Natural and anthropogenic influences on the scaling of discharge with drainage area for multiple watersheds

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ABSTRACT

Discharge is the independent variable primarily responsible for shaping the hydraulic geometry and longitudinal profile of rivers. The assumption is frequently made that discharge and drainage area scale linearly or nearly linearly, i.e., $Q = kA^c$, where k is the theoretical discharge for a unit area watershed ($A = 1$), Q is river discharge (m^3/s), A is drainage area (m^2), and c is the scaling power dependency. Watershed and longitudinal profile modeling enjoy simplified assumptions if discharge grows linearly with drainage area, and this assumption is widely applied. This paper investigates the scaling relationship between discharge and drainage area for five large rivers, with an emphasis on exploring the linearity of the discharge-area relationship and suggesting causes for significant departure from linearity. The five large mainstem rivers explored (John Day, Salmon, Wabash, Greenbrier, and Yellowstone) all have a minimum of 60 years of continuous discharge records and have been selected to represent a wide geographic area spanning different land uses, climate, and topography. Peak annual flow and mean annual flow are compiled from the U.S. Geological Survey national surface-water database, and a linear regression analysis was completed for each year for the discharges. The five rivers were selected to minimize, but not eliminate, the impacts of dams and diversions such as for irrigation on river discharges.

The scaling factor (c) exhibits both secular and nonsecular trends over the length of record for these five rivers. The results show that the studied watersheds can be grouped into two broad categories based on their respective c values: (1) those rivers where c is 1 or nearly 1, and (2) those rivers where c is significantly <1. The John Day, Salmon, Wabash, and Greenbrier rivers scale at values of ~0.8 with natural variables including slope, elevation, and evapotranspiration potentially accounting for c values slightly <1. The second category is c values of ~0.5, as exhibited by the Yellowstone River. The Yellowstone watershed is unique for our study because of its secular trend, as well as its overall lower average c values. Climatic trends that control the timing of winter snowpack melting, increased frequency and intensity of forest fires, and increased human consumptive water use in downstream areas may all contribute to the observed behavior in c for this watershed. The results from this set of rivers have broad implications for studies ranging from the modeling of fluvial erosion in numeric landscape evolution models to allocations of water resources for human and environmental purposes.

Keywords: watersheds, discharge, drainage area, Yellowstone River.

INTRODUCTION

Discharge is the independent variable primarily responsible for shaping the hydraulic geometry and longitudinal profile of rivers. Discharge also influences sediment transport, ecologic habitats, and over long time scales, landscape evolution. A river's drainage basin is the source area for the discharge and is commonly used as a proxy for discharge, following the logical assumption that discharge grows as drainage basin area increases. The precise scaling relationship between drainage area and discharge is influenced by substrate, precipitation distribution, and climate, but generally speaking, has been traditionally cast as the empirical relationship:

$$Q = kA^c, \tag{1}$$

where k is not a useful measure of discharge behavior and can be influenced by hydrologic variables such as antecedent moisture conditions and precipitation characteristics (the units on k will vary depending on the values for Q and A), Q is river discharge (m^3/s), A is drainage area (m^2), and c is the scaling power dependency. Simple geometric scaling from area (m^2) to discharge (m^3/s) predicts that c should be 1 or nearly 1. This linear scaling appears to hold in basins with uniform hydrology, including distribution of precipitation and runoff generation (Dunne and Leopold, 1978), although the scaling may depend on the exact discharge (i.e., peak annual versus mean annual) chosen for analysis.

There are distinct advantages for channel and watershed modeling assuming that discharge grows linearly with drainage area. For example, modeling of longitudinal profiles using the stream power equation (Whipple, 2004) enjoys relative simplicity when drainage area, which can be measured rapidly from digital elevation models, is used as a proxy for discharge. Similar approaches in numerical landscape evolution models use various erosion laws where drainage area substitutes for discharge (Kooi and Beaumont, 1994; Tucker and Slingerland, 1997; Gasparini et al., 2004; Bishop et al., 2005). Engineering and land management practices use area as the principal independent factor responsible for runoff, soil erosion, and channel discharge. In summary, substituting drainage area for discharge appears to be a reasonable first-order estimate to a wide range of geologic, hydrologic, and engineering approaches to watershed management. However, previous analysis of large datasets compiled from multiple watersheds suggests that the linear relationship may not apply as well for large flood events (O'Connor and Costa, 2004; Solyom and Tucker, 2004). These and related studies explore the empirical relationship between discharge and drainage area by commonly aggregating data across different watersheds. The paucity of multiple, long-operating gauging stations on rivers makes it more rare for studies that have focused on data compiled from a single watershed (Goodrich et al., 1997; Gupta and Waymire, 1998; Ogden and Dawdy, 2003), an approach that enjoys the advantage of exploring the geologic, hydrologic, land use, and climatic differences that exist between watersheds with different scaling relationships.

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This paper explores the nature of the scaling relationship between discharge and drainage area for single watersheds. For the case in which the scaling relationship is not linear, this paper attempts to isolate the natural and anthropogenic factors that might cause that scaling (*c*) to deviate from unity. The linear scaling relationship between discharge and drainage area is implicitly assumed to be temporally invariant, although that assumption has not been widely investigated for a single watershed. Secular changes in *c* may carry information on how watershed hydrology is evolving or changing in response to natural or anthropogenic changes. Some fluctuation in *c* for any basin is expected because of spatial nonuniformity in substrate, and temporal unsteadiness in precipitation, soil moisture, and timing of snow melt that determine river discharge (Gupta and Waymire, 1998; Furey and Gupta, 2005). These variables will drive variance in discharge at the annual and decadal scale, but if the variability in scaling fluctuates around a linear mean, rather than displaying a secular trend, then it can be assumed that the scaling is linear for longer (century or millennial) time scales. Over decadal time scales factors such as substrate, soils, and potentially vegetation might be expected to remain relatively constant, leaving decadal climate changes and land uses as the key variables affecting discharge records. However, if a secular trend is revealed, then the assumption of *c* being 1 or nearly 1 may prove false for both short and long time scales. Four of the rivers presented here have *c* values that approximate but are slightly <1, while one river has a scaling value closer to 0.5. The geographic, land use, substrate, and climatic variability among the five watersheds allows for an examination of their contributory effects.

