir storage <100 megaliters per square kilometer; impervious cover >10 percent; row-crop cover <50 percent.
Mix	All remaining watersheds that did not meet the criteria listed above.

Quantification of Effects of Climate Variability

As part of this study, we compared the relative effects of climate variability to those of LWM on the magnitude, frequency, and duration of low and high flows. The variability, seasonality, skew, and daily rises HMs were excluded from this portion of the analysis because these HMs were more difficult to interpret. We estimated the E_{HM} values for each HM by using RF models developed with two climate time periods: 1980 to 2014 and 1950 to 2014. The E_{HM} values for both time periods are published in Eng (2018). Comparison of the E_{HM} values between the two periods isolated the effects of climate variability and change as described below.

Quantification of HM alteration caused by LWM is described in the previous section and was based on RF models developed with measured climate data for 1980 to 2014 (Wolock and McCabe, 2018), which is the period used to compute O_{HM} values from observed flow data. Because E_{HM} values were based on the same climate period as O_{HM} values, the effects of climate variability are minimized in the computed ratios of O_{HM}/E_{HM}. Hence, deviations of O_{HM} from E_{HM} result mostly from LWM.

To quantify the climate-related effects on HMs, we developed RF models identical to those described above to compute E_{HM} values for each HM, but we used climate data averaged over 1950–2014 instead of 1980–2014 (Wolock and McCabe, 2018). These new RF models were then applied to all 3,355 streamgages using the measured climate record (1950–2014) for each streamgage's watershed, which generated E_{HM} values based on average conditions over the last 60 years.

At each of the 3,355 streamgages, the difference between the two E_{HM} values generated from different climate periods (1950–2014 and 1980–2014) represents an estimate of the climatic effect at the streamgage. Importantly, this climate effect is limited in definition; it represents the climate difference between the two periods and not necessarily the long-term (for example, postindustrialization) effects of climate. For each HM, the percent change ($[E_{1980–2014}–E_{1950–2014}]/E_{1950–2014}$) was compared to the percent change ($[O_{HM}–E_{HM}]/E_{HM}$) from the assessment described above, which represents the effects of LWM. These two effects were aggregated across streamgages within each ecoregion and summarized graphically.

Severity and Extent of Alterations to Natural Streamflow Regimes

The severity and extent of alterations to natural streamflow regimes in the conterminous United States for 1980–2014 are described in this section. First, the degree of flow regime alteration and the geographic distribution at 3,355 streamgages is described. Second, associations between flow alteration and types of LWM are described. Lastly, a comparison of the relative contributions of climate variability and LWM to flow alteration is provided.

Degree of Flow Regime Alteration and Geographic Distribution

The degree of flow regime alteration and the geographic distribution were assessed by using the 12 HMs used to quantify flow alteration (table 1). Ten of these HMs are associated with low- and high-flow events (magnitude, variability, frequency, duration, and timing/seasonality), and two describe the distributional asymmetry (skew) and stochasticity (number of rises) of daily flows.

Low Flows

Flow alteration for the low-flow magnitude, variability, frequency, and duration HMs (fig. 4*A*–*D*) was quantified as the observed HM (O_{HM}) divided by the estimated natural HM (E_{HM}). O_{HM}/E_{HM} values greater than 1 are associated with inflation of the HM, and O_{HM}/E_{HM} values less than 1 indicate diminishment of the HM. For the timing/seasonality HM (fig. 4*E*), flow alteration was quantified as the difference between O_{HM} and E_{HM} and reported as a percentage of flow events. Streamgages were classified as indeterminant if the change in the HM did not exceed the error associated with the E_{HM} values.

Low flows were altered to some degree at about 85 percent of the 3,355 assessed streamgages (fig. 4). However, there was wide variation among the five components of low flow (magnitude, variability, frequency, duration, and timing/seasonality) and the severity of alteration (fig. 4*A*–*E*). Changes in the season of low flows (seasonality shift, fig. 4*F*) also indicate effects of alterations to the natural streamflow regime.

In the conterminous United States, streamgages with diminished low-flow magnitude were as common (about 40 percent of streamgages) as streamgages with inflated low-flow magnitude, but diminishment was most pervasive in the western ecoregions (Western Plains, Western Mountains, and Western Xeric) and the Southeast Coastal Plains (fig. 4*A*). Diminishment was most severe in the western ecoregions, where magnitudes were diminished by more than 75 percent at one-half of assessed streamgages. In contrast, inflated low-flow magnitudes were more pervasive in the central and eastern ecoregions, but the changes were less severe than those at streamgages with diminished magnitudes.

Relative to natural conditions, low flows were less variable (annually), more frequent, and of shorter duration (within a year) at more than 60 percent of the assessed streamgages (fig. 4*B*–*D*, respectively). The annual variability of low flows was overwhelmingly diminished in all ecoregions. The most severe alterations were in the Southeast Coastal Plains, Southeast Plains, Central Plains, and Western Plains, where nearly one-half of assessed streamgages had at least a 50-percent diminishment in variability. Diminished frequency was most common in the western ecoregions and Southeast Coastal Plains ecoregion, but diminished and inflated frequency occurred in approximately equal percentages between most regions. In all ecoregions, duration was diminished at most streamgages, and at about one-third of assessed streamgages, the duration was less than 50 percent of the natural estimates.

The seasonality of low flows was altered at more than 80 percent of streamgages in the conterminous United States and within most ecoregions (fig. 4*E*). In all ecoregions, more than 10 percent of streamgages experienced dispersal of more than 10 percent of low-flow events to other seasons. The Western Plains, Western Mountains, and Western Xeric ecoregions had the most streamgages with 10 percent or more of low-flow events concentrated in fewer seasons.

Changes in the season of low flows occurred at about 20 percent of assessed streamgages in the conterminous United States and at frequencies of 20 to 40 percent in western ecoregions (fig. 4*F*). The most common seasonal change was a shift from fall to other seasons. The second most prevalent change was a shift from winter to other seasons; this change was primarily in the Western Mountains and Western Xeric ecoregions.

High Flows

Flow alteration for the high-flow HMs was quantified similar to the low-flow HMs described in the previous section. High flows were altered at more than 80 percent of assessed streamgages, but there was wide variation among the type and prevalence of alterations and the ecoregions that experienced the changes (fig. 5).

In the conterminous United States, diminishment of high-flow magnitude (O_{HM}/E_{HM} values less than 1; approximately 70 percent of streamgages) was much more common than inflation (O_{HM}/E_{HM} values greater than 1; approximately 16 percent of streamgages) (fig. 5*A*). The Southeast Coastal Plains and western ecoregions (Western Plains, Western Mountains, and Western Xeric) had the most severe diminishments; magnitudes were less than 50 percent of natural estimates at about one-third of assessed streamgages.

Relative to natural conditions, high flows across the conterminous United States were generally less variable, less frequent, and of shorter duration (fig. 5*B*–*D*, respectively). Most streamgages in all ecoregions had diminished annual variability of high flows, and about one-third of streamgages had diminishments that were greater than 25 percent. In all ecoregions, frequency was diminished at most streamgages, and frequency was diminished by more than 25 percent at one-third of streamgages. Proportions of diminished and inflated duration were similar among most ecoregions, but the Southeast Coastal Plains and Western Xeric ecoregions had the most streamgages with diminished duration and the most severe diminishments.

The seasonality of high flows was altered at more than 80 percent of streamgages in the conterminous United States and within most ecoregions (fig. 5*E*). At most streamgages, less than 10 percent of high-flow events were redistributed (concentrated or dispersed) from when they would have occurred naturally; however, in the Western Mountains and Western Xeric ecoregions, about 30 percent of streamgages had more than 10 percent of the high-flow events redistributed.

