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THE IMPACT OF DAMS ON FLOOD FLOWS IN THE UNITED STATES

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ABSTRACT

Natural flood regimes provide a wide array of important ecological functions. Our goal is to assess the hydrologic impact of dams on flood flows throughout the United States. Regional regression models of the median annual 1-day maximum flow were developed as a function of natural watershed characteristics, dam storage, and population density. Most of the regressions have adjusted R2 values in excess of 0.80, and overall the models covered 78% of the area of the continental U.S. Alteration of flood flows is present in every region of the country, and is more severe west of the Mississippi and especially in the southern Great Plains, desert Southwest, and northern California. The percent of U.S. rivers with greater than a 25% reduction in the median annual flood is 55% for large rivers, 25% for medium rivers, and 10% for small rivers. The majority of freshwater ecoregions in the country have at least 10% of their rivers with 25% or greater alteration in all three river size classes. A simple model based on the ratio of dam storage to mean annual runoff was developed for assessing alteration in ungauged rivers, and was found to be generally useful for classifying rivers into categories of potential alteration. Overall, we document the alteration of natural flood flows across the U.S. in more detail than has been previously accomplished, and demonstrate the efficacy of multivariate regional regression models and other indicators for assessing hydrologic alteration. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: dams; hydrologic alteration; environmental flows; floods; flood control; hydrology; ecological flows

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INTRODUCTION AND BACKGROUND

Introduction

Natural flood regimes provide a wide array of ecological functions that are essential for the health of river, floodplain, riparian and estuarine ecosystems, as has been detailed in the literature (Junk *et al*., 1989; Bayley, 1995; Poff *et al*., 1997; Alber, 2002; Lytle and Poff, 2004; Mathews and Richter, 2007; Piazza and La Peyre, 2007). Ecological benefits of floods include providing fish and other organisms with access to floodplain habitats that can be used for feeding, spawning and rearing; maintaining and rejuvenating plant habitats in the riparian zone and floodplain; influencing the geomorphology of the streambed; importing woody debris and organic material into the river channel; refreshing water quality conditions and helping transfer nutrients and maintain salinity conditions in estuaries. High flows just below flood stage (i.e. below bankfull stage) move sediment through the channel, provide respite for organisms from stressful low-flow conditions and improve connectivity to upstream and downstream habitats.

Conversely, alteration of natural flood events can have serious consequences for ecosystem health. The typical impact of dams is to reduce the magnitude of peak flood flow magnitudes, quite often dramatically (Richter *et al.*, 1998; Magilligan and Nislow, 2005; Graf, 2006), which degrades or eliminates many of the important functions described above. Reduction of flood flows in river systems can alter ecological communities and facilitate invasions by non-native species (Poff *et al.*, 1997), and lead to a variety of negative geomorphological consequences (Magilligan *et al.*, 2003). Given the importance of floodplain and estuarine ecosystems from the perspective of species richness, productivity and provisioning of ecosystem services (Costanza *et al.*, 1997; Tockner and Stanford, 2002), assessing the degree and extent of alteration of flood flows in the United States and elsewhere is an important research question that has bearing on a range of environmental and water management issues.

The goal of this paper is to assess the impact that existing dams have had on peak flood flows throughout the United States, in as comprehensive a fashion as is possible given available data. Previous sub-national studies have reported on the impact of dams on natural flow regimes (including flood flows) in the Colorado River basin (Richter *et al.*, 1998), the Connecticut River basin (Magilligan and Nislow, 2001), the state of Texas (Asquith, 2001) and the Wabash River basin in Indiana (Pyron and Neumann, 2008). Magilligan and Nislow (2005), Graf (2006) and Poff *et al.* (2006) analysed the impacts of dams on flows for a subset of rivers across the country (21, 36 and 43, respectively). Till date, the most comprehensive study of hydrologic alteration by dams

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was by Poff *et al.* (2007), who analysed the impacts of dams on intermediate size (3rd–7th order) rivers across the United States, using streamflow data for 186 stations below dams and 317 stations on undammed rivers. Similarly, Gao *et al.* (2009) examined several indicators for their ability to reflect changes in overall hydrologic alteration for 189 rivers with dams across the United States. These two studies covered the majority of the United States, using more streamflow data than in previous national evaluations, but still did not use all available streamflow data, for reasons described below.

The hydrologic impacts of dams are typically analysed by comparing various streamflow statistics from periods before and after the dam was constructed. An important constraint on applying this method for a national assessment of the alteration of flood flows is the availability of reference data on natural flows before dam construction. Typically 20 years of pre- and post-dam data are recommended in order to be able to reliably detect shifts in high flow statistics (Richter *et al.*, 1997; Huh *et al.*, 2005). These requirements make the number of stations available for use with such a standard pre- versus post- analysis necessarily limited. For example, of the 4859 gaging stations for which data were used in this study, only 564 had 20 years of data both before and after construction of a dam or dams. But an additional 1808 stations had at least 20 years of data after construction of upstream dams, without sufficient pre-dam data. Another concern with the pre- and post-method of analysis is the possibility that climate is shifting in the United States in ways that affect flood flows, as has been suggested by Hodgkins *et al.* (2003) and Stewart *et al.* (2005). Thus, instead of assuming stationarity of the flow records, we employ a method that explicitly takes into account temporal changes in both climatic and land-use factors.

We employ regional multivariate regression methods to assess impacts of dams and other factors on the behaviour of flood flows. The idea is to construct regional multivariate regression models that predict flood flows as a function of climatic, physiographic and anthropogenic characteristics of the watershed contributing to each gaging station. The US Geological Survey (USGS) has a long and rich history of developing such multivariate regression models for predicting both peak flow and low flow statistics at ungauged sites across the United States and a computer program is even available for the application of the resulting models at ungauged sites (Turnipseed and Ries, 2007). Such regional statistical models have also been developed for predicting annual average streamflows (Vogel *et al.*, 1999),and low flow statistics (Kroll *et al.*, 2004) across the United States, and for a variety of streamflow statistics in Washington, Colorado and Oregon (Sanborn and Bledsoe, 2006). Thus the method employed here has been well tested and vetted in the literature and in practice, and can be applied to large regions by generating data on watershed characteristics using standard GIS methods.

The streamflow statistic that will be analysed here is the median annual 1-day maximum flow for each decade in the 1900s, which we term as the median annual flood (MAF). We employ a nonparametric estimator of the MAF, which does not depend on the assumption of a frequency distribution. Since the MAF has a 50% chance of being exceeded in any year, it has an average return period of 2-years. This statistic is attractive from a geomorphological perspective, because in natural stream channels, the discharge necessary to reach bankfull flow occurs, on average, with a 2 year recurrence probability (Leopold *et al.*, 1964; Magilligan *et al.*, 2003). Magilligan *et al.* (2003) states that ‘the bankfull discharge has also been shown to be the dominant discharge for sediment transport and channel maintenance’, and it ‘also sets other geomorphic and ecological thresholds, because floods that exceed this discharge are capable of inundating the adjacent river floodplain’. Hence, the flow statistic considered here is closely related to bankfull discharge and has a number of critical geomorphological and ecological functions.

Our primary goal is to develop regression models for hydrologic units across the United States that relate the decadal MAF to watershed characteristics. The regression models are then used to discern the impacts of dams on flood flows across the country. Statistically significant impacts are summarized by river size and according to the freshwater ecoregions developed by Abell *et al.* (2008). The models and analysis presented here should provide the most comprehensive picture to date of the wide extent of dam impacts on flood flows in the United States, and will also highlight the potential for restoration of flood flows that exists in many parts of the country. This study will also test the efficacy of multivariate regression modelling for assessing the significance and degree of hydrologic alteration, an approach that to our knowledge has received little attention.

Use of regional regression models to evaluate influence of dam storage on flood flows

While the regression approach used here is standard in many ways, there are also some important differences from previous studies. Typically regional regression models are developed using period of record flow statistics which assume a stationary historical period. Since our goal is to model changes in flood flows due to the impact of dams during the 20th century, we examine flood data by decade. Decades are used because on the one hand they allow for assessment of trends over time, yet they also average out stochastic year-to-year variability that would otherwise be difficult to account for. Watershed characteristics that change over time, such as climate, land use and dam storage, are also calculated by decade, enabling the regressions to quantify the impacts of these different factors on the MAF.

Another important difference from earlier regional regression studies is that most previous studies focused on

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reference streamflow gaging stations, i.e. those stations that are mostly free of anthropogenic influences, so that streamflow measured at these sites is primarily influenced by natural factors. Instead we use all available streamflow gaging stations, whether impacted or not. To account for anthropogenic influences on flood flows, we included dam storage and watershed population density as potential independent variables in the regression, also computed by decade. Population density provides a surrogate measure of the influence of land development and is often highly correlated with residential impervious area. Other than dam storage and population density, there were no other variables in the regressions to represent anthropogenic impacts. While we recognize that there are other potential anthropogenic impacts on flood flows, such as land-cover changes other than impervious surfaces, and water withdrawals, it was not possible to consider the impacts of these variables in the regressions since there are no datasets representing the historical evolution of these variables during the 20th century.

The use of multivariate regional regression methods provides a number of important advantages over alternative approaches for testing hypotheses. Most importantly, the analysis 'replaces time with space'. That is, by incorporating many flow gaging stations in space, we effectively increase the sample size of the regression equations. Alternatively, each hypothesis test would only be on a single flow record, over perhaps two different periods of time (i.e. altered and unaltered). By integrating all stations within a region, the analysis effectively increases the sample size available by replacing limitations on the temporal extent of data at a single site with the fact that many sites are considered, in space, thus 'replacing time with space'.