METHODS

Five large main-stem rivers with a minimum of 60 years of continuous discharge records are selected to represent a wide geographic area spanning different drainage areas, land use, climate, and topography (Fig. 1). The trunk channels of these rivers are undammed (Figs. 2–6), with the exception of the Wabash River, which has a dam located in the far upstream reach so that the trunk channel operates essentially dam free. If the main trunk of the channel is free of dams the anthropogenic affect on river discharge is reduced, although there may still be large diversions for irrigation purposes. However, dams are present on the tributaries of the five trunk channels. Tributary dams dampen the peak discharges and decrease the mean annual discharges because of increases in evaporation and diversions for human use, but because the discharges reported here are from the undammed main branch, these effects are lessened.

Peak annual flow and mean annual flow are compiled from the U.S. Geological Survey (USGS) national surface water database (http://waterdata.usgs.gov/nwis/sw) for each water year, October 1 to September 30. Annual peak discharges commonly approximate bank-

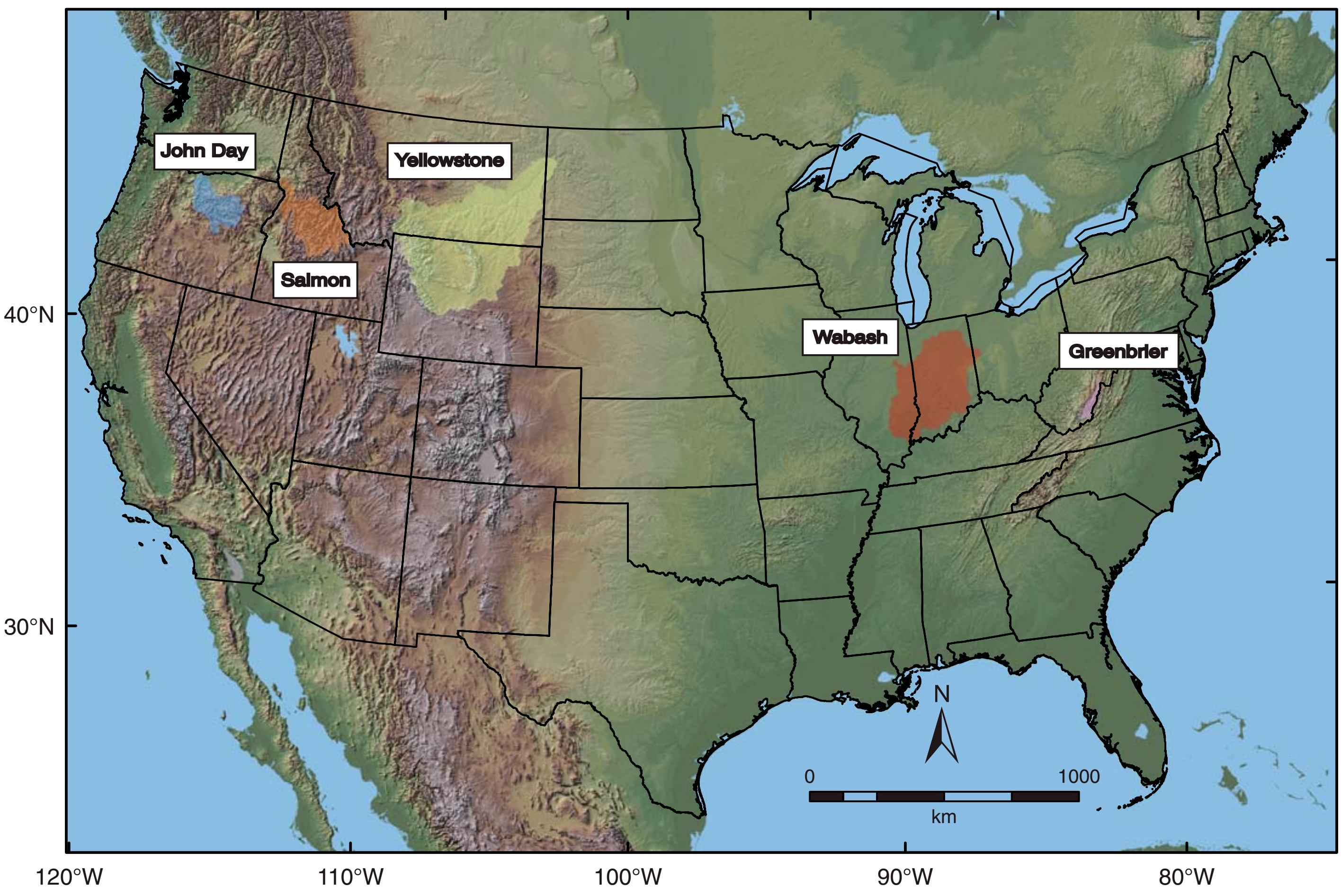


Figure 1. Location map of the six studied watersheds, John Day, Salmon, Yellowstone, Wabash, and Greenbrier Rivers. The base map is constructed from the 1 km elevation data (U.S. Geological Survey National Center for EROS, 2003).