Changes in the season of high flows occurred at about 25 percent of the assessed streamgages (fig. 5*F*). The most common seasonal changes were shifts of high flows from spring or winter to other seasons. Notably, less than 10 percent of streamgages in the Northeast/Mixed Wood Shield and Central Plains had changes to the season of high flows.

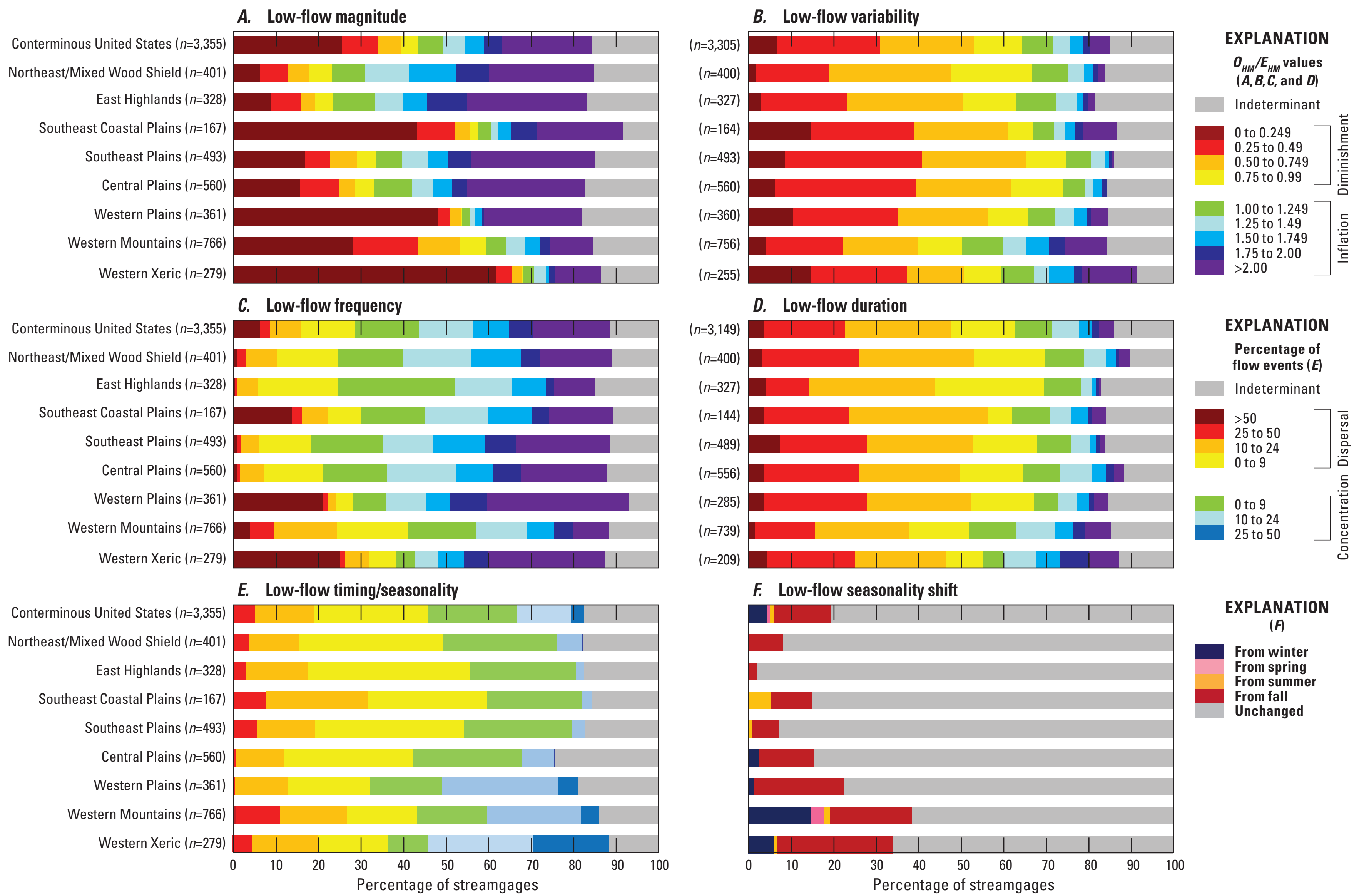

Figure 4. Percentages of streamgages with changes in low-flow (*A*) magnitude, (*B*) variability, (*C*) frequency, (*D*) duration, (*E*) timing/seasonality, and (*F*) seasonality mode (that is, seasonality shifts) across the conterminous United States and within eight ecoregions. *n*, number of streamgages; O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