A second advantage of the multivariate statistical approach is that it does not require that one specify beforehand that a particular station is or is not impacted by human activities, since the multivariate analysis adjusts for differences in flow that are related to anthropogenic factors. A third advantage is that a typical pre- and post-data analysis is difficult to implement in cases where dam storage has increased gradually on a river, due to construction of multiple dams over time, yet the regression method is well equipped to handle such situations. Lastly, because climatic data are in the regressions, the regressions will adjust for temporal climatic change across decades so that such climatic trends can be taken into account when assessing the impacts of dam storage on flood flows.

Limitations of approach

There are numerous concerns and caveats regarding the resulting regression equations. Regressions yield average impacts of dams on the MAF across a given region, thus they may be less precise in computing impacts at a particular location than the standard pre- and post-data analysis methods. While our use of regional regressions yields a more comprehensive picture of the impacts of dams on flood flows than alternate methods, it comes at the expense of losing some specificity about the impacts at a particular location. Partly for this reason, the regression results are only presented as averages for the hydrologic units for which the regressions were produced. As with all regression methods, it would be dangerous to extrapolate the results of our models, thus they should only be used within the regions and for the sites considered in our analyses.

DATA AND METHODOLOGY

Due to space limitations the data and methods used in this study are briefly summarized here, further details can be found in a separate report (FitzHugh and Vogel, 2010) available on the internet.

Databases

Decadal values for the MAF were obtained from daily streamflow data for 4859 USGS streamflow stations across the United States, using the Indicators of Hydrologic Alteration (IHA) software (Richter *et al.*, 1996; Mathews and Richter, 2007). The stations used here had to satisfy one of two criteria: (1) they had data for the most recent available decade (the 1990s) and at least one earlier decade; or (2) they were reference stations that had data for two decades or more from the 1900s to the 1980s. Reference stations used in this study are those stations identified in Slack and Landwehr (1992), Poff (1996) and Carlisle *et al.* (2009). The data for these stations yielded 23 228 individual decadal values of the MAF.

GIS analysis was used to compute a series of watershed characteristics to use as potential independent variables in the regressions (see Table I). These characteristics were selected from a much larger initial group of possible characteristics, and variables were only used if it was possible to generate a plausible qualitative hypothesis regarding the relationship between that variable and 1-day maximum flows (see Table I). Two other sources of information compiled to aid in this research are (1) codes from the annual instantaneous peak flow database in USGS National Water Information System (USGS NWIS, 2009), which indicate whether the peak flow for each year is altered by either regulation or diversion; (2) remarks that accompany each USGS streamflow station which describe, among other things, sources of alteration of natural streamflows, such as dams, irrigation withdrawals, etc.

Methods

We employ ordinary least squares multivariate regression procedures which are discussed elsewhere (Helsel and

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Table I. Watershed characteristics used as potential independent variables

Variable name	Definition	Log-transformed	Units	Hypothesized relationship with 1-day max	Source
DrArea	Drainage area	Yes	Sq. km.	+	USGS NWIS (2009)
Slope	Basin average slope	Yes	Per cent	+	1 km DEM from USGS
Flat	Per cent flat area (with <1% slope)	Yes	Per cent	−	1 km DEM from USGS
Precip	Median annual precipitation for each decade	Yes	Mm year^{-1}	+	PRISM data (Daly *et al.*, 2002)
Nov6pre, Feb3pre, May2pre, etc.	Average of median monthly precipitation for each decade, for months of high flow	Yes	Mm year^{-1}	+	PRISM data (Daly *et al.*, 2002)
Jan3pre, Dec4pre, etc.	Average of median monthly precipitation for each decade, for months with most snowfall	Yes	Mm year^{-1}	+ (snowmelt systems only)	PRISM data (Daly *et al.*, 2002)
May2tmp, Mar5tmp, etc.	Average of median monthly temperatures for each decade, for months of high flow	Yes	Degrees Kelvin	+ (snowmelt systems only)	PRISM data (Daly *et al.*, 2002)
Snow	Snowfall, long-term average	Yes	Mm year^{-1}	+ (snowmelt systems only)	National Climatic Data Center (2009)
Runoff	Runoff, long-term average	Yes	Mm year^{-1}	+	Gebert *et al.* (1987)
Aqperm	Aquifer permeability	Yes	Classes 1–7 (lowest–highest)	−	Wolock (2003)
Sand	Per cent sand	Yes	Per cent	−	Wolock (2003)
Soilthi	Soil thickness	Yes	Mm	−	STATSGO (Wolock, 1997)
Soilawc	Soil available water capacity	Yes	Fraction	−	STATSGO (Wolock, 1997)
Soildep	Soil depth to water table	Yes	Mm	−	STATSGO (Wolock, 1997)
Storatio	Total maximum storage capacity of all upstream dams, divided by average annual runoff (Runoff), for each decade	No	Years of runoff in storage	−	Army Corps of Engineers National Inventory of Dams database from BASINS 2.0 (1999)
Popdens	Population density, by decade	No	Persons per sq. km.	+	US Census Bureau (2009)

Hirsch, 2002). Regression models were developed for each of 209 hydrologic units (HUs) that cover the bulk of the United States (except for a few areas without streamflow stations). Maps of the HU's are given later in Section 3 and in Figure A1 in Appendix 1. The dependent variable was log-transformed prior to creating the regressions, as were all independent variables except Storatio (maximum dam storage capacity/mean annual runoff) and Popdens (population density), because use of those two variables in real space led to more precise regression coefficients. The climatic variables used as potential independent variables varied by HU, depending on the timing of flood flows and precipitation during the year and whether the flood response of the HU was dominated by rainfall or snowmelt processes.

Due to the computational complexity associated with the model selection procedure, the best regression in each HU was identified automatically using an algorithm written in the *R* statistical package (R Development Core Team, 2006). This algorithm is described in detail in FitzHugh and Vogel (2010), so it is only briefly summarized here. The algorithm evaluates independent variables in a stepwise manner, evaluating each variable according to its *p*-value (must be < 0.05), its Variance Inflation Factor (VIF, must be < 5), whether its model coefficient matches the hypothesis in Table I, and whether addition of the variable both increases the adjusted *R*-squared and decreases the prediction sum of squares PRESS statistic. From this procedure a series of candidate regressions are identified, and then the final regression for each HU is selected based on a comparison of values of the PRESS statistic. Residuals were evaluated using the correlation coefficient of a normal probability plot of the model residuals, and if necessary, outliers were removed either by visual assessment of this plot or using the DFITS criterion.

RESULTS AND DISCUSSION

Screening and evaluation of regression models

Implementation of the regression selection algorithm yielded 201 HUs with a final regression that was acceptable based on the above criteria, i.e. only eight HUs ended up without a regression. Table A1 in Appendix 1 lists the final

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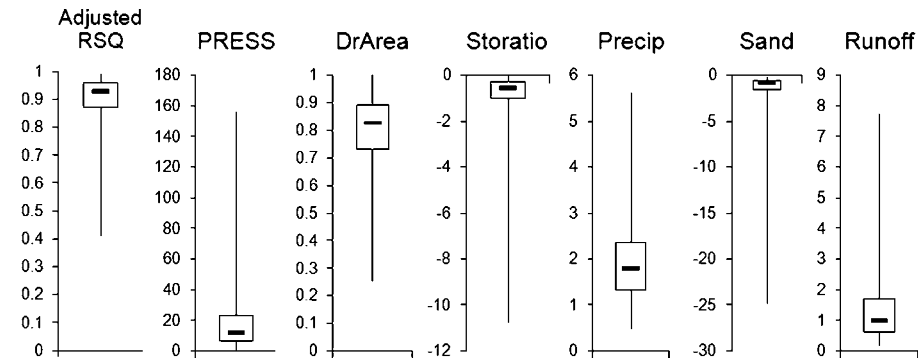

Figure 1. Boxplots of adjusted R^2, PRESS and the coefficients of the five most common independent variables in regressions

regression models for each HU. Figure 1 shows some key results for the regressions. In general, the regressions performed well, with generally high adjusted R^2s and low PRESS statistics.

The regression models were then used to quantify the degree to which dams are currently reducing the MAF in each HU. This was done by setting the maximum storage/mean annual runoff variable, Storatio, to 0, and then recalculating the MAF for all stations that had data in the 1990s. The per cent difference was then computed between this value and the fitted value of MAF from the original regression, and this per cent difference was used as an estimate of the reduction in the MAF during the 1990s due to dam storage. For a few HUs where there were no sites with Storatio = 0, we set the Storatio to the minimum value in that HU, because it is dangerous to use the regressions outside the range of the data used in their development.

Next we used ancillary information available from USGS to screen and evaluate the regressions. We calculated the percentage of years in the 1990s when the peak flows at each streamflow station were coded as altered by regulation or diversion. Then we computed the proportion of total estimated alteration in each HU that was assigned to stations that have no such codes in the peak flow data. One could think of this as an estimate of the proportion of alteration estimated in an HU that is likely to be erroneous.

We used this proportion to examine the degree to which regressions that identified statistically significant relationships between Storatio and MAF were estimating an average alteration in the 1990s that was generally representative of conditions in that HU. All HUs where this percentage was greater than 33% were judged to have significant errors, so these 18 HUs were dropped from further analysis. The one exception was the HU for the Susquehanna mainstem, where although this percentage was 51%, there were USGS remarks for all streamflow stations of slight regulation of flows by flood control reservoirs, including those with no alteration indicated in the peak flow codes.

We also eliminated eight regressions for HUs that have a high percentage of peak flows coded as altered and gage remarks of impacts of regulation, but where the coefficient for Storatio was not statistically significantly different from zero in the regression. Finally, four more regressions were eliminated because their adjusted R^2 was below 0.5 indicating that the statistical relationship was very weak. Overall, this left 171 regressions where the estimated per cent alterations were considered to be representative enough to continue with further analysis (shown in Figure 2). These models cover 78% of the area of the continental United States.