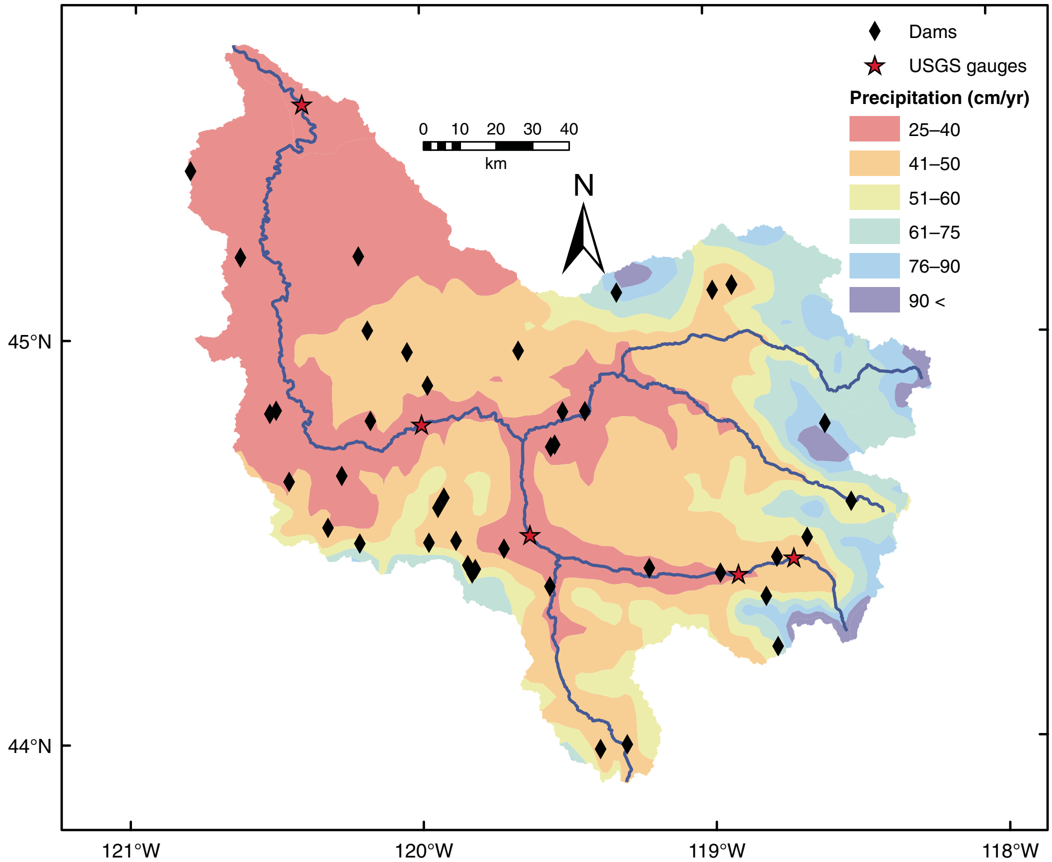


Figure 2. Map of the John Day watershed showing the gradient in precipitation across the watershed, the locations of the U.S. Geological Survey (USGS) gauges, and the dams on the tributaries. Flow is from the southeast to northwest.

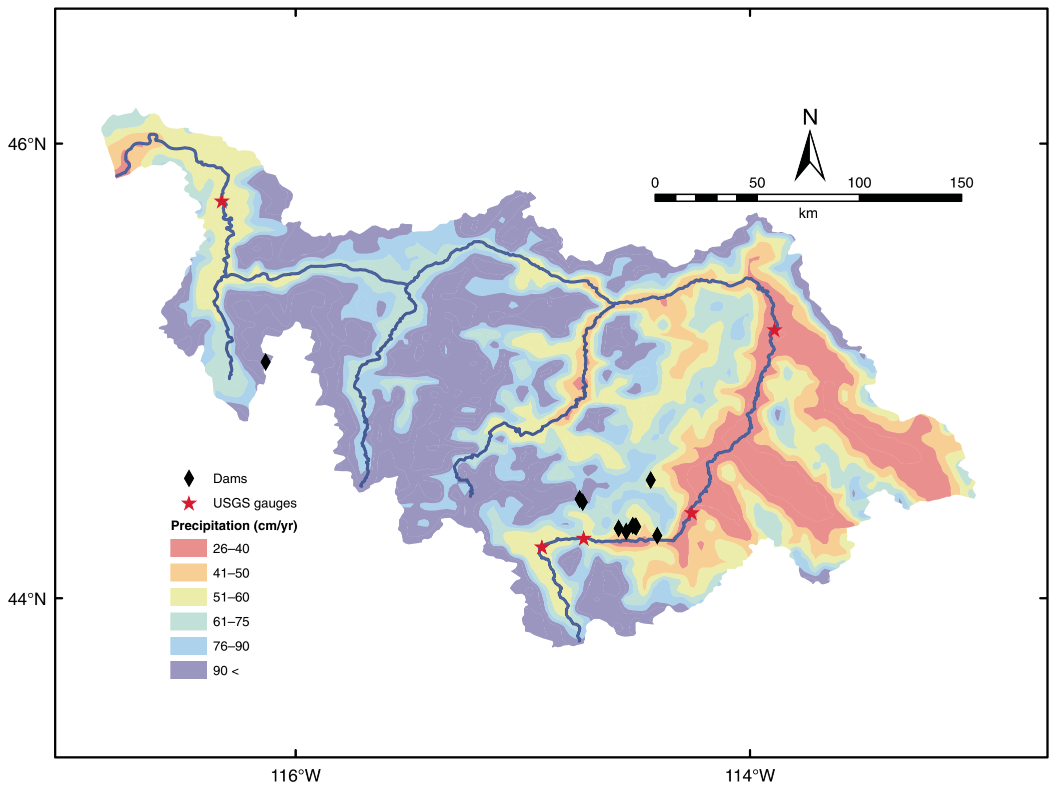


Figure 3. Map of the Salmon River watershed showing the precipitation, U.S. Geological Survey (USGS) gauges, and locations of dams. Flow is generally to the west-northwest.