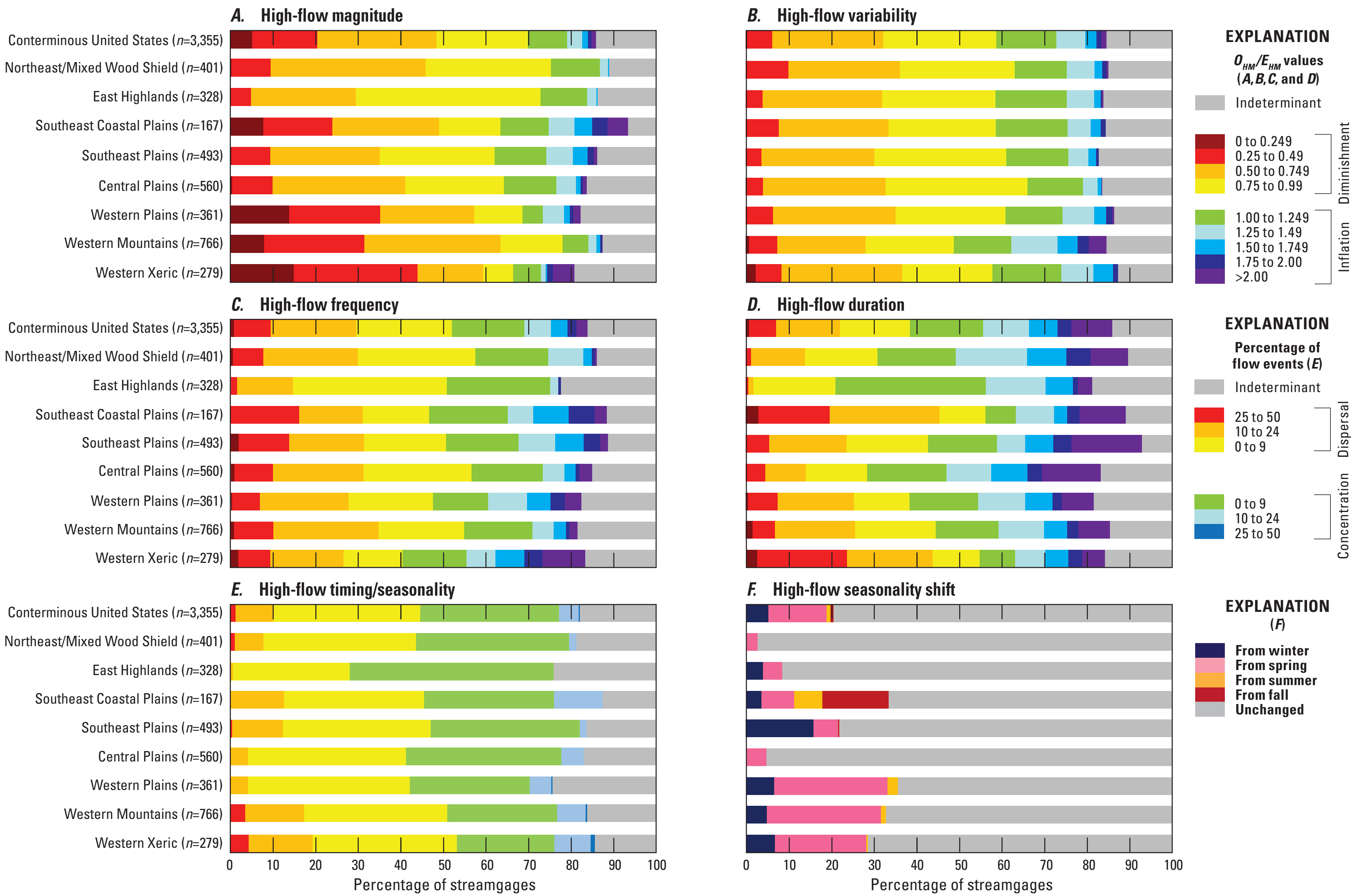

Figure 5. Percentages of streamgages with changes in high-flow (*A*) magnitude, (*B*) variability, (*C*) frequency, (*D*) duration, (*E*) timing/seasonality, and (*F*) seasonality mode (that is, seasonality shifts) across the conterminous United States and within eight ecoregions. *n*, number of streamgages; O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

Skew and Daily Rises

Flow alteration for skew and daily rises was quantified using O_{HM}/E_{HM} values as described previously for the low- and high-flow HMs. O_{HM}/E_{HM} values greater than 1 are associated with inflation, and O_{HM}/E_{HM} values less than 1 indicate diminishment of the HM. Streamgages were classified as indeterminant if the change in the HM did not exceed the error associated with the E_{HM} values.

The skew and number of rises of daily flows were altered at approximately 90 percent of assessed streamgages across the conterminous United States and within all ecoregions (fig. 6). Relative to natural conditions, most streamgages had inflated daily rises (fig. 6*A*) and diminished skew (fig. 6*B*; that is, fewer extreme high- or low-flow events). Streamgages in the Western Mountains and Western Xeric ecoregions had the most severe diminishments of flow symmetry and stochasticity, but they also had the most severe inflations.

Associations Between Flow Alteration and Land and Water Management

This section describes the associations between flow alteration and various classes of LWM defined in table 2. Of the 3,355 streamgages assessed, 355 were classified as row-crop agriculture; 668, irrigation; 796, dams; 256, urban; and 1,280, mix (Eng, 2018).

Associations are described by HMs for low flow, high flow, skew, and daily rises. As described previously, the flow alteration for the magnitude, variability, frequency, and duration HMs was quantified by using O_{HM}/E_{HM} values. O_{HM}/E_{HM} values greater than 1 are associated with inflation, and O_{HM}/E_{HM} values less than 1 indicate diminishment of the HM. For the seasonality HM, flow alteration was quantified as the difference between O_{HM} and E_{HM} and reported as a percentage of flow events. Streamgages were classified as indeterminant if the change in the HM did not exceed the error associated with the E_{HM} values.

Low Flows

Patterns of low-flow alteration differed among types of LWM. The highest occurrence and severity of diminished low-flow magnitude were in irrigated agriculture settings (fig. 7*A*). In contrast, urban settings had the highest occurrence and severity of inflated magnitudes. The frequencies of inflation and diminishment in low-flow magnitude were similar among all other land-use settings.

Streamgages with diminished variability (fig. 7*B*) and duration (fig. 7*D*) were common in all settings, but the most extreme diminishments occurred in urban settings, where more than one-half of assessed streamgages had diminishments greater than 50 percent. Low-flow frequencies were inflated in all settings, with urban settings having the largest proportion of streamgages with greater than 200 percent inflation (fig. 7*C*).

Most streamgages in dam and urban settings experienced dispersal of low-flow events to other seasons, whereas most streamgages in irrigation settings experienced concentration of low-flow events into fewer seasons (fig. 7*E*). Seasonal changes were typically fall and winter low flows shifting to other seasons, occurring mostly in irrigation, dam, and row-crop agriculture settings (fig. 7*F*).

High Flows

Patterns of high-flow alteration differed among types of LWM. Although diminished high-flow magnitude was common in most settings, the highest occurrence and severity of diminishment were in irrigated agriculture settings, followed closely by dam settings (fig. 8*A*). In contrast, urban settings had the highest occurrence and severity of inflated magnitudes. Diminished high-flow variability was predominant in all types of LWM (fig. 8*B*). High-flow frequency and duration were also diminished in most settings, with the notable exception of urban settings, where most streamgages had inflated high-flow frequency (fig. 8*C*) but extremely severe diminishments in the duration of high flows (fig. 8*D*). In dam and urban settings, most streamgages had dispersal of high-flow events to other seasons (fig. 8*E*). Redistribution of high flows was less than 10 percent for most streamgages in other settings. Seasonal changes were typically winter and spring high flows shifting to other seasons; such changes occurred mostly in irrigation and dam settings (fig. 8*F*).

Skew and Daily Rises

Although diminished skew was common in most types of LWM, the most severe diminishments occurred in dam and agricultural settings (fig. 9*A*). Skew values were diminished because of less frequent high-flow events and (or) more frequent low-flow events, which would cause flow distributions to be more normally distributed. In contrast, both diminished and inflated skews were common in urban settings. This mixed behavior can occur because urbanization increases the frequency of high- and low-flow events unequally. Inflated daily rises in flows were prevalent in all types of LWM (fig. 9*B*).