Analysis of the impact of dams on flood flows in the United States

Figure 2 is striking because it shows the wide extent of alteration of natural flood flows by dams in the continental United States. The HUs where a statistically significant relationship was found between reduction of flood flows and dam storage cover about 64% of the country, but they cover 84% of the area of the HUs where good regressions were created (those shown in Figure 2). Alteration of flood flows is present in every region of the country, though less so in the mid-Atlantic, Southeast and upper Midwest. Alteration is generally more severe west of the Mississippi and especially in the southern Great Plains, desert Southwest and northern California. Using the estimated alterations for individual gauges, we further summarize these results by freshwater ecoregion (Abell *et al.*, 2008) and river size (see Figure 3). Overall, 3453 stations are available for this analysis.

Table II and Figure 4 summarize our results. One obvious and expected conclusion is that the degree of alteration of flood flows increases as the size of the river increases. In the majority of ecoregions, alteration is greater in large rivers than in medium rivers, and greater in medium rivers than small rivers. Across the country, estimated reduction of MAF for large rivers averages 29%, for medium rivers 15% and for small rivers 7%. These data indicate that a large number of rivers in the United States have had significant reduction in flood flows due to dams. To put these numbers in perspective, we compare them to some research results on

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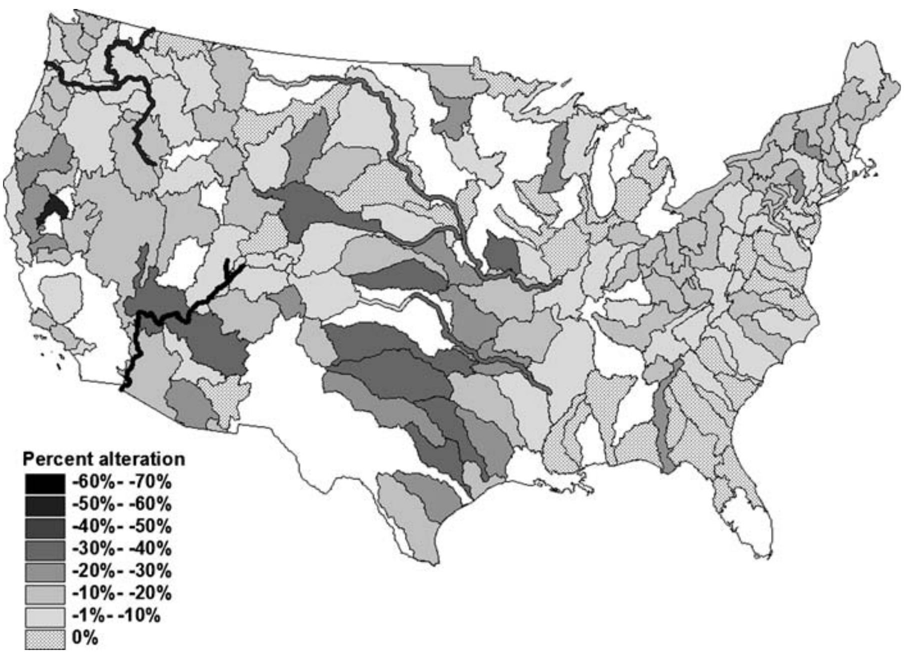

Figure 2. Estimated per cent alteration (reduction) of MAF by dam storage, for 1990s. This percentage is the average of the estimated per cent alterations for stations in each hydrologic unit that have data in the 1990s

natural variability of flood flows due to long-term climate trends and also on the relationships of flood flow reduction to ecological impacts.

Long-term variation in bankfull discharges during the Holocene has been quantified in streams in southwestern Wisconsin (Knox, 2000) and northeastern Utah (Carson *et al.*, 2007), and in both cases compared to modern bankfull discharges. In Wisconsin the maximum variability of Holocene bankfull discharge was $\pm 30\%$ from modern discharges, and in Utah it was $\pm 20\%$. Thus, the maximum decrease

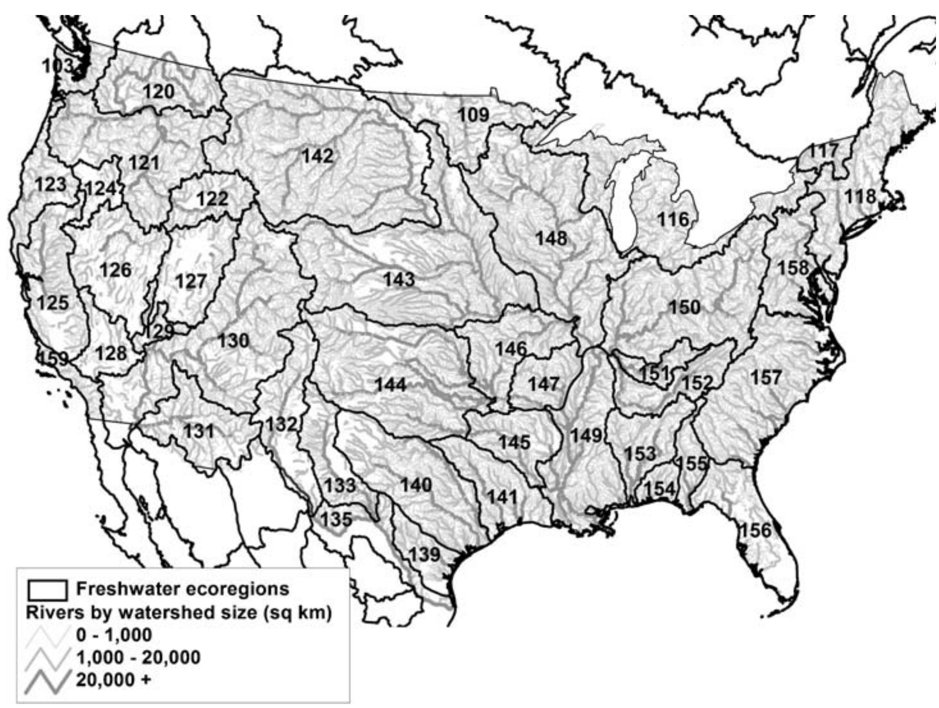

Figure 3. Freshwater ecoregions from Abell *et al.* (2008), and river and streams, by size. Numbers are ecoregion ids, referenced in Table II

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Table II. Average per cent decrease in MAF in 1990s due to dam storage. Numbers are the average of the estimated alterations for all streamflow stations in each ecoregion and river size category. River size classes are 0–1000 km^2 watershed (small), 1000–20 000 km^2 (medium) and 20 000+ km^2 (large). Numbers in bold are size classes where there were fewer than two stations per 1000 km of river length in the size class. This could occur because a portion of the ecoregion did not have a good regression, or because of a lack of stations in general. Table also shows the per cent of area in the US part of the ecoregion that is covered by hydrologic units with valid regressions

Freshwater ecoregion	ID	Per cent of area in United States covered by hydrologic units (%)	Average per cent alteration			
			Small rivers and streams (%)	Medium rivers (%)	Large rivers (%)	All rivers and streams (%)
Alaska & Canada Pacific Coastal	103	100	−10	−12	—	−10
Apalachicola	155	100	−1	−24	−22	−14
Appalachian Piedmont	157	100	−4	−9	−15	−6
Bonneville	127	61	−10	−31	—	−17
Central Prairie	146	100	−18	−18	−30	−19
Chesapeake Bay	158	100	−5	−4	−9	−5
Colorado	130	92	−5	−15	−44	−12
Columbia Glaciated	120	92	**0**	−10	−30	−12
Columbia Unglaciated	121	100	**−10**	−12	−27	−12
Cumberland	151	100	**−10**	−3	−66	−14
Death Valley	128	9	—	—	—	—
East Texas Gulf	140	58	**−17**	−31	−42	−27
English—Winnipeg Lakes	109	66	**−1**	−16	−19	−13
Florida Peninsula	156	65	0	0	0	0
Gila	131	100	0	−10	−40	−11
Lahontan	126	97	−7	−20	−34	−14
Laurentian Great Lakes	116	69	−5	−7	—	−6
Lower Mississippi	149	76	**0**	−1	**−41**	−1
Lower Rio Grande—Bravo	135	11	—	—	—	—
Middle Missouri	143	80	**−7**	−19	−38	−21
Mobile Bay	153	61	**−1**	−10	**0**	−6
Northeast US & Southeast Canada Atlantic Drainages	118	94	−7	−19	−15	−10
Oregon & Northern California Coastal	123	100	−5	−17	−17	−10
Oregon Lakes	124	92	—	—	—	—
Ouachita Highlands	145	100	**−1**	−19	−40	−15
Ozark Highlands	147	100	**0**	−15	−53	−17
Pecos	133	0	—	—	—	—
Sabine—Galveston	141	85	−10	−42	−37	−25
Sacramento—San Joaquin	125	76	−14	−29	−44	−21
Southern California Coastal—Baja California	159	62	−9	−27	–	−13
St.Lawrence	117	98	−12	−16	—	−14
Teays—Old Ohio	150	92	−7	−14	−14	−11
Tennessee	152	55	**−3**	−10	**−48**	−6
Upper Mississippi	148	53	**0**	−10	−13	−5
Upper Missouri	142	82	**−6**	−9	−19	−10
Upper Rio Grande—Bravo	132	13	**−31**	−17	—	−24
Upper Snake	122	75	**−4**	−14	−10	−11
US Southern Plains	144	73	**−17**	−23	−28	−23
Vegas—Virgin	129	100	−18	−35	—	−27
West Florida Gulf	154	100	**0**	0	—	0
West Texas Gulf	139	97	**−1**	−10	−48	−11
Total		78	−7	−15	−29	−12