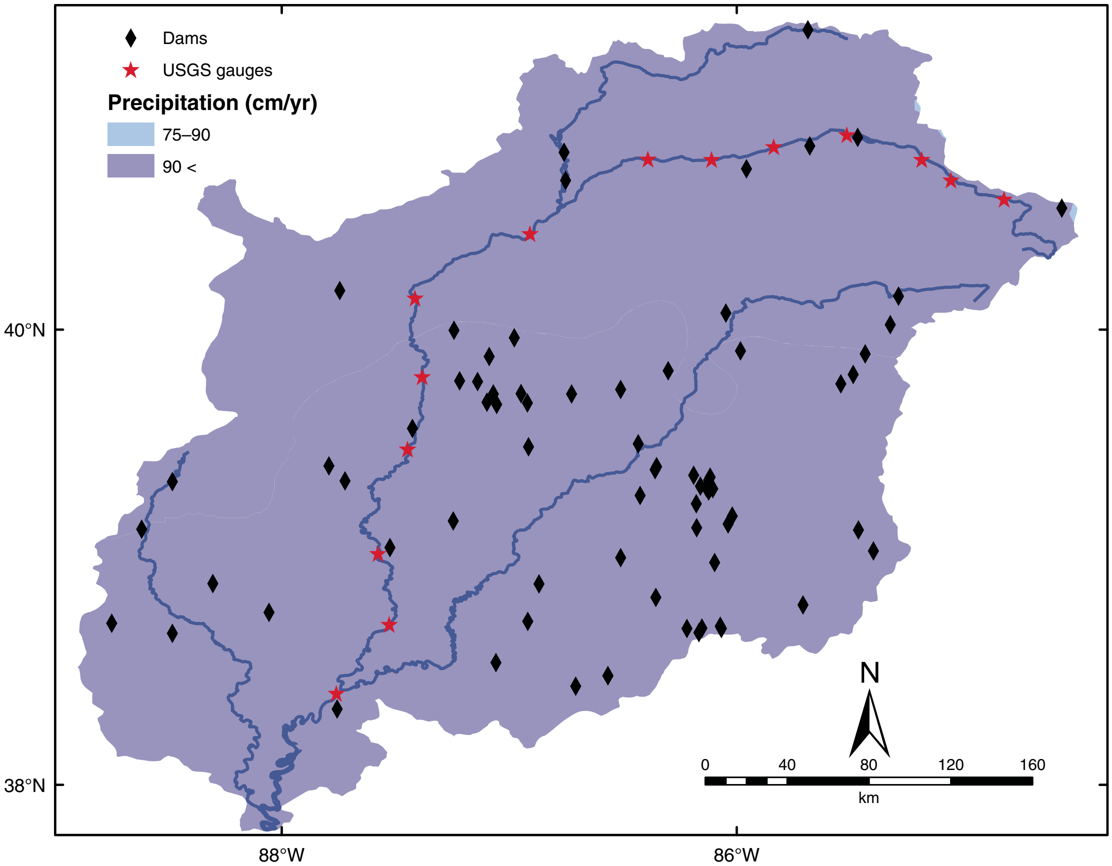


Figure 4. The Wabash watershed with the annual precipitation, U.S. Geological Survey (USGS) gauges, and locations of dams. The precipitation is uniform except for the far-eastern corner of the watershed.

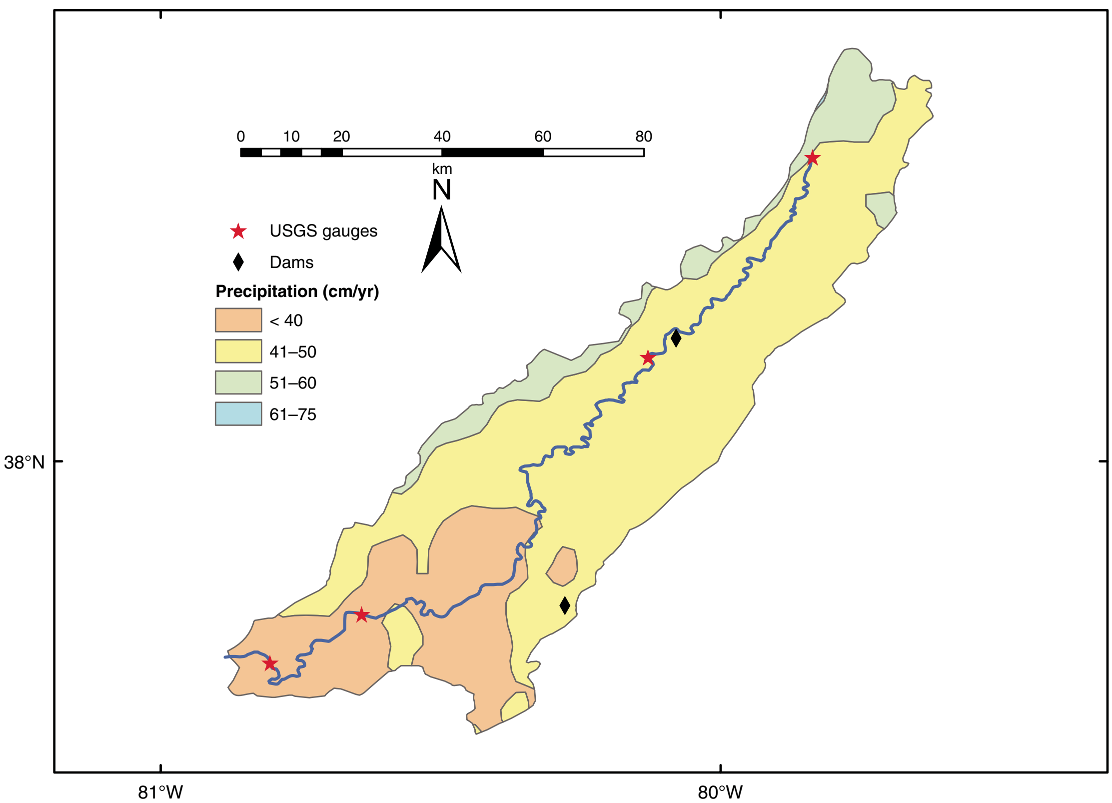


Figure 5. The Greenbrier watershed showing the annual precipitation, U.S. Geological Survey (USGS) gauges, and the locations of the two dams. The Greenbrier has the highest average precipitation values of the six watersheds in this study.