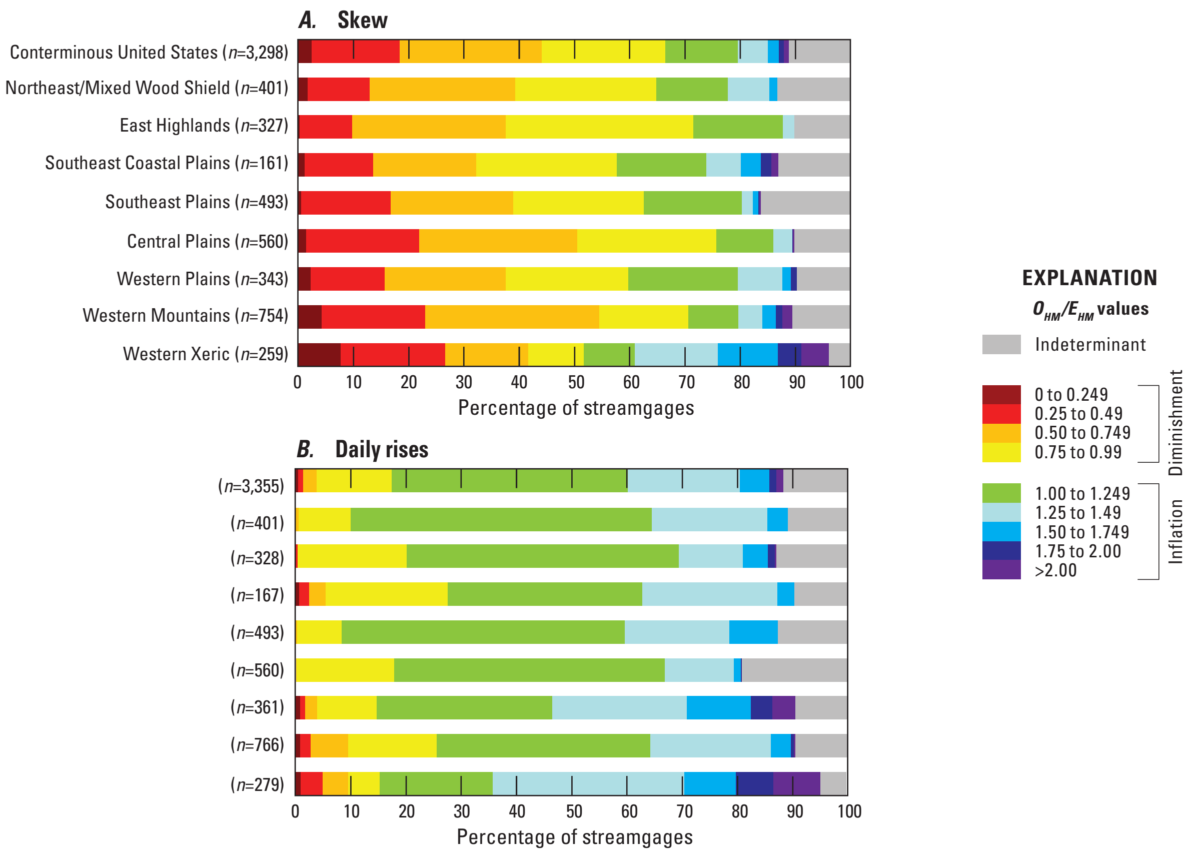

Figure 6. Percentages of streamgages with changes in the (*A*) skew and (*B*) daily rises hydrologic metrics across the conterminous United States and within eight ecoregions. *n*, number of streamgages; O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

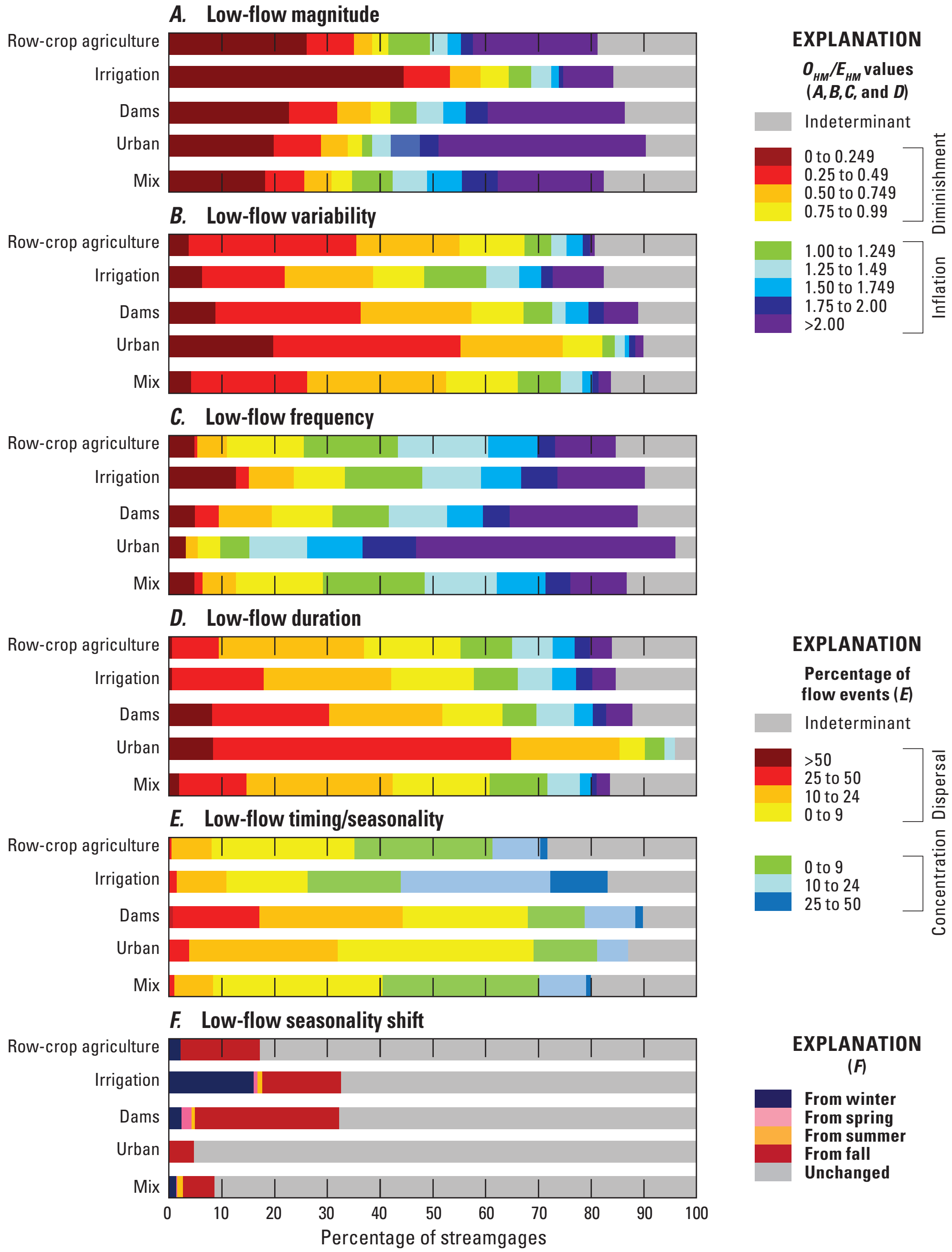

Figure 7. Percentages of streamgages with changes in low-flow (*A*) magnitude, (*B*) variability, (*C*) frequency, (*D*) duration, (*E*) timing/seasonality, and (*F*) seasonality mode (that is, seasonality shift) associated with land and water management across the conterminous United States. O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