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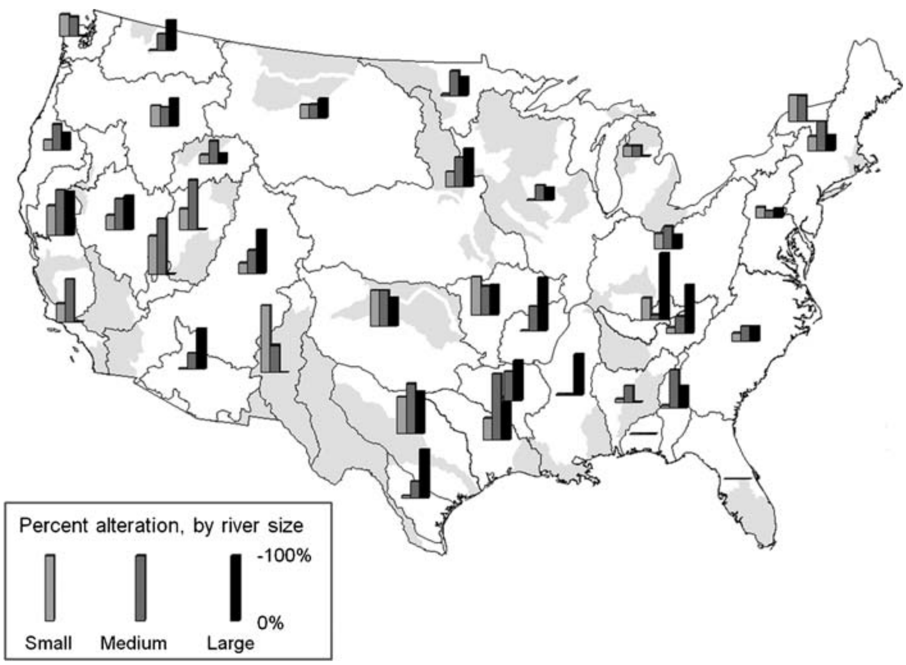

Figure 4. Average per cent decrease in MAF for 1990s due to dam storage, for small, medium and large rivers. Data are from Table II. Light grey shading shows areas not covered by regression models

from current natural conditions that has occurred in the last 12 000 years from natural climate variability is approximately 25%. For comparison, when Arora and Boer (2001) modelled impacts of global climate change (by 2100) on floods with an average 2-year return period in 10 major rivers, the average reduction was also similar (−21% for the seven rivers that experienced a reduction). Figures 5–8 are used here to assess the extent of reductions in MAF due to dam storage beyond a threshold of −25%, for small, medium and large rivers.

Figure 5 shows the per cent of stations that have reductions in MAF of greater than a series of thresholds from

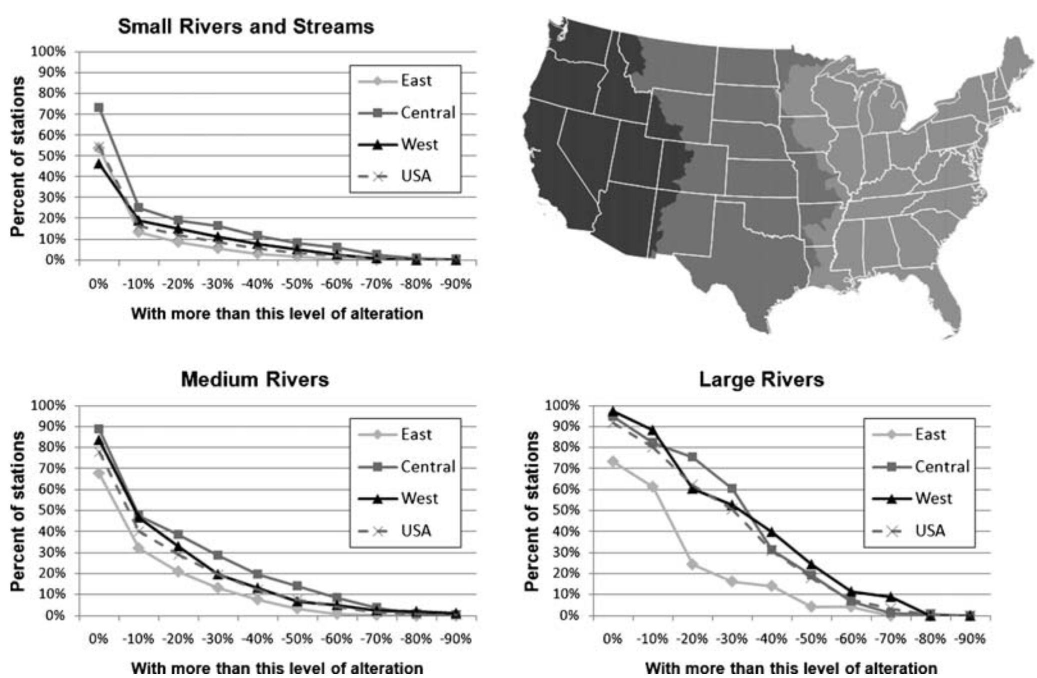

Figure 5. Per cent of stations on small, medium and large rivers with different levels of reduction in MAF, for the Eastern, Central and Western United States

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0 to 90%, for the entire United States and for three large regions of the country. Here it can be seen that depending on river size class and US region, from 10 to 70% of rivers have seen reductions in MAF of greater than 25%. For the country as a whole, the per cent of rivers with greater than a 25% reduction in MAF is 55% for large rivers, 25% for medium rivers and 10% for small rivers. Alteration is most severe in the central and western United States: 70% of large rivers in the central United States and 55% of large rivers in the West are beyond the 25% threshold. Small and medium rivers also have greater levels of alteration in the central and western United States. Figures 6–8 show the per cent of stations with greater than a 25% reduction in MAF by freshwater ecoregion. Though alteration is consistently lower for the eastern United States as a whole, from Figure 6 it can be seen that high levels of alteration do occur for medium and large rivers in a few eastern ecoregions. Figures 7 and 8 show that most ecoregions are experiencing at least some degree of reduction in MAF, even if it is not widespread enough for the ecoregion to appear in Figure 6. In the majority of ecoregions at least 10% of rivers have a 25% or greater reduction in MAF in all three river size classes.

It is important to note that such changes have occurred over a vastly shorter period of time than occurred naturally during the Holocene, giving the geomorphology and ecology of rivers and streams far less time to adjust. Magilligan *et al.* (2003) have enumerated some of the likely consequences of reductions in bankfull discharge, including significant adjustments in channel morphology and substratum composition, channel armouring, disconnection of some or all of the floodplain and riparian area from the channel and alteration of both riparian and in-channel biological community structure.

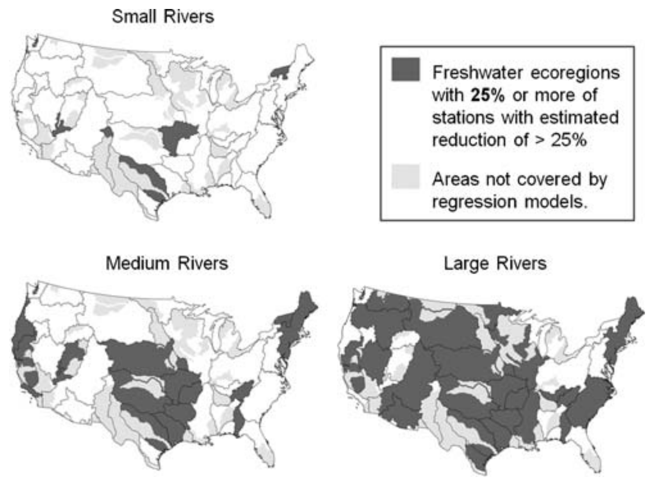

Figure 7. Freshwater ecoregions with 25% or more of stations having estimated reduction in MAF of $>25\%$, by river size

A few previous studies have reported the ecological impacts of flood flow reductions on biota. For example, Wilding and Poff (2008) have developed some quantitative relationships for streams in Colorado that give some perspective on possible impacts. For riparian vegetation, their quantified relationship was that each 10% reduction in peak flows led to a maximum per cent change in riparian vegetation community composition of approximately 12%. This being a maximum response, actual response could vary from 0–12%, depending on other biotic and hydrologic factors. For macroinvertebrates, the relationship was exponential, with maximum response of invertebrate metrics to reductions of peak flows of 10, 50 and 80% calculated at approximately 20, 90 and 250%, respectively. Though these

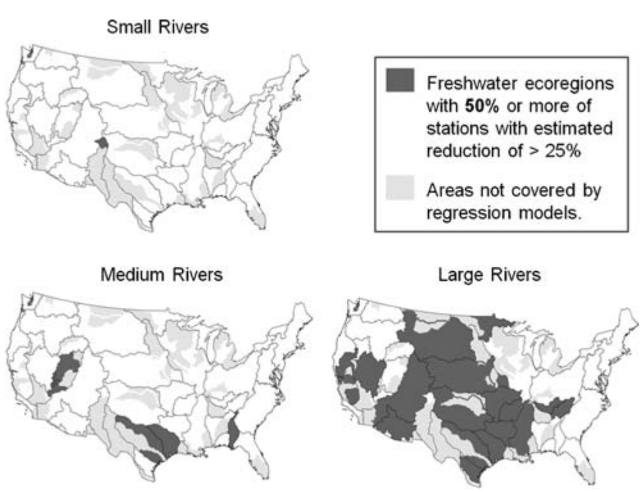

Figure 6. Freshwater ecoregions with 50% or more of stations having estimated reduction in MAF of $>25\%$, by river size

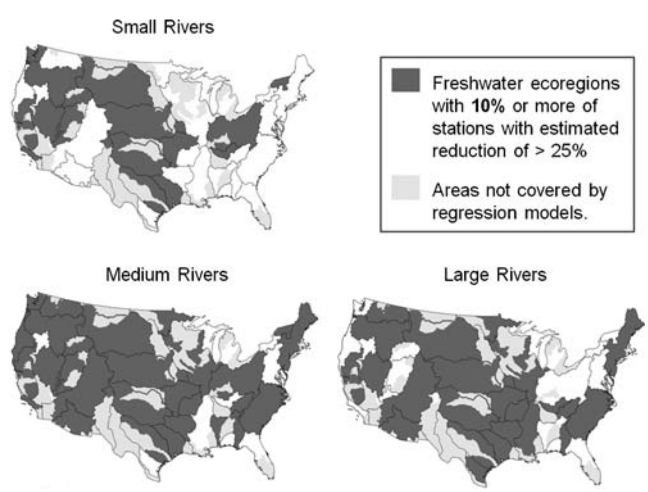

Figure 8. Freshwater ecoregions with 10% or more of stations having estimated reduction in MAF of $>25\%$, by river size

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relationships are for streams in just one part of country, this gives us at least a general idea of how the reductions of flood flows displayed in Figures 5–8 could affect biota.