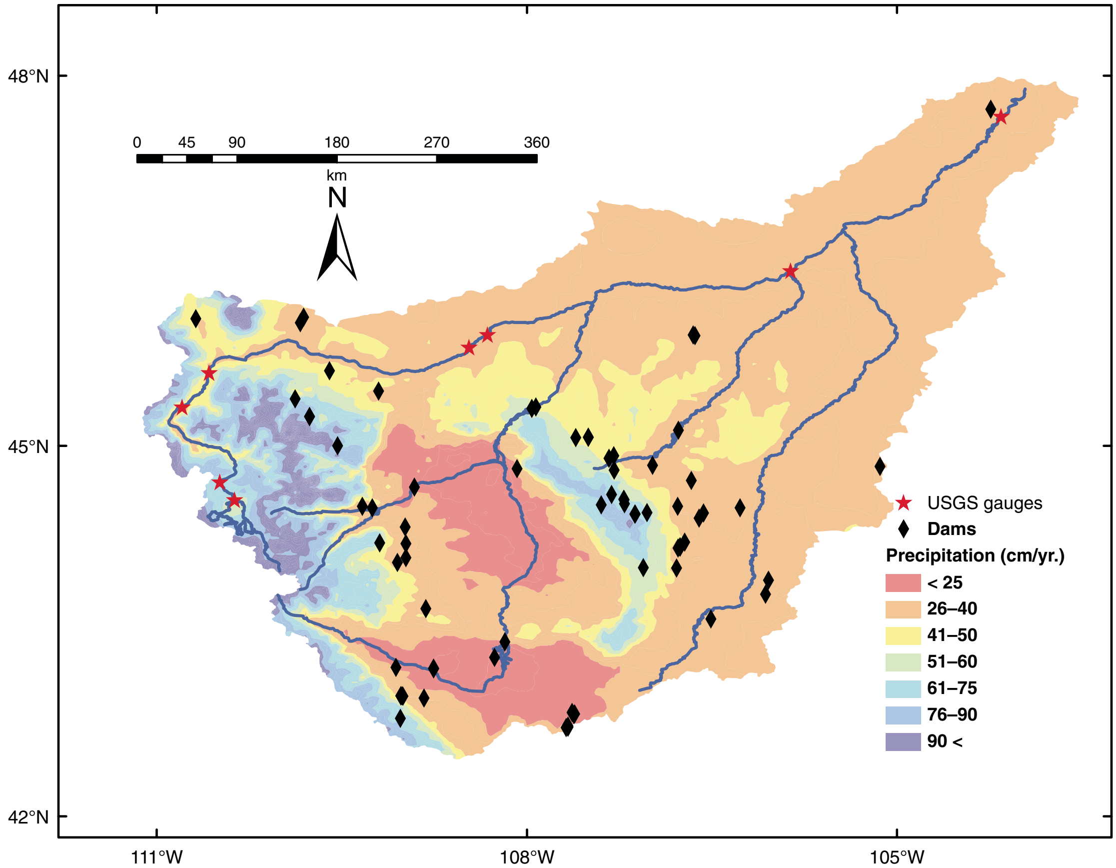


Figure 6. A map of the Yellowstone watershed showing the strong west-east gradient in annual precipitation values, the locations of the U.S. Geological Survey (USGS) gauging stations, and dams and major reservoirs on the tributaries.

full discharges, which are the most effective (i.e., do the most work) discharges in a fluvial system (Wolman and Miller, 1960), while the mean annual discharge represents a baseline of average river flow that is important for human uses such as irrigation as well as environmental considerations such as aquatic habitat. English units (square miles, cubic feet per second) from the USGS site are converted into SI units (square kilometers, cubic meters per second) for drainage area and discharge. For peak discharges, which represent a discrete flood event, the peak flood events were filtered to ensure that the data were all within 30 days of each other. For each water year the particular 30 day window was defined as having the most gauging stations record a peak discharge during that 30 day time period. This filter maximizes the likelihood that the linear regression for that year represents only one continuous event and not separate floods that occurred in different parts of the watershed at different times. However, this filter ignores localized peak discharges that may accomplish much geomorphic work but do not affect the entire basin. Mean discharges are only used to refer to the mean annual discharges, while average refers to the mathematical average of a variable such as precipitation or even a discharge over time. Thus, it is possible to discuss the average mean annual discharge at a point, which would be the average of each of the annual mean discharges recorded at a gauging station.

A linear regression analysis was completed for each year for the discharges, using the logarithm of drainage area as the independent and the logarithm of discharge as the dependent variables in the statistical program SPSS (version 13.0) (Fig. 7). A minimum of three points was used for each regression. The slope of the linear regression represents c in equation 1 and is the scaling value for discharge (Q) with drainage area (A). This technique allows for annual values of c for both peak and mean annual discharges to be plotted over time, giving a temporal record of the variation in c. The 95% confidence interval of the annual regression value was calculated as being twice the standard error, and the 95% confidence interval is used as the expression of error throughout.

Digital elevation models were compiled from the U.S. Geological Survey's National Elevation Data 1″ data for the watersheds of the Greenbrier, John Day, Salmon, and Wabash Rivers, and Shuttle Radar Topography Mission 3″ for the Yellowstone watershed. The models were compiled into a geographic information system (Arc v. 9.0, Environmental Systems Research Institute) to determine watershed relief and area.

WATERSHED CHARACTERISTICS

The John Day River, north-central Oregon (Fig. 1), is 400 km long and has a watershed area of 20,550 km^2 that receives an average annual precipitation of 46 cm. The relief of the watershed is 1070 m, and the bedrock lithology is primarily extrusive igneous rocks. There are five gauging stations for both mean and peak annual discharges, with three stations (the minimum number for the linear regressions) operating since 1927 for peak and 1928 for mean discharges. Although there are not large dams or reservoirs on the John Day River, there are some small diversions, mostly for irrigation (Herrett et al., 2005).

The 630-km-long Salmon River, Idaho (Fig. 1), has a watershed of 36,300 km^2 that averages 76 cm of precipitation annually (Fig. 3). The watershed has 3580 m of relief and contains mostly intrusive and extrusive igneous bedrock lithologies. Five gauging stations were used for linear regression; the records begin in