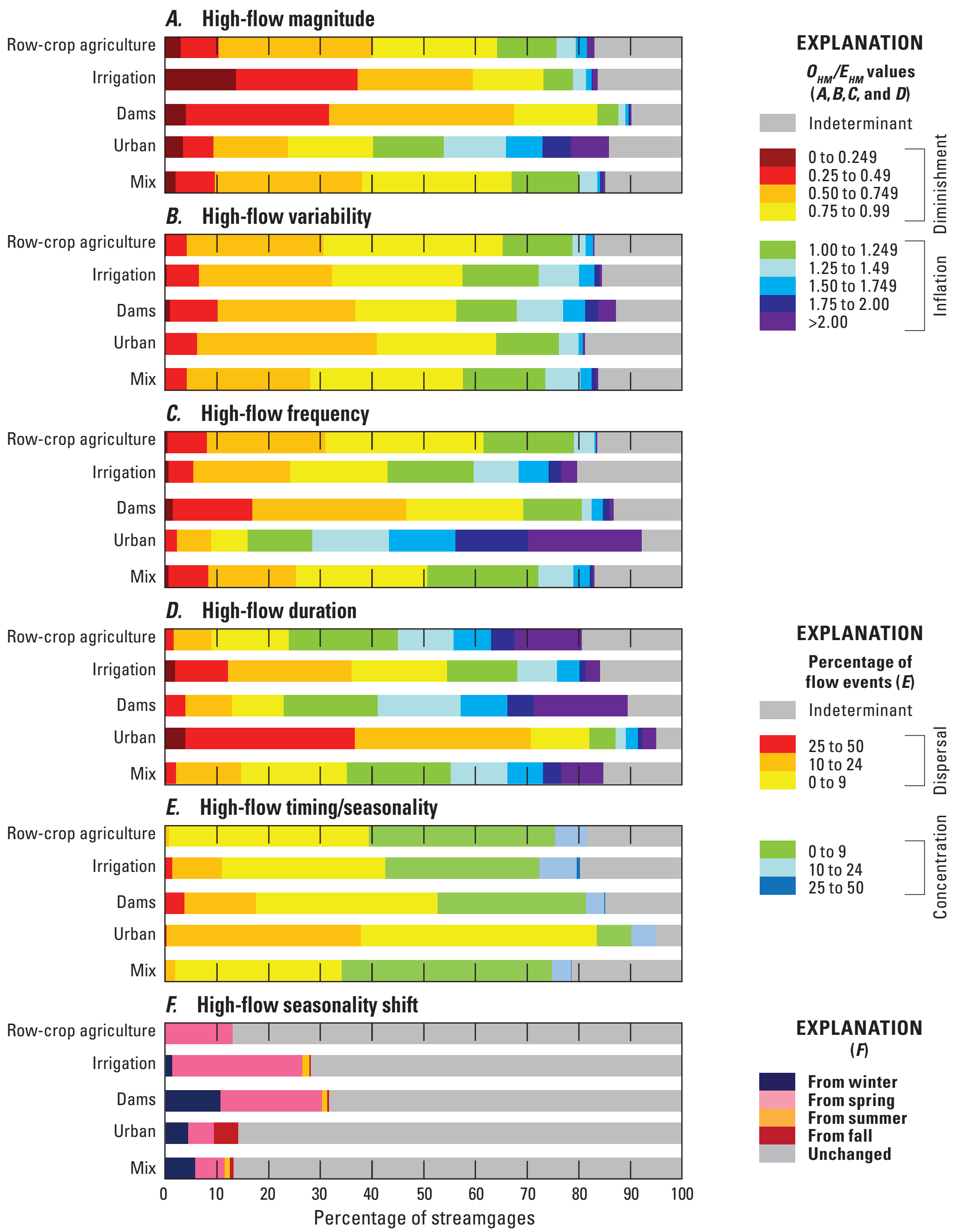

Figure 8. Percentages of streamgages with changes in high-flow (*A*) magnitude, (*B*) variability, (*C*) frequency, (*D*) duration, (*E*) timing/seasonality, and (*F*) seasonality mode (that is, seasonality shift) associated with land and water management across the conterminous United States. O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

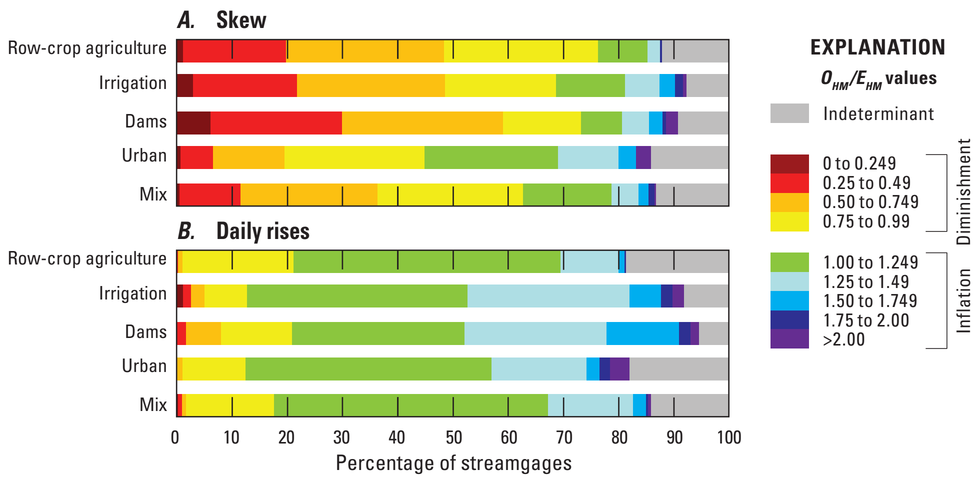

Figure 9. Percentages of streamgages with changes in the (*A*) skew and (*B*) daily rises hydrologic metrics associated with land and water management across the conterminous United States. O_{HM}, observed hydrologic metric; E_{HM}, estimated hydrologic metric; O_{HM}/E_{HM}, degree of flow alteration.

Relative Contributions of Climate Variability and Land and Water Management to Flow Alteration

In most ecoregions, climate variability during 1980–2014 had a relatively minor effect on HMs compared to the effects of LWM during the same period, but there were strong regional differences (fig. 10). In all but two ecoregions (Central Plains and Western Plains), LWM had more effect on low-flow magnitude than did climate variability (fig. 10*A*). In ecoregions with widespread irrigation (Southeast Coastal Plains, Western Plains, Western Mountains, and Western Xeric) the LWM effect was negative (that is, tendency for diminished low-flow magnitude), whereas the climate effect was positive (that is, tendency for inflated low-flow magnitude).

Low-flow duration (fig. 10*C*) and frequency (fig. 10*E*) were changed little by climate variability relative to LWM in all ecoregions. Collectively, LWM tended to diminish the duration and inflate the frequency of low flows in all ecoregions. In the western ecoregions and, to a lesser extent, the Central Plains ecoregion, climate effects on the duration of low flows were opposite those of LWM. Climate effects on low-flow frequency were both positive and negative, but they were small in comparison to the effects of LWM.

In most ecoregions, climate effects on high flows for 1980–2014 were relatively minor compared to the effects of LWM during the same period (fig. 10*B*). There were, however, some regional differences in the relative contribution of climate, likely caused by geographic patterns in land use and climate variability. In all ecoregions, high-flow magnitude was affected more by LWM than by climate. Further, the effects of LWM were consistently negative, in that high-flow magnitudes tended to be diminished. Climate contributions were relatively small in all ecoregions except Western Xeric and Western Plains, where climate variability tended to cause an inflation in high-flow magnitude—in sharp contrast to the diminishment caused by LWM.

High-flow duration was also affected more by LWM than by climate, but the direction of effects varied regionally (fig. 10*D*). In most ecoregions, LWM was associated with inflated high-flow duration, but it was associated with diminished high-flow duration in the Southeast Coastal Plains, Western Xeric, and to a lesser extent in the Western Mountains and Western Plains. The effects of climate on high-flow duration were small (less than 5-percent change).

Generally, LWM contributed to diminishment in high-flow frequency, whereas climate variability contributed to both inflation and diminishment (fig. 10*F*). In the East Highlands and Southeast Plains, inflated high-flow frequency was attributed to climate variability and was similar in size to the diminished frequency attributed to LWM. Inflated high-flow frequencies also were evident in the Central Plains and Northeast/Mixed Wood Shield ecoregions, attributed to climate variability; however, diminished frequencies attributed to LWM effects were larger. Climate and LWM effects contributed to diminished frequencies in the Southeast Coastal Plains ecoregion, but the climate effect was larger than that of LWM.