Evaluation of a dam storage metric for predicting flow alteration

Metrics such as dam storage per unit stream length or watershed area have been used as indicators of downstream freshwater ecosystem condition in regional biodiversity conservation planning projects such as The Nature Conservancy's ecoregional assessments (Groves *et al.*, 2002; FitzHugh, 2005). Here we evaluate the variable Storatio (ratio of upstream dam storage to mean annual runoff) for its ability to characterize one component of hydrologic alteration, alteration of flood flows. Figure 9 shows the relationship between regression estimates of flow alteration and Storatio, for individual stations and as averages for HUs. The boxes on the figure characterize approximate thresholds of Storatio as it relates to different levels of flood flow alteration. The box on the right, above a Storatio value of 0.5, contains watersheds and stations with a large range of levels of alteration, from none to very high alteration, but with the majority of the points above 10% alteration. The middle box, between 0.05 and 0.5, contains HUs with moderate to no alteration, and the left box contains units with either low or no alteration.

Figure 9 documents that the variable Storatio is related to the level of alteration of flood flows, but that within each of the three categories (boxes) there is a wide range of levels of alteration. Graphing stations and HUs by region of the country was not found to improve the relationship shown in this figure. It appears that the appropriate use of such a metric would be as an indicator of the maximum potential level of alteration of flood flows (and by inference ecological condition), and also the range of possible levels of alteration.

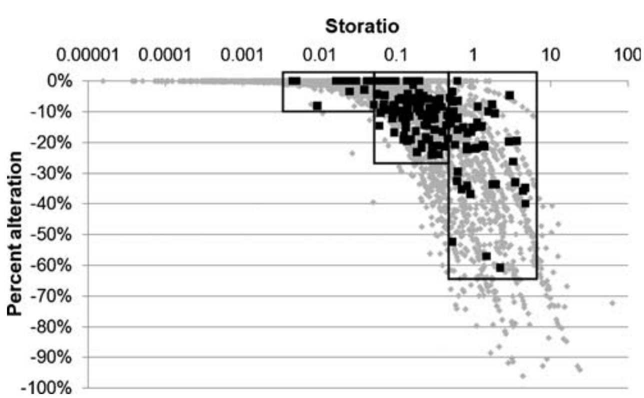

Figure 9. Storatio versus estimated per cent alteration of MAF. Black points in foreground are averages for each hydrologic unit. Light points in background are points for individual stations in these hydrologic units. The values of Storatio at the boundaries between the three boxes are 0.05 and 0.5

However, it would be inappropriate to assume that any given river actually reaches this maximum level of alteration, at least without more detailed analysis. With those caveats, the Storatio thresholds presented here may be useful in regional planning exercises in regions where it is not possible to better quantify the degree of alteration in flood flows.

CONCLUSIONS

This research has highlighted the wide extent of alteration of flood flows by dams in the United States, particularly on large rivers and in the western United States. While reduction of flood flows has undoubtedly had widespread and significant ecological consequences for the nation's river ecosystems, we also recognize the importance of dams for managing the flood response of rivers and for providing numerous other benefits ranging from irrigation and water supply to recreation and navigation. Floods can cause major damage to human lives and property, and flood damage has devastated cities and towns in the United States. The Army Corps of Engineers estimates that its flood control activities have prevented $706 billion of flood damages, mostly in the last 25 years (USACE-IWR, 2000). But at the same time, Pielke *et al.* (2002) has shown that despite the billions of dollars spent on dams and other structural flood control measures, both total and *per capita* flood damages continue to rise.

The interrelated issues of declining ecosystem health and continuing increases in flood damages have spurred the Association of State Floodplain Managers, a leading voice in floodplain management practice and policy in the United States, to call for reforms in floodplain management (for example ASFPM, 2003, 2008). Among their proposals is an urgent call for greater emphasis on maintaining natural and beneficial functions of floodplains (ASFPM, 2008), a key component of which would be restoration of more natural flood flows in places where they can be accommodated without causing economic damage. The results of our national study re-emphasize not only this need but also the opportunities that exist nationwide for such restoration. ASFPM and other organizations have developed cogent proposals for what needs to be done, which include relocation of development from flood-prone areas and greater accounting for natural floodplain functions (ASFPM, 2008). With respect to re-operation of dams to restore flood flows, there are good examples in the environmental flow science literature of how to define ecosystem needs in terms of flow and how to implement a dam re-operation plan for maximum ecological benefit (Richter *et al.*, 2006; Richter and Thomas, 2007; Vogel *et al.* 2007).

This paper has enumerated the reduction in flood flows due to dams throughout the United States, while at the same

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time demonstrating the efficacy of regional regression analysis for assessments of hydrologic alteration. In some ways assessing the impacts of dams on flood flows was the most straightforward analysis of alteration that could be conducted comprehensively on a national scale, because it is (1) generally easier to create regression models for peak flows than for other flow statistics such as low flows, (2) historical data on dam storage is better than data on other types of impacts and (3) there are ancillary sources of information on flood alteration (USGS codes for alteration of instantaneous peak flows) that do not exist for other types of flow impacts. However, clearly there is potential for using similar methods for assessment of impacts of dams and other factors on other flow statistics and components of the hydrologic regime.

Though USGS has been most successful in creating regressions for peak flows, there are other studies that have successfully modelled a variety other flow statistics (Vogel *et al.*, 1999; Kroll *et al.*, 2004; Sanborn and Bledsoe, 2006; Carlisle *et al.*, 2009). While historical records of land-cover (other than impervious surface) and water withdrawals are not nearly as extensive as climatic and streamflow datasets on a national basis, there are methodological and data collection solutions that could resolve these issues. For land-cover, space could be substituted for time in the regression analysis, as has already been done by Poff *et al.* (2006) for some parts of the country. While the USGS national data on water withdrawals (Hutson *et al.*, 2004) has too coarse a spatial scale and too limited a temporal scale for this sort of analysis, some states that are compiling more detailed water rights and withdrawal data that could be useable for this purpose (see CWCB-CDWR, 2009; TCEQ, 2009).

With regard to further analysis of alteration of flood flows in the United States, there are a number of additional research questions that could be addressed using the data and models introduced here. First, an analysis of the impacts of population density on flood flows is possible because the regressions include a population density variable. Second, the National Inventory of Dams includes information on the operating purposes of dams (i.e. flood control, water supply, hydropower, irrigation, etc...), which may lead to improvements in the explanatory power of the regressions. Third, similar methods could be used to quantify the impacts that dams operated by certain large agencies (such as the Army Corps of Engineers) are having on flood flows.

Another potentially useful extension of this research would be to analyse the estimated impacts of dams on flood flows for specific river reaches. Since it is possible to generate all the independent variables for each river reach using GIS data, this could be done with some additional GIS and database work Reach-scale estimates of alteration for at least some parts of the country could be very useful. They could be used to address additional questions, such as the distance downstream that dams have impacts on flood flows, and also have practical applications, such as highlighting important locations for environmental flow restoration. They could also be combined with other datasets, such as biological data, to assess other questions such as the impact of altered flows on biological communities.