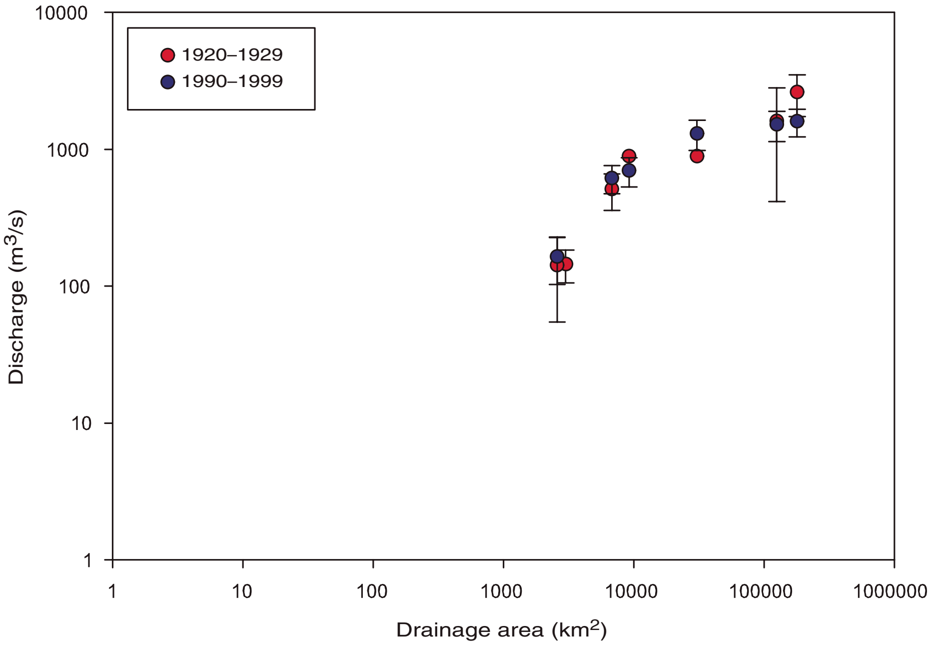


Figure 7. The average peak annual discharges for two decades (1920s and 1990s) from the Yellowstone River with the 95% confidence interval displayed for each gauging station. Compared to the 1920s, the average peak annual discharges were larger from 1990 to 1999 at smaller drainage areas, resulting in a lower *c* ($Q = kA^c$, equation 1; see text) value for the 1990s.

1922 for both mean and peak annual discharges. The Salmon River is the least human-affected watershed in this study, with few dams and little consumptive water withdrawals (Fig. 3).

The Wabash River watershed covers 85,400 km^2 and is almost entirely within Indiana (Fig. 1). The watershed averages 103 cm of annual precipitation, contains mostly siliciclastic and carbonate bedrock lithologies, and has 570 m of relief (Fig. 4). The main channel is 780 km long and has 14 USGS gauges that are used in this study; records date to 1902 for peak annual and 1924 for mean annual discharges.

The Greenbrier River, West Virginia (Fig. 1), is the smallest river in this study at 218 km and an area of 4200 km^2 (Fig. 5). The watershed averages 108 cm of annual precipitation, has limestone and shale bedrock lithologies, and has 1070 m of relief. There are four gauging stations on the Greenbrier, the earliest from 1936.

The Yellowstone River (Fig. 1) is 970 km long and has 8 gauges used in this study. The watershed averages 42 cm of precipitation annually, is 182,000 km^2, contains mostly sedimentary and extrusive and intrusive igneous lithologies, and has relief of 3600 m. Eight gauging stations recorded peak annual and five stations recorded mean annual discharges on the Yellowstone. The Yellowstone watershed has some unique characteristics that may influence the discharge-drainage area relationship. First, the tributary of the Wind-Bighorn River actually has more upstream drainage area (58,052 km^2) than the main-stem Yellowstone (30,549 km^2) when the two join. Second, there are more reservoirs on the tributaries than in the other five watersheds, which most likely influence the discharge characteristics of the main stem.

RESULTS

The physical characteristics of each watershed include area, length of the main trunk channel, watershed relief, precipitation, number of USGS gauging stations used in this study, and the length of discharge records (Figs. 2–7). The watersheds vary from small and in a humid-temperate setting (Greenbrier, Fig. 1) to much larger and located in a semiarid setting (Yellowstone, Fig. 1).

The scaling factor (*c*) exhibits both secular and nonsecular trends over the length of record. The rivers can be categorized based on the long-term averages and trends of their *c* values. The first group, comprising the John Day, Salmon, Wabash, and Greenbrier, has *c* values from ~0.7 to 1.0 and are relatively steady for the length of the record (Table 1; Figs. 8–12). Whereas there are differences in the amount of variability of the scaling factor across and within a river's *c* values, these four rivers have long-term averages that approximate but are <1.

The second category is *c* values of ~0.5, as seen in the Yellowstone River (Table 1). For the Yellowstone the peak *c* approaches maximum values of 0.8 and averages ~0.6 from 1911 to 1940, and then follows a secular decline to a present average of 0.4 (Fig. 12). The mean annual *c* values display a similar but dampened trend with the maximum values of ~0.6

DISCUSSION

The results show that the studied watersheds can be grouped into two broad categories based on their respective *c* values: (1) those rivers where *c* is 1 or nearly 1, and (2) those rivers where *c* is statistically <1, defined here as a majority of annual *c* values that do not have 95% confidence intervals intersecting with 1. The rivers where *c* is ~0.8 roughly follow the proposed simple geometric scaling relationship between discharge and drainage area. As a river gains drainage area with additional downstream tributaries, those tributaries also contribute discharges that are proportional to the added drainage area. The Yellowstone River, where *c* is closer to 0.5, does not follow this simple geometric pattern.

Discharges Scaling from 0.8 to 1.0

In larger watersheds the travel time of water from the divide to the mouth of a watershed complicates the scaling of discharge with drain-

TABLE 1. *c* VALUES ($Q = kA^c$)*

River	Average *c* for peak annual discharge	Average *c* for mean annual discharge
John Day	0.97 ± 0.05	0.88 ± 0.02
Salmon	0.82 ± 0.01	0.82 ± 0.01
Wabash	0.65 ± 0.04	0.75 ± 0.04
Greenbrier	0.73 ± 0.05	0.86 ± 0.01
Yellowstone	0.49 ± 0.02	0.50 ± 0.01

*k is a coefficient that can represent various hydrologic variables (units vary), Q is river discharge (m^3/s), A is drainage area (m^2), and c is the scaling power dependency.