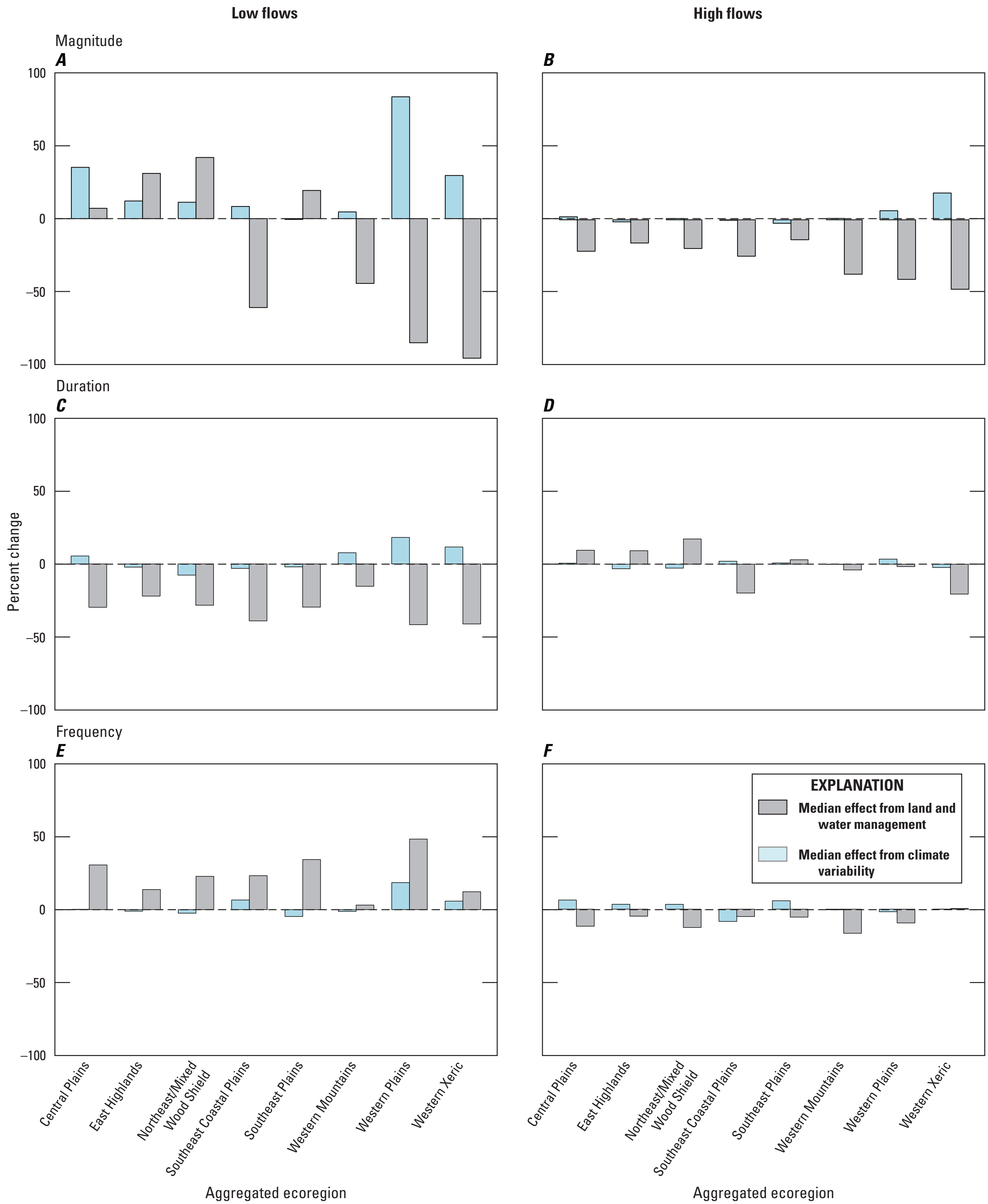

Figure 10. Median effects of climate variability and land and water management on the (*A*, *B*) magnitude, (*C*, *D*) duration, and (*E*, *F*) frequency of low and high flows by ecoregion.

Synthesis of Alterations to Natural Streamflow Regimes

Some level of flow alteration compared to the natural conditions was indicated for 80 percent of all assessed streamgages. The severity of change differed among ecoregions owing to LWM being dominant in certain parts of the United States (for example, irrigation is a dominant modification in ecoregions with arid and semiarid climates). This section provides a synthesis of study results for alterations to natural streamflow regimes. For LWM, results of the current study are compared with recent literature. Limitations of comparisons between effects of climate variability and LWM are described. Lastly, correlations among HMs are described.

Land and Water Management

Numerous studies in the current literature have analyzed the effects of LWM on streamflows; however, most are limited in both geographic scope and the breadth of streamflow attributes (HMs) analyzed. In addition, many of the findings are contradictory. Unlike previous studies, the current study provides a comprehensive and consistent analysis across the conterminous United States, and the following synthesis compares the results of the current study with recent literature.

Low Flows

The effects of row-crop agriculture on low-flow magnitudes are mixed (Blann and others, 2009). The results of the current study show approximately equal proportions of inflated and diminished low-flow magnitudes (fig. 7*A*), which is consistent with the literature. The direction of change is dependent on the type of surface and (or) subsurface drainage present and soil conditions.

Dams can either diminish or inflate low-flow magnitudes (Yang and others, 2004; Poff and others, 2006, 2007). These inconsistent changes appear to be dependent on the operation of the dam. For example, some dams are used to maintain a minimum flow during the naturally lowest flow periods of the year. In the current study, the larger proportion of streamgages with diminished low-flow variability compared to streamgages with inflated low-flow variability (fig. 7*B*) is consistent with the findings of Poff and others (2007). Unlike the current study, Poff and others (2007) studied streamflow over a variable time period for sites having a minimum of 15 years of streamflow records before and after the dam completion date. More streamgages were associated with inflation than diminishment in low-flow frequency (fig. 7*C*); however, Poff and others (2007) reported diminishments in low-flow frequency. Lastly, we found that a higher proportion of streamgages had diminished low-flow duration compared to inflated low-flow duration (fig. 7*D*). Dams used for regulation are associated with diminished seasonality metrics, which is expected because low-flow events can be introduced in any season (Poff and others, 2007).

We found urbanization effects on low-flow magnitudes to be mixed (fig. 7*A)*. These changes are not related to location of the urban area relative to the natural portions of the watershed (Walsh and others, 2005; Poff and others, 2006; Eng, Wolock, and Carlisle, 2013). Diminishments in low-flow magnitudes are typically associated with reduced infiltration or recharge to aquifers and therefore reduced base-flow conditions. Inflations can be caused by leaky water-supply or sewage infrastructure, urban irrigation, and stormwater detention ponds.

In irrigated settings, more of the assessed streamgages were associated with diminished low-flow magnitudes than inflated low-flow magnitudes (fig. 7*A*). Low flows occur in different times of the year in different ecoregions. Irrigation practices redistribute the natural flows throughout the year, and depending on when the stored flows are supplied during the irrigation season, the natural low-flow magnitudes can either be inflated or diminished. Examples include inflated flows in California during the summer when flows are naturally low (Kondolf and Batalla, 2005) and storing flows (that is, reducing flows) in Utah during winter when flows are naturally low (Carlisle and others, 2012). Temporal redistribution of natural flows for irrigation causes substantial changes to the seasonality (that is, when low flows occur in a calendar year), and this corresponds to the substantial number of assessed streamgages with inflated seasonality (fig. 7*E*) and shifts (fig. 7*F*) from when low-flow events would naturally occur.

High Flows

The effects of row-crop agriculture on high-flow magnitudes are inconsistent in the literature. Inflated and diminished high-flow magnitudes are primarily a function of the type of drainage—surface and (or) subsurface—and soil conditions. Inflations are commonly associated with subsurface drainage, which reduces storm runoff and increases infiltration and hence base flow into streams (Skaggs and others, 1994; Blann and others, 2009). Our results show a large proportion of streamgages (approximately 65 percent) with diminished high-flow magnitude associated with row-crop agriculture (fig. 8*A*). These diminishments are consistent with the findings by Gebert and Krug (1996) and Zhang and Schilling (2006). These researchers found that conversion from natural vegetation to annual row crops introduces practices such as terracing, conservation tillage, and contour cropping that slow or capture storm runoff and, as a result, increase infiltration and base flows to streams. High-flow frequencies and durations can be inflated or diminished depending on the level of subsurface drainage (Blann and others, 2009); however, we found substantial diminished frequencies (fig. 8*C*) and inflated durations (fig. 8*D*) associated with row-crop agriculture.