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APPENDIX 1: REGRESSION MODELS AND HYDROLOGIC UNITS

Table A1. Regression models for 209 hydrologic units. All variables have p-value < 0.05 and VIF < 5. Variables are defined in Table I. Hydrologic units marked with * are those used in the final analysis, presented in Table II and Figures 2 and 4–9. The first part of the table shows rainfall systems, the second part shows snowmelt systems

Hydrologic Unit	Map ID	Intercept	DrArea coeff.	Other variables and coefficients					Adj. R^2	PRESS	Degrees of Freedom
Rainfall systems											
109final	1	−13.54	0.772	precip 1.748879	popdens 0.000386				88.5%	16.84	156
110final*	2	−10.00	0.792	aqperm -0.184598	storatio -0.2307	slope 0.244504	precip 1.324847		96.3%	7.04	134
20301010203final*	3	−26.09	0.892	storatio -0.1272	nov6pre 2.509237	runoff 7.756577	popdens 0.00016	soilthi -1.6039	93.1%	9.46	133
203010405final*	4	−3.90	0.882	sand -0.61951	precip 1.043576	soildep -0.299019			92.1%	18.65	123
20302final	5	−1.11	0.724	popdens 0.00038	slope 0.937151	aqperm -0.770891			49.8%	16.48	79
204010506final*	6	4.95	0.900	aqperm -0.392621	soilthi -2.472017	precip 1.698408	storatio -0.3249		87.6%	30.36	150
2040201020305final*	7	−6.24	0.893	sand -0.784324	storatio -0.535	popdens 0.000818	precip 1.175241	flat -0.111892	95.5%	21.64	161
204020607030102final*	8	−1.15	0.732	precip 2.351119	sand -6.844305	soilawc -5.424875			85.5%	6.84	56
2050106070301final*	9	−2.57	0.843	storatio -2.3284	precip 1.321504	soildep -1.007072			94.4%	4.17	78
20502final*	10	−9.27	0.949	soilawc -2.738212	storatio -0.5375	aqperm -0.632792	dec6pre 0.594825		97.8%	4.48	106
205030203040506final*	11	−12.35	0.927	storatio -0.343	flat -0.072082	soilawc -1.097663	precip 1.289503		96.3%	7.47	123
Susquehanna_mnfinal*	12	−2.41	0.780	dec6pre 0.61746	storatio -0.8656				94.8%	0.80	67
206final*	13	−14.11	0.964	storatio -1.421	aqperm -0.261417	popdens 0.000569	precip 1.803646		92.6%	12.41	107
207000102030506final*	14	−10.66	0.905	precip 1.065043	soilawc -0.96473				96.1%	11.86	186
207000407080910final*	15	−2.04	0.904	precip 1.537751	soilthi -1.35369	popdens 0.000222	aqperm -0.226318		96.8%	20.86	172
20801final*	16	−15.80	0.893	slope 0.233068	precip 2.349929	sand -0.552076			96.9%	7.71	94
208020102final*	17	−4.68	0.889	soilthi -1.170376	storatio -0.4492	precip 1.708377			98.5%	4.54	129
208020304050607final*	18	−20.37	0.887	slope 0.117272	precip 2.74286	aqperm -0.626182			94.0%	5.61	78

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30101final*	19	−15.01	0.874	precip 1.992149	popdens 0.002198	storatio -0.6861			95.1%	14.01	163
30102final*	20	−16.24	0.696	aqperm -0.755598	precip 2.353098				92.5%	4.54	66
302final*	21	−20.46	0.753	sand -1.785038	storatio -0.3997	soilawc -3.850312	precip 2.654913		94.8%	8.03	108
303final*	22	−32.54	0.886	popdens 0.003196	storatio -0.702	sand -1.496149	precip 4.976699	soilawc -0.649457	96.5%	7.96	85
304final*	23	−11.37	0.829	aqperm -0.428115	storatio -0.7348	sand -0.643647	precip 1.837678		95.9%	12.27	154
30501final*	24	7.57	0.812	soilthi -2.249074	aqperm -2.888125	precip 1.182322	storatio -1.1445		96.5%	5.58	68
30501splitfinal*	25	−8.36	0.849	sand -0.916417	precip 1.603909	popdens 0.001093	flat -0.210508		95.1%	12.61	89
30601final*	26	−0.71	0.741	storatio -0.2828	jan4pre 1.490572	sand -1.795244			97.1%	10.20	70
305020602final*	27	836.92	0.763	soildep -1.085561	jan4pre 1.860854	soilthi -114.4799			91.7%	3.27	46
30701final*	28	14.96	0.761	soilthi -3.866739	sand -0.705864	precip 2.19576			97.0%	8.41	131
308final*	29	−3.90	0.624	runoff 1.894858	slope 0.615186				86.1%	27.09	123
309final	30	−12.16	0.986	aug3pre 2.735394	storatio -0.0536	soildep -0.648401	flat -0.090177		89.5%	25.15	67
310final	31	−5.64	0.840	soildep -0.487651	storatio -0.2113	runoff 2.854907			77.1%	10.39	71
310splitfinal*	32	−47.58	0.778	runoff 2.763124	flat -0.112593	precip 5.622899			84.6%	28.72	95
3071112final*	33	−4.25	0.776	runoff 1.302391	slope 0.182441				87.1%	23.37	124
313final*	34	−8.14	0.823	popdens 0.000478	storatio -0.6758	precip 1.062563	aqperm -0.232751		95.5%	9.49	107
313splitfinal*	35	21.44	0.785	soilthi -6.023149	precip 3.078651				95.6%	5.66	67
314final*	36	−10.81	0.842	feb3pre 2.058155					91.6%	7.17	73
315final*	37	−2.18	0.837	storatio -1.1338	sand -1.053303	soilthi -1.068022	precip 1.769791		94.5%	8.59	100
315splitfinal	38	−8.93	0.827	storatio -0.013944	precip 1.476599	sand -0.552402			97.4%	4.56	72
316final*	39	−11.50	0.809	jan4pre 1.263095	runoff 2.474325	sand -0.691313			95.6%	18.74	158
317final	40	−10.32	0.708	storatio -2.6747	precip 1.768951	sand -0.593158			94.6%	5.34	95
318final*	41	−5.52	0.647	soildep -0.710911	precip 1.575251				96.0%	2.43	67
405final*	42	−4.97	0.849	aqperm -1.073638	runoff 1.703397				90.2%	41.94	161
410final	43	131.57	0.860	precip 1.157145	sand -0.45814	popdens 0.002183	storatio -0.3847	soilthi -19.02451	96.6%	4.21	106

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Table A1. (Continued)

Hydrologic Unit	Map ID	Intercept	DrArea coeff.	Other variables and coefficients				Adj. R^2	PRESS	Degrees of Freedom
41112final*	44	−2.80	0.855	storatio -2.063	aqperm -0.231315	sand -0.606692	jan4pre 0.987187	91.3%	4.91	87
413final*	45	−6.36	0.864	storatio -2.1723	precip 2.325974	aqperm -0.690526	soildep -1.490585	96.1%	3.14	55
414final*	46	−13.35	0.798	precip 1.790107	storatio -0.4585			91.3%	16.71	87
501final*	47	−4.19	0.876	storatio -1.0131	runoff 1.640667	jan3pre 0.372673	soilthi -0.481191	98.4%	6.42	167
502final*	48	4.90	0.899	soilthi -1.086985	storatio -0.9853	flat -0.069714	dec5pre 0.462053	98.2%	6.62	191
503final*	49	−1.25	0.858	storatio -0.4501	sand -0.47571	soilawc -0.92694		95.1%	13.64	178
504final*	50	−12.28	0.884	storatio -1.5348	sand -0.618206	precip 1.888747		95.2%	9.55	100
505final*	51	0.34	0.898	soilthi -0.975811	storatio -1.7336	dec5pre 1.243576		97.3%	7.38	174
506final*	52	0.54	0.859	jan4pre 0.982822	soildep -0.808001	slope 0.403423	storatio -0.2751	97.2%	5.41	94
507final*	53	−17.56	0.875	precip 2.406891	storatio -0.008745			94.1%	4.17	58
508final*	54	−11.28	0.952	runoff 4.946363	soildep -1.15992	storatio -0.3848	jan5pre 1.259083	97.5%	3.33	121
509final*	55	−1.48	0.853	storatio -1.0093	soildep -0.442999	sand -0.790692	jan5pre 1.431535	94.0%	5.19	59
510final*	56	−17.86	0.842	sand -0.410461	storatio -3.026	soilawc -1.906444	precip 2.121573	97.9%	3.43	106
511final*	57	0.68	0.656	sand -0.823733	storatio -0.2388	dec5pre 0.540675		97.3%	1.75	41
5120101020 30405final*	58	−7.03	0.827	sand -1.004997	aqperm -0.396152	storatio -1.1821	jan5pre 2.273204	95.4%	10.52	118
512010809 101112final*	59	47.23	0.760	jan5pre 0.862878	storatio -0.7637	soilthi -6.987562		96.0%	17.18	136
512020102 03final*	60	−4.93	0.820	storatio -0.4697	aqperm -0.29848	jan5pre 1.068194		97.4%	8.24	121
51202040 5060708final*	61	0.80	0.723	storatio -0.5927	soildep -0.805125	runoff 1.867411		92.3%	14.53	110
513final*	62	−17.33	0.849	storatio -1.5512	precip 2.400959			96.0%	6.76	112
514final	63	−6.11	0.784	storatio -0.5652	slope 0.343184	sand -0.620285	precip 1.097628	95.0%	8.37	90
60101final*	64	−12.49	0.880	precip 1.109221	soilawc -1.756097	storatio -1.5916		95.1%	13.61	162
60102final*	65	−2.31	0.878	storatio -1.4897	soilthi -0.582294	sand -0.676417	precip 1.113442	96.3%	9.95	156