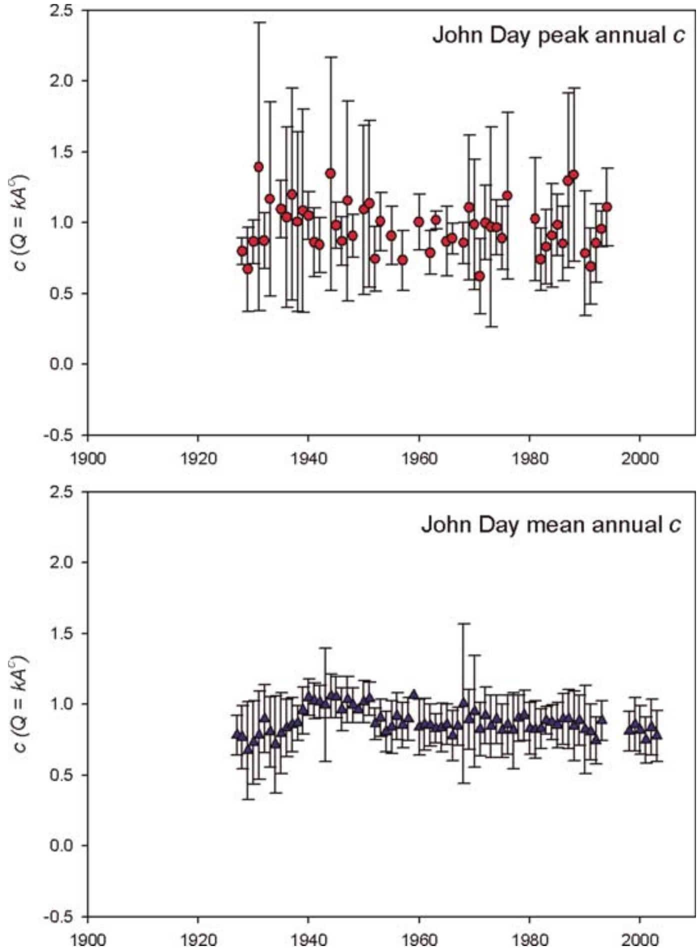


Figure 8. The *c* (scaling power dependency) values for peak and mean annual discharges on the John Day River, Oregon, as determined through linear regression of discrete gauge station discharge data.

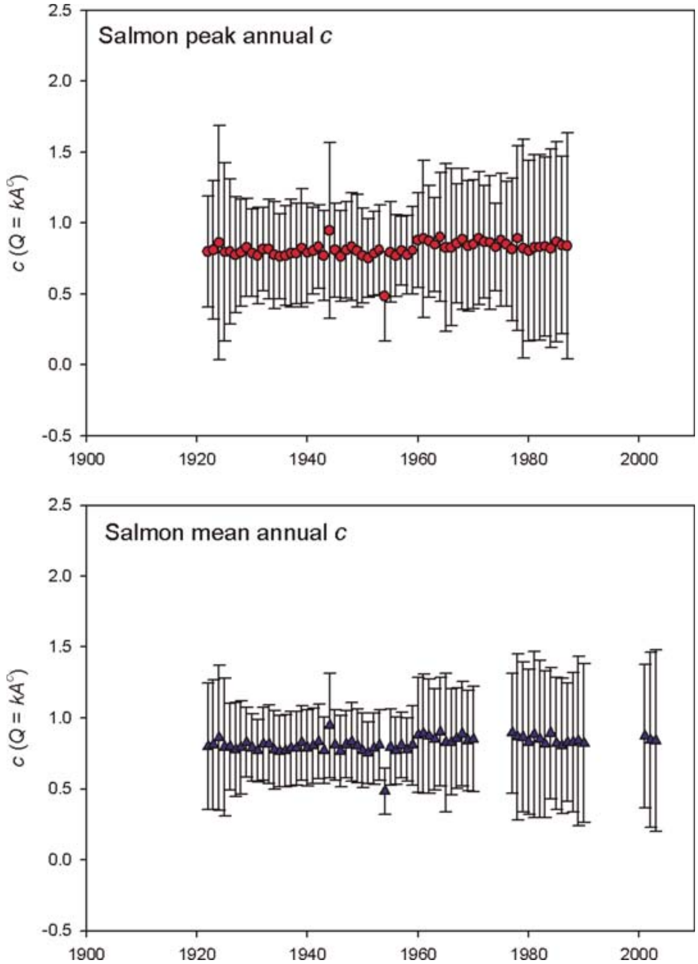


Figure 9. The *c* (scaling power dependency) values for the peak and mean annual discharges on the Salmon River.

age area (Solyom and Tucker, 2004), a complication that does not exist in smaller, particularly undisturbed watersheds that more commonly exhibit a c value near 1 (Galster et al., 2006). Nevertheless, our study and others show that some watersheds as large and complex as the John Day River in Oregon and the Susquehanna River in Pennsylvania (Slingerland et al., 1994) essentially have c values = 1. The John Day River is interesting from the perspective that it has both higher precipitation and a greater concentration of dams in the upstream areas of the watershed. In terms of the effect on the c value, the precipitation gradient and the upstream distribution of dams may counteract each other, the former acting to increase peak and mean annual discharges and the latter decreasing discharges.

A river with a c value of 0.8 has proportionally less discharge being added to the channel by the downstream tributaries than the upstream tributaries. There are several ways to interpret these results. One would be to argue for a downstream influent trunk channel, but this is unlikely for all of these rivers except the Greenbrier, which is underlain by carbonate. Other watershed variables such as slope, elevation, and evapotranspiration may account for scaling values of 0.8 rather than 1. Higher slopes in headwater regions increase the amount of discharge generated by a unit area of drainage area. The headwaters of a watershed are commonly steeper (with many exceptions), the steep slopes generating larger amounts of overland flow and runoff with less water infiltrating into the ground than more gentle slopes (Knighton, 1998). Higher elevations also create orographic effects that tend to increase precipitation amounts in the headwater of a watershed, creating more runoff (Dunne and Leopold, 1978; Smith, 1979). More runoff will consequently generate higher discharges, especially peak annual discharge. In addition, the mean annual discharge will also be increased because it compiles all flows, including both higher and lower, into its value. This unequal distribution of precipitation influences a river's discharge as well as the river's long profile (Roe et al., 2002).

Higher elevations also create orographic effects that tend to increase precipitation amounts in the headwater of a watershed (Smith, 1979). The orographic effect on weather systems and subsequent increased precipitation can spatially skew the total annual precipitation toward the headwaters, decreasing the value of c (Dunne and Leopold, 1978). This unequal distribution of precipitation influences a river's discharge as well as the river's long profile (Roe et al., 2002). Higher elevations in a watershed also tend to shift precipitation toward snowfall rather than rainfall. As a snowpack grows over a winter season it stores water that, when quickly melted in spring,