Dams are used for a variety of purposes (for example, flood control, municipal supply, and electricity generation), but independent of their function, a large fraction (about 85 percent) of streamgages affected by dams had diminished high-flow magnitude (fig. 8*A*). This finding is consistent with findings by Graf (2006), Poff and others (2006, 2007), and Eng, Wolock, and Carlisle (2013). In general, dams intercept and store storm runoff for later release for consumptive and nonconsumptive uses. Dams are also associated with both inflated and diminished high-flow variability, with a greater tendency for diminishments (Poff and others, 2007), consistent with the findings in the current study (fig. 8*B*). A substantial proportion of streamgages affected by dams had diminished high-flow frequency (fig. 8*C*), which is intuitive because dams are often used to mitigate the effects of high-flow events (that is, flood control and storage). This result, however, is contrary to Graf (2006) and Poff and others (2007) who found little change in high-flow frequency. In the current study, dams tended to inflate the duration of high-flow events (fig. 8*D*), which is consistent with the findings of Poff and others (2006) and Graf (2006) but contrary to diminishments reported by Poff and others (2007).

The reported effects of urbanization on high-flow magnitudes are inconsistent in the literature, which is reflected in our findings: approximately equal numbers of streamgages had inflated and diminished values (fig. 8*A*). In general, impervious surfaces and piped stormwater drainage commonly are introduced in urbanizing environments, which increases storm runoff to streams while minimizing infiltration to groundwater. Several studies of highly urbanized watersheds found inflated high-flow magnitudes with urbanization (for example, Paul and Meyer, 2001; Walsh and others, 2005; Poff and others, 2006; Eng, Wolock, and Carlisle, 2013). Diminished high-flow magnitudes can be caused by the introduction of storage or flow-detention mechanisms that prevent high-flow magnitudes from exceeding natural conditions (Walsh and others, 2005). In less urbanized watersheds, the location of urban areas relative to natural areas can change the timing of when storm runoff accumulates (Paul and Meyer, 2001). For example, if an urban area is located near the lower part of the watershed, urban stormwater runoff will leave the watershed before contributions from the upper part of the watershed can join the urban stormwater runoff and accumulate. Eng, Wolock, and Carlisle (2013) reported high-flow magnitudes that were diminished at lower levels of urbanization and eventually inflated as the level of urbanization increased. The introduction of impervious surfaces reduces infiltration and temporary storage of storm events; therefore, stormwater runoff goes directly into streams, increasing the frequency and shortening the duration of high-flow events. In the current study, the inflated high-flow frequency (fig. 8*C*) caused by urbanization is consistent with findings by Walsh and others (2005) and Eng, Wolock, and Carlisle (2013). The observed diminished high-flow durations (fig. 8*D*) are consistent with results from several studies (Paul and Meyer, 2001; Poff and others, 2006; Brown and others, 2009; Steuer and others, 2010); however, some studies have reported inflated high-flow durations (MacRae, 1996; Hawley and Bledsoe, 2011). We found that high-flow events were dispersed throughout the year owing to the pervasive diminished high-flow seasonality values (fig. 8*E*), which could be caused by the introduction of impervious surfaces.

In general, irrigation in watersheds is related to diminished high-flow magnitudes (for example, Kondolf and Batalla, 2005; Carlisle and others, 2012; Dale and others, 2015), which is consistent with the results of the current study (fig. 8*A*). Irrigation dams often collect and store natural runoff from high-flow events and later release the runoff downstream for use during the irrigation season. This practice leads to substantial seasonal shifts of when high-flow events occur. For example, in areas where there is light snowpack (such as the upper Central Plains; Buttle and others, 2012), the high-flow period is artificially extended beyond the natural spring snowmelt, and as a consequence, no-flow periods that naturally occur late in the year are reduced or eliminated.

Limitations of Comparisons Between Effects of Climate Variability and Land and Water Management

Comparisons of climate effects to those caused by LWM indicate that from 1980–2014 climate shifts have generally played a minor role in the alteration of flows across the conterminous United States. There is, however, an important caveat in that our definition of climate variability is limited. The climate analysis was done to compare the effects on flow alteration between climate variability and LWM. Climate-related effects were considered by comparing the period 1980–2014—the same period over which the effects of LWM were evaluated—to the period 1950–2014. Therefore, ecoregions where precipitation and air temperature in the latter period differed from the long-term averages were most likely to yield strong climate-related flow alteration. Despite this caveat, the findings from our study indicate that in some watersheds, decadal shifts in climate may either ameliorate or exacerbate the effects of LWM on flows. Indeed, climate variability in many ecoregions is often extreme and warrants consideration in management plans designed to mitigate the effects of LWM on flow.

Correlations Among Hydrologic Metrics

In addition to knowing the spatial distribution and severity of changes in HMs, it is important to know which HM changes are substantially correlated to others in an observed environment. HMs were considered substantially correlated if the absolute value of the Spearman rank correlation coefficient (ρ; Wilks, 1995) was greater than 0.749. The consequences of LWM to streams are reductions in the natural correlations among different measures of the flow regime (Carlisle and others, 2017) and possibly the introduction of new correlations among HMs. These correlations for the observed and natural conditions (figs. 11 and 12, respectively) can provide information on how resistant natural correlations, such as the correlation between high- or low-flow frequency and duration, are to the effects of LWM. This information also can be used to determine which natural correlations are diminished substantially in the observed conditions, such as low-flow magnitude and variability, and to identify correlations introduced into the observed environment, such as skew and high-flow frequency.

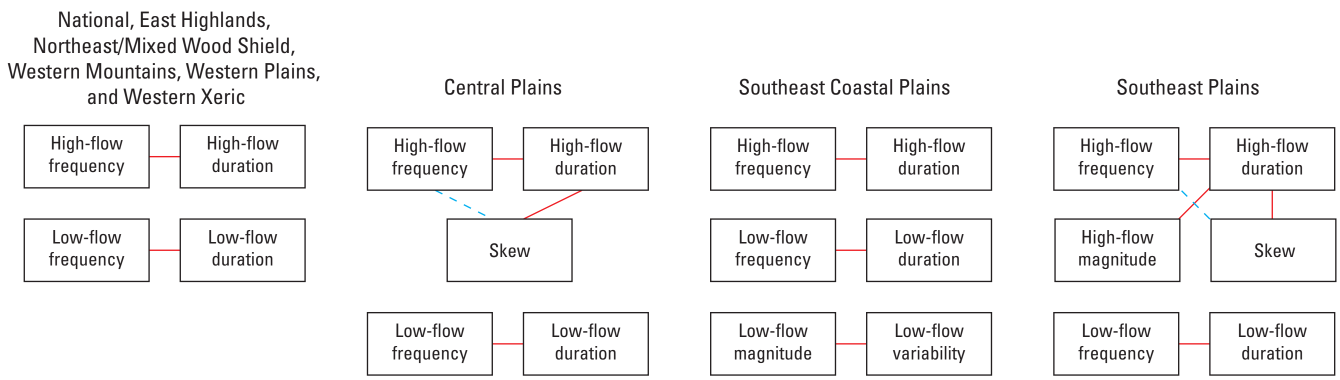

Figure 11. Linked hydrologic metrics for observed flow conditions by ecoregion. Metrics were considered linked if the absolute value of the Spearman rank correlation coefficient (ρ) was greater than 0.749. Solid red lines represent negative correlations, and dashed blue lines represent positive correlations.