60304final	66	−8.61	0.757	precip 1.443554	storatio -0.5168	flat -0.173926	sand -0.20764	98.8%	3.17	87
706final*	67	−4.45	0.769	jan6pre 0.943959				88.2%	5.30	46
70801final*	68	−3.84	0.681	precip 1.714914	soildep -1.052451	slope 0.596237		94.1%	3.88	70
70802final	69	−12.99	0.728	runoff 1.791667	precip 2.052425	soildep -0.680068	storatio -1.1949	94.9%	10.93	134
709final	70	−4.31	0.819	precip 1.690451	storatio -10.737	sand -0.678054	soildep -0.917539	86.6%	24.94	133
710final	71	−18.16	0.776	storatio -0.665	precip 2.367689	runoff 0.945392	slope 0.365303	94.0%	8.73	131
711final*	72	30.98	0.712	flat -0.246472	storatio -0.5923	soilthi -6.614832	precip 2.777642	92.2%	8.06	103
712000102 050607final*	73	−7.99	0.892	sand -1.192445	soildep -1.103184	popdens 0.001065	precip 2.575715	96.8%	8.87	139
7120404final*	74	−14.60	0.754	soilawc -1.782144	sand -0.21018	precip 1.639959		90.8%	15.79	170
713final*	75	−11.16	0.685	slope 0.551215	precip 2.254533	soildep -0.52465		94.0%	9.78	138
714final*	76	−4.92	0.602	storatio -0.2663	slope 0.315098	precip 0.893269		91.1%	12.20	150
Mississippimnfinal	77	−21.23	0.898	precip 2.794883				98.3%	2.45	113
8010203final*	78	−1.38	0.533	precip 2.655432	flat -3.254972	storatio -0.8056	aqperm -0.988716	90.5%	4.82	63
80405final*	79	−14.64	0.629	slope 0.543026	storatio -0.1875	precip 2.203323		89.2%	9.62	65
80607final*	80	2561.13	0.649	flat -15.49326	precip 1.556772	soilthi -341.1298		84.6%	5.87	64
808final	81	938.13	0.343	storatio -3.2594	aqperm -846.4351	soildep -0.831317		56.4%	25.80	47
10040506final	82					No acceptable regressions				
101113final*	83	−4.50	0.701	runoff 0.470903	mar4pre 1.597672	storatio -0.1189	sand -0.963175	83.8%	23.10	116
1012final*	84	−12.79	1.013	mar4pre 2.464344	storatio -0.0664	aqperm -1.923792	flat -0.156613	83.6%	62.21	131
101415final*	85	−8.69	0.882	mar4pre 1.55799	runoff 0.520502	aqperm -1.046833		87.2%	33.18	94
101617final	86	−24.22	0.546	slope 0.666011	precip 3.768187			72.0%	43.35	109
102021final*	87	−2.91	0.653	popdens 0.011823	runoff 2.00444	storatio -0.2714		85.9%	15.91	84
102223final*	88	−9.49	0.720	precip 2.94874	flat -2.37764			79.6%	15.78	90
1024final	89	−5.77	0.728	soildep -1.624082	slope 1.174142	precip 2.603189	storatio -0.3916	88.2%	3.61	68
1025final*	90	−4.46	0.775	runoff 0.753054	soilawc -1.007709	storatio -0.0681		79.5%	85.37	140

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Table A1. (Continued)

Hydrologic Unit	Map ID	Intercept	DrArea coeff.	Other variables and coefficients					Adj. R^2	PRESS	Degrees of Freedom
1026final*	91	−16.00	0.846	runoff 0.775606	storatio -0.127	soilawc -7.897968			72.3%	62.62	123
1027final*	92	−17.28	0.753	slope 0.528791	precip 2.150739	storatio -0.3751	soilawc -1.485419		94.3%	8.83	111
1028final*	93	−30.23	0.814	precip 4.376126	storatio -0.66				93.3%	6.85	63
102930final*	94	−1.56	0.641	runoff 0.934563	soildep -0.752228	storatio -0.2633	mar4pre 1.233113		88.3%	19.98	150
1101final*	95	−5.50	0.688	slope 0.598275	storatio -0.5978	popdens 0.007945	precip 0.825918		89.1%	11.87	130
1103final	96	−1.07	0.787	runoff 1.252685	slope 1.540541	storatio -0.1275			83.1%	23.32	67
11040506final	97					No acceptable regressions					
1107final*	98	−0.03	0.662	storatio -0.2712	soilthi -1.117805	mar4pre 1.898961			90.5%	18.06	171
1108final*	99	11.75	0.847	soilthi -2.156468	storatio -0.1523				84.5%	22.83	86
110910final*	100	9.30	0.909	storatio -0.125	runoff 1.11046	sand -3.492059			76.5%	64.00	98
1111final*	101	−4.55	0.907	soilthi -1.301836	storatio -1.0219	precip 1.858926			92.3%	8.31	99
111213final*	102	36.24	0.808	storatio -0.1178	flat -1.19089	soilthi -4.489169			78.1%	76.41	168
1114final*	103	6.85	0.632	soilthi -0.74201	aqperm -0.838317	storatio -0.2766			87.8%	20.34	135
Arkansasmnfinal*	104	0.97	0.402	storatio -0.3299	runoff 2.609774				88.6%	14.81	53
120102final*	105	−21.84	0.606	aqperm -1.220662	storatio -0.1956	precip 2.914013	soilawc -1.620151		88.0%	14.72	117
1203final*	106	−1.05	0.705	sand -0.254776	storatio -0.1373	precip 2.037161	flat -2.681471	popdens 0.000971	87.2%	32.13	164
1204final*	107	24.04	0.872	storatio -0.3265	precip 0.902843	runoff 0.703801	soilthi -4.481047	popdens 0.000526	88.8%	5.24	68
120506final*	108	181.99	0.756	storatio -0.1185	soilawc -13.51739	soildep -28.01821			83.8%	43.99	119
1207final*	109	−4.18	0.813	soildep -1.367562	storatio -0.2957	precip 2.13483	sand -0.321318		94.6%	10.51	90
120809final	110					No acceptable regressions					
1210final*	111	−20.34	0.727	storatio -0.2871	popdens 0.001028	precip 3.066756	aqperm -0.654343		77.4%	49.61	177
1211final*	112	−20.10	0.595	popdens 0.020199	precip 1.663952	soilawc -4.691189	storatio -0.6283	aqperm -0.838687	77.2%	24.25	103

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1302020302final	113	−9.93	0.712	storatio -0.1596	mar7pre 1.963525				49.2%	111.29	55
130607final	114	−0.78	0.446	runoff 0.379946					41.0%	125.68	152
150102final*	115	7.16	0.696	sand -2.571621	storatio -0.8852	runoff 0.161557			80.8%	43.94	93
15030708final*	116	3.09	0.318	storatio -0.1926	aqperm -2.656263				59.8%	70.72	58
1504final*	117	−17.93	0.932	aug8pre 1.024542	soilawc -4.576342	runoff 0.817399			83.9%	18.40	74
1505final*	118	−2.17	0.782	storatio -0.6394	runoff 1.745899				52.1%	39.47	56
1506final*	119	−9.20	0.961	runoff 0.571066	storatio -1.3039	dec5pre 1.413548			81.5%	77.96	107
170103final*	120	1.84	0.909	runoff 1.226903	sand -2.050156	storatio -10.0689			94.8%	9.59	68
170701020 30405final*	121	14.29	0.940	dec5pre 1.736187	soildep -3.113489	storatio -0.0848	sand -0.400664		91.7%	17.32	94
1708final*	122	−8.20	0.943	precip 1.219388	storatio -0.863	sand -0.447697			94.9%	11.73	104
170900010 20304final*	123	−3.25	0.887	slope 0.605894	storatio -1.769	sand -0.952883	nov4pre 0.844616		96.6%	9.38	164
170900050 60708final*	124	19.21	0.976	storatio -1.8859	precip 1.428572	sand -0.450339	popdens 0.001635	soilthi -4.132058	95.2%	11.14	128
17100102final*	125	−7.52	0.887	storatio -0.8388	precip 0.994865				94.7%	6.83	121
171003final*	126	−5.93	1.039	storatio -1.2612	aqperm -0.610338	sand -0.952283	nov4pre 1.48535		94.2%	28.00	184
171100020 30405final*	127	13.52	0.834	precip 1.30377	storatio -1.2423	soildep -3.742771	runoff 0.844567		96.8%	4.26	85
171100091 01112final*	128	10.70	0.901	storatio -2.2385	runoff 1.484762	soildep -2.381067			95.5%	18.17	119
171100131 41516final*	129	−5.04	0.940	nov4pre 0.9428	storatio -1.5757	runoff 0.672703	soildep -0.529641		91.0%	22.85	140
180101final*	130	−5.27	0.938	runoff 0.415916	precip 0.492158	storatio -0.2692			96.0%	9.13	132
180102final*	131	−1.65	1.032	dec6pre 2.285966	storatio -0.9341	sand -3.074662			93.3%	14.26	103
180200final*	132	−12.00	1.319	storatio -0.2399	slope 3.38372				93.9%	14.58	62
1802010102 0304final*	133	0.45	0.699	storatio -0.7578					91.7%	21.05	130
1802010607 0811final*	134	0.54	0.729	storatio -0.7412	flat -0.201656				77.5%	61.89	69
1802split1final	135					No acceptable regressions					
1802split2final	136					No acceptable regressions					
1805final*	137	−7.23	0.877	storatio -0.088	dec4pre 1.178645	runoff 0.325205			91.0%	20.03	90

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Table A1. (Continued)