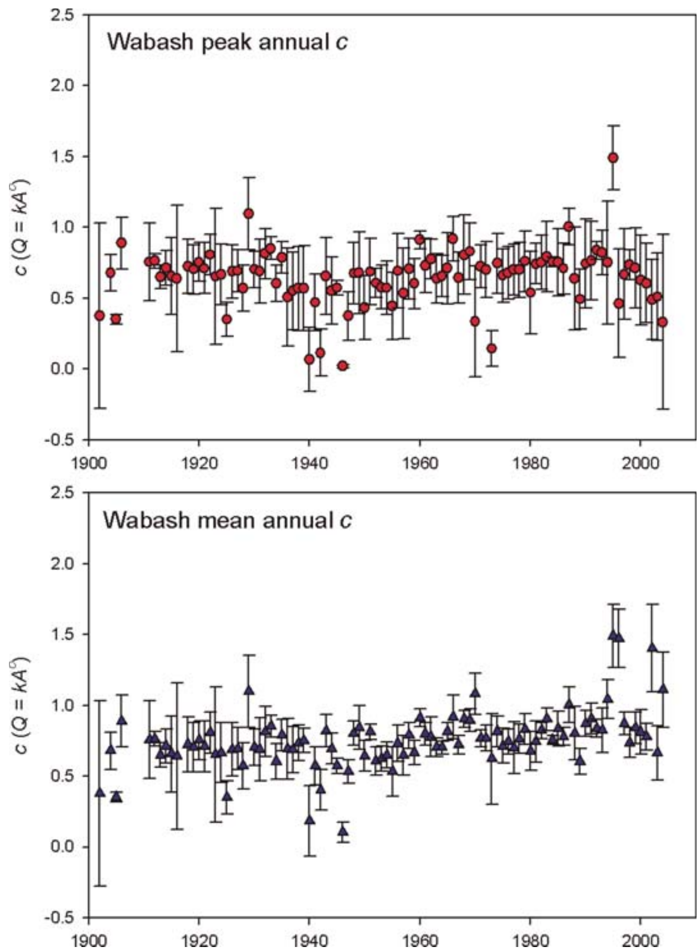


Figure 10. The results for the linear regressions of peak and mean annual discharges for the Wabash River.

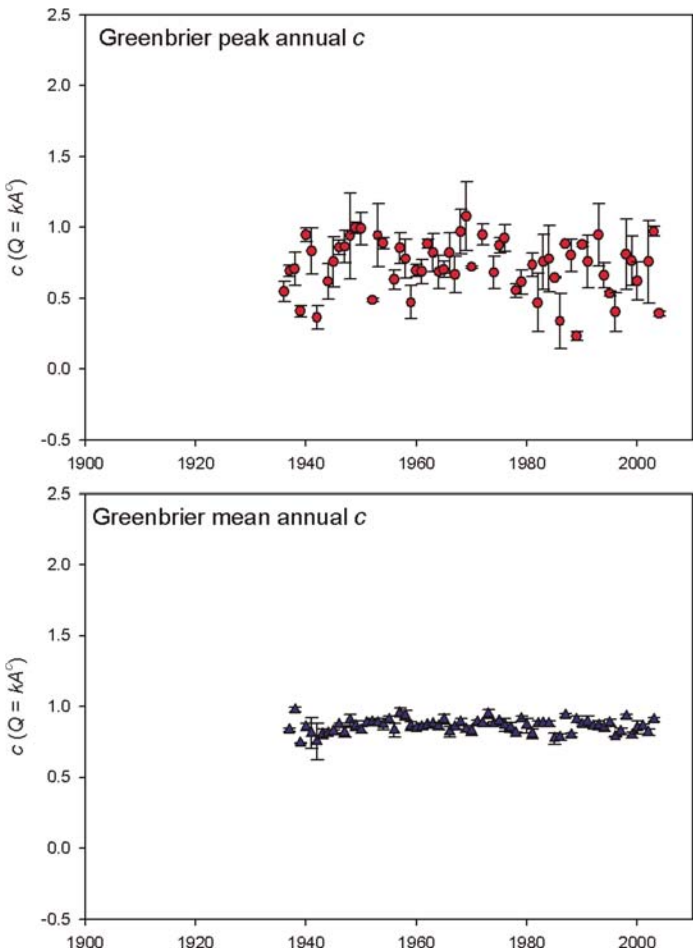


Figure 11. The *c* (scaling power dependency) values for the peak and mean annual discharges on the Greenbrier River.

releases months of precipitation over days or weeks, thereby increasing the peak annual discharge. While the melting of winter snow does not dominate the hydrology of all of the studied watersheds, it is a critical factor for generating peak discharges in some watersheds, as discussed here for the Yellowstone watershed. Conversely, these same mechanisms that act to relatively increase the upstream discharge decrease the downstream discharge. Downstream areas of a watershed are generally less steep and have less relief, causing the abovementioned processes to work in reverse and lessen the amount of runoff delivered to the river channel. Furthermore, the gentler slopes produce lower flow velocities and higher transit times for the runoff to the main channel that would tend to spread a peak discharge out over time, decreasing the maximum value of the peak discharge.

Gentler slopes and lower elevations in the downstream part of a watershed would also drive higher evapotranspiration (ET) rates. ET is inversely correlated with elevation in both arid (Shevenell, 1996) and humid environments (Kovnee, 1954; Swift et al., 1988; Gurtz et al., 1999), and gentle slopes promote ET by reducing runoff and increasing soil moisture, where the water can be returned to the atmosphere. These higher rates of ET would transfer larger amounts of precipitation back to the atmosphere, decreasing the amount of runoff generated. Lower-elevation areas are generally warmer, which would also mean a smaller or nonexistent winter snowpack, resulting in a smaller available reservoir to melt and produce runoff and peak discharges.

Collectively, slope, elevation, and evapotranspiration work to relatively increase the discharge generated per unit area of watershed in the drainage headwaters while concurrently acting to decrease discharge per unit area down basin. The change in relative amounts of discharge generated in different areas of the watershed reduces the slope on the regression lines and lowers the *c* value from a theoretical value of 1 to the observed value of ~0.8 for a majority of large watersheds (Fig. 13).

The *c* values of the Wabash River are the lowest of these four rivers. The long-term average for both the peak (0.65 ± 0.04) and mean (0.75 ± 0.04) annual discharges are low enough that it may belong in its own group. In spite of the long-term averages, only ~15% of the *c* values for peak and mean discharges are not significantly (95% confidence) different from $c = 1$. The Wabash River watershed is unique in this set of four rivers: it has the lowest relief and the lowest gradient in precipitation, and is also the only one of the four that was mostly glaciated during the most recent glacial period. However, it remains unclear why the glaciation or glacial drift cover would cause the Wabash to systematically have lower *c* values. There may be other factors than the previously invoked relief and precipitation gradient