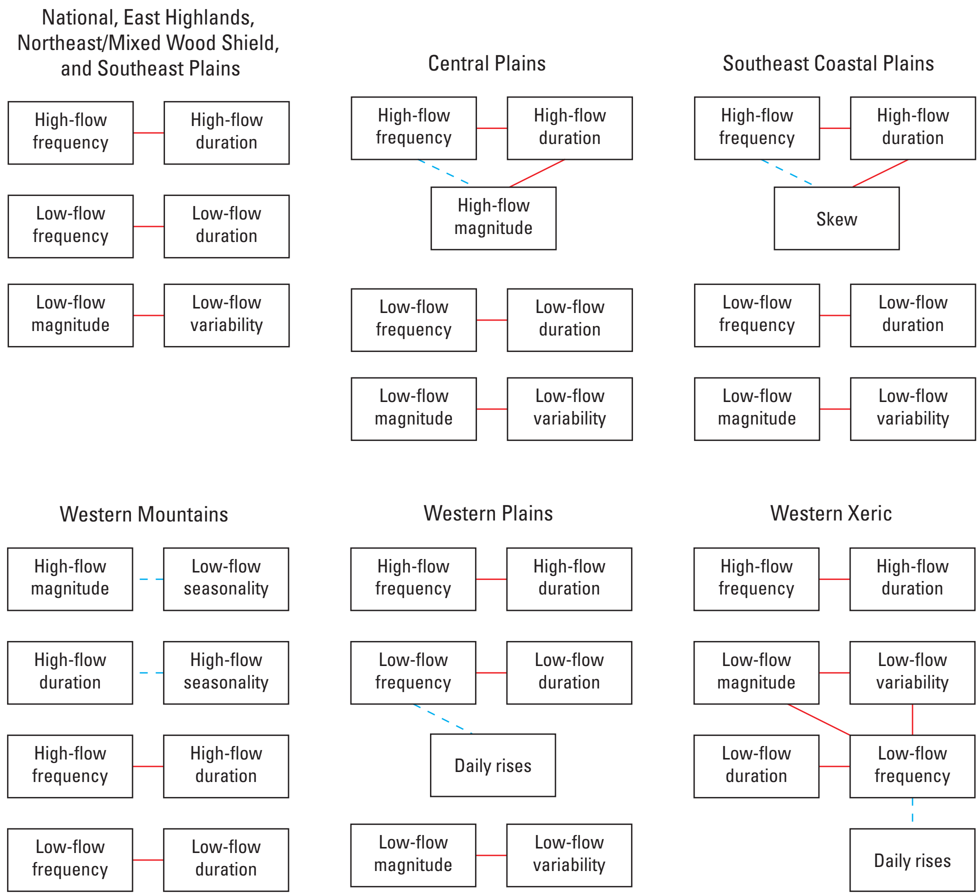

Figure 12. Linked hydrologic metrics for natural flow conditions by ecoregion. Metrics were considered linked if the absolute value of the Spearman rank correlation coefficient (ρ) was greater than 0.749. Solid red lines represent negative correlations, and dashed blue lines represent positive correlations.

Summary

Alterations to the natural streamflow regimes were found to be prevalent in all ecoregions across the conterminous United States for the period 1980–2014. Hydrologic metrics (HMs; magnitude, variability, frequency, duration, timing/seasonality, skew, and number of daily rises) were altered to some degree at about 80 percent of the 3,355 assessed streamgages. However, there was wide variation in the severity and prevalence of alterations among ecoregions for the different components of the streamflow regime.

Patterns of low-flow alteration differed among types of land and water management (LWM). The frequencies of inflation and diminishment in low-flow magnitude were similar among all land-use settings. Streamgages with diminished low-flow variability and duration were common in all settings, and low-flow frequencies were inflated in all settings. Irrigated agriculture was associated with the highest occurrence and severity of diminished low-flow magnitudes and concentration of low-flow events into fewer seasons. Seasonal changes were typically fall and winter low flows shifting to other seasons. Urban settings generally had the highest occurrence and severity of inflated low-flow magnitudes and the most extreme diminishments of low-flow variability and duration. Urban settings had the largest proportion of streamgages with greater than 200 percent inflation in the low-flow frequencies. Dam settings typically experienced dispersal of low-flow events to other seasons and seasonal changes of fall and winter low flows shifting to other seasons. Row-crop agriculture also was associated with seasonal changes of low-flow events shifting from fall and winter to other seasons.

Similar to low flows, patterns of high-flow alteration also differed among types of LWM. Diminished high-flow magnitude, frequency, and duration were common in all settings except urban. Diminished high-flow variability was predominant in all types of LWM. Irrigated agriculture was associated with the highest occurrence and severity of diminished high-flow magnitudes and high flows shifting from winter and spring to other seasons. Urban settings had the highest occurrence and severity of inflated high-flow magnitudes and frequencies and had severe diminishments in high-flow durations. Urban settings had the most streamgages with dispersal of high-flow events to other seasons. Similar to urban settings, dams also had high occurrence and severity of diminished high-flow magnitudes. Dam settings had the highest percentage of high-flow events dispersed from winter or fall to other seasons.

Although diminished skew was common in most types of LWM, the most severe diminishments occurred in dam and agricultural settings. Skew values were diminished because of less frequent high-flow events and (or) more frequent low-flow events, which would cause flow distributions to be more normally distributed. In contrast, both diminished and inflated skews were common in urban settings. This mixed behavior can occur because urbanization increases the frequency of high- and low-flow events unequally. Inflated daily rises in flows were prevalent in all types of LWM.

In most ecoregions, climate variability during 1980–2014 had a relatively minor effect on HMs compared to the effects of LWM during the same period, but there were strong regional differences. In all but two ecoregions (Central Plains and Western Plains), LWM had more effect on low-flow magnitude than did climate variability. In ecoregions with widespread irrigation (Southeast Coastal Plains, Western Plains, Western Mountains, and Western Xeric) the LWM effect was negative (that is, tendency for diminished low-flow magnitude), whereas the climate effect was positive (that is, tendency for inflated low-flow magnitude).

Low-flow duration and frequency were changed little by climate variability relative to LWM in all ecoregions. Collectively, LWM tended to diminish the duration and inflate the frequency of low flows in all ecoregions. In the western ecoregions and, to a lesser extent, the Central Plains ecoregion, climate effects on the duration of low flows were opposite those of LWM. Climate effects on low-flow frequency were both positive and negative, but they were small in comparison to the effects of LWM.

In most ecoregions, climate effects on high flows for 1980–2014 were relatively minor compared to the effects of LWM during the same period. There were, however, some regional differences in the relative contribution of climate, likely caused by geographic patterns in land use and climate variability. In all ecoregions, high-flow magnitude was affected more by LWM than by climate. Further, the effects of LWM were consistently negative, in that high-flow magnitudes tended to be diminished. Climate contributions were relatively small in all ecoregions except Western Xeric and Western Plains, where climate variability tended to cause an inflation in high-flow magnitude—in sharp contrast to the diminishment caused by LWM.

High-flow duration was also affected more by LWM than by climate, but the direction of effects varied regionally. In most ecoregions, LWM was associated with inflated high-flow duration, but it was associated with diminished high-flow duration in the Southeast Coastal Plains, Western Xeric, and to a lesser extent in the Western Mountains and Western Plains. The effects of climate on high-flow duration were small (less than 5-percent change).

Generally, LWM contributed to diminishment in high-flow frequency, whereas climate variability contributed to both inflation and diminishment. In the East Highlands and Southeast Plains, inflated high-flow frequency was attributed to climate variability and similar in size to the diminished frequency attributed to LWM. Inflated high-flow frequencies also were evident in the Central Plains and Northeast/Mixed Wood Shield ecoregions attributed to climate variability; however, diminished frequencies attributed to LWM effects were larger. Climate and LWM effects contributed to diminished frequencies in the Southeast Coastal Plains ecoregion, but the climate effect was larger than that of LWM.

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Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Reston and Sacramento
Publishing Service Centers

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20195001

Eng and others—**Severity and Extent of Alterations to Natural Streamflow Regimes Based on Hydrologic Metrics in the Conterminous United States, 1980–2014**—SIR 2019–5001