Hydrologic Unit	Map ID	Intercept	DrArea coeff.	Other variables and coefficients					Adj. R^2	PRESS	Degrees of Freedom
18060007080910final*	138	83.76	0.863	runoff 1.574052	dec4pre 1.83874	storatio -0.6597	soildep -12.80393		65.0%	61.13	80
18060001020506final	139	−9.49	0.848	storatio -0.1098	aqperm -0.589269	runoff 0.325988	dec4pre 1.697909		82.7%	41.02	102
180701final*	140	29.36	0.985	popdens 0.001321	storatio -0.0904	sand -3.909988	soilthi -2.727684		78.4%	54.47	79
180702final*	141	−6.18	0.507	slope 1.721219	popdens 0.003156	dec4pre 1.120463	storatio -0.1054	sand -0.937221	81.7%	36.01	101
180703final	142					No acceptable regressions					
180910final	143	95.75	0.658	sand -24.8209	popdens 0.017101	dec5pre 1.299792			46.7%	155.87	87
Snowmelt systems											
10102final*	144	−9.42	0.963	runoff 3.429738	sand -2.127321	storatio -1.4667	apr2pre 0.886071		93.6%	6.57	82
10304final*	145	3.38	0.768	slope 0.663399	mar3pre 0.708047	soildep -1.08272	storatio -0.9282		93.4%	5.96	99
10506final*	146	−6.17	0.769	storatio -0.2551	jan3pre 1.670898	sand -0.471979			77.7%	25.67	88
107final*	147	−1.81	0.874	slope 0.500159	soildep -0.519738	storatio -0.5559	mar2pre 0.881066		98.9%	3.00	93
10801final*	148	−258.83	0.932	runoff 1.655196	storatio -1.4035	mar3tmp 44.98681	sand -0.541137	jan3pre 0.344002	99.1%	2.79	127
1080201020304final*	149	−5.99	0.878	storatio -0.3333	slope 0.595963	jan3pre 0.97435			98.0%	12.51	147
10802050607final*	150	−133.73	0.896	storatio -0.6663	aqperm -0.813722	runoff 2.5981	precip 2.039923	mar2tmp 19.55209	96.4%	5.48	74
201111final*	151	−1.77	0.959	aqperm -0.739766	sand -0.639574	storatio -1.1539	mar2pre 0.650369		86.1%	12.98	125
20200010203final*	152	1.76	0.886	storatio -1.7302	aqperm -0.140284	soilthi -1.455167	popdens 0.002673	precip 1.080321	98.7%	3.29	114
202000405060708final*	153	−6.30	0.927	slope 0.366456	mar2pre 0.74863	storatio -0.4304	sand -0.642056	snow 0.47777	95.4%	7.87	113
2040101020304final*	154	−12.30	0.968	storatio -1.0934	precip 1.416069	aqperm -0.326881	runoff 0.379286		99.3%	3.28	129
205010102030405final*	155	−7.71	0.931	sand -2.071368	storatio -0.4303	precip 1.039139	soilawc -2.843557		97.6%	6.14	122
40102final*	156	−1.67	0.911	storatio -0.3988	slope 0.320492	aqperm -0.325968			88.7%	19.32	93
403final*	157	−4.74	0.761	sand -0.77595	runoff 1.344424	storatio -0.2288	mar2pre 0.809756		91.4%	11.47	136
40607final	158	9.60	0.881	soildep -0.846563	dec4pre 0.724894	storatio -3.2291	sand -1.999154		91.6%	8.25	73

408final*	159	23.99	0.875	soildep -1.475089	flat -4.775314	precip 0.918421			95.6%	3.45	65
409final	160	−10.47	1.007	storatio -0.499	popdens 0.001191	aqperm -1.423016	precip 1.41821	flat -0.154003	93.7%	15.84	119
415final*	161	−11.26	0.829	soilawc -1.822015	precip 1.686712	storatio -1.7476	sand -1.318944		94.9%	2.64	85
701final	162	−26.57	0.868	precip 3.138232	runoff 1.2208	soilawc -0.739049	storatio -0.2797		93.7%	6.39	56
702final*	163	−22.39	0.817	precip 3.814107	sand -1.300864	storatio -0.2525	aqperm -0.729328		90.4%	12.61	81
70305final	164	2.55	0.967	aqperm -1.710078	mar3pre 1.028941	flat -1.772027			96.1%	5.46	90
704final	165	7.04	1.038	soildep -1.124744	sand -0.510674	storatio -2.2486			93.5%	3.43	48
707final*	166	3.37	0.922	soildep -1.437666	storatio -1.4642	snow 1.129829	flat -0.705807		96.9%	6.16	84
901000202final	167					No acceptable regressions					
90201final*	168	−23.21	0.830	precip 3.216392	storatio -0.1973				50.0%	40.35	73
90203final*	169	-182.22	0.680	dec4pre 0.706204	mar2pre 1.386291	soilawc -1.393325	soildep -0.458184	storatio -0.1467	90.5%	23.30	101
Cont. 90203final*								mar2tmp 31.24551			
903final*	170	−3.56	0.812	mar2pre 0.542881					93.1%	5.08	44
1000103final*	171	11.02	0.815	dec5pre 1.167917	storatio -0.7161	sand -0.67548	soilthi -2.110532		98.3%	3.95	89
1002final*	172	−669.04	0.854	dec5pre 2.48414	aqperm -0.810556	storatio -0.607	may2tmp 115.8222	soilawc -1.630334	86.8%	6.46	52
Missourimnfinal*	173	65.38	0.972	dec5pre 1.787851	soildep -10.20494	storatio -0.2204			93.8%	4.96	83
100710final*	174	−17.68	1.096	slope 1.677612	precip 1.578275				96.7%	12.62	88
1008final*	175	−6.04	0.640	storatio -0.2152	soilawc -1.410595	dec5pre 0.637018			93.2%	12.36	117
1009final*	176	−8.29	0.784	may2pre 0.803712	storatio -1.321	dec5pre 0.97376	flat -0.177753		92.3%	8.34	72
1018final*	177	−12.08	0.805	precip 2.649399	storatio -0.7407	aqperm -0.361204	sand -1.781574		87.1%	42.70	150
1019final*	178	149.20	0.778	soildep -25.37127	storatio -0.0501	snow 5.009695			83.0%	34.58	154
1102final*	179	−1.34	0.534	aqperm -2.140173	runoff 0.514155	storatio -0.0204	popdens 0.008019		76.2%	88.43	169
1301final*	180	−11.14	0.562	dec5pre 2.064225	storatio -0.9213	slope 1.328185			88.9%	16.15	91
130201final	181	−12.96	0.551	sand -1.390279	dec4pre 1.466889	soildep -12.2507	apr3tmp 18.34315		91.4%	30.20	146
1401000 102final*	182	−4.73	0.828	dec5pre 0.718047	storatio -0.6464				89.9%	27.70	120

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Table A1. (Continued)

Hydrologic Unit	Map ID	Intercept	DrArea coeff.	Other variables and coefficients					Adj. R^2	PRESS	Degrees of Freedom
14010003 0405final*	183	−125.38	0.777	slope 1.969525	may2tmp 22.85269	storatio -0.5558	soilthi -1.365057		97.6%	9.91	100
140203final*	184	−87.95	0.806	runoff 0.601632	dec5pre 1.462954	may2tmp 13.99727	storatio -0.3507		88.8%	26.49	148
1404final*	185	−3.79	0.737	runoff 1.0695	storatio -0.5369				96.1%	7.86	79
1405final*	186	216.68	1.009	soildep -29.88733	slope 2.033094				85.3%	43.56	101
140607final*	187	−5.58	0.802	dec5pre 0.702399	storatio -0.1515	runoff 0.627814	aqperm -0.880167		81.9%	42.08	142
1408final*	188	−6.55	0.828	may2pre 0.638889	slope 1.037039	storatio -0.5996			92.5%	24.65	123
Coloradomnfinal*	189	−12.81	0.748	precip 1.844	storatio -0.4907				70.7%	3.88	46
1601final	190	53.91	0.597	runoff 0.969712	soildep -7.665739				86.8%	10.30	55
1602final*	191	−14.06	0.894	soilawc -4.26901	storatio -0.9737	may2pre 0.620874	aqperm -0.734257		89.2%	27.75	103
1603final	192	33.27	0.411	precip 2.061103	aqperm -1.30383	soildep -6.095877			79.4%	20.82	108
160406final*	193	89.14	0.452	sand -3.997605	storatio -0.3225	soildep -10.2105			80.7%	61.21	101
1605final*	194	−3.22	0.706	aqperm -1.036341	may2pre 0.760486	storatio -0.3036			80.1%	61.61	159
170101final*	195	−259.71	0.848	soilawc -3.89573	slope 2.491392	apr3tmp 43.10998			95.0%	6.19	56
170102final*	196	−51.60	1.009	snow 6.127009	runoff 0.833608	flat -0.096475	storatio -0.3913		98.9%	8.12	149
1702000809 1011final*	197	−13.20	0.888	runoff 0.573314	storatio -0.7368	snow 0.95615	soilawc -1.140276		98.0%	3.13	84
1704010103 0405final*	198	−2.03	0.935	aqperm -0.175694	storatio -0.4675	precip 1.828428	soilthi -1.781836		95.3%	9.46	102
1704021011 1213final	199	−516.58	0.253	runoff 1.002365	soildep -6.298388	may2tmp 97.87904	precip 1.777061		65.3%	17.46	74
1704splitfinal*	200	−5.92	0.724	precip 0.674475	runoff 1.006412	storatio -0.2043	aqperm -1.587449		97.6%	17.58	130
1705final*	201	−6.12	0.804	dec4pre 0.722332	storatio -0.321	runoff 0.865825	sand -0.220659		95.5%	8.65	114
1705splitfinal*	202	139.80	1.022	precip 2.10538	storatio -0.2012	soildep -20.81165	aqperm -0.85629		87.5%	12.89	50
1706final*	203	−7.69	0.942	may2pre 0.273441	dec4pre 0.725568	aqperm -0.221263	runoff 0.422043	storatio -0.839	98.2%	6.03	138
1707020312final*	204	−302.68	0.777	storatio -0.4992	slope 1.104123	soilthi -0.658896	apr2tmp 53.86104		93.3%	29.54	122

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Columbia_ Snake_mnfinal*	205	−15.43	1.110	dec5pre 2.242369	storatio -1.4052	may3pre 0.374139		97.3%	2.14	65
1803final*	206	4.45	0.792	runoff 1.23161	sand -2.267852	storatio -0.0767		87.6%	23.87	89
18040003051012final*	207	−5.77	0.842	storatio -0.3792	aqperm -0.951153	dec5pre 0.567774	soilawc -0.825025	87.6%	20.65	129
18040001020607final	208					No acceptable regressions				
18040001020607splitfinal*	209	1.73	0.604	slope 1.389219	storatio -0.5002	soilthi -0.664268		90.1%	12.67	106

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Figure A1. Map of hydrologic units. Map ID numbers are referenced in Table A1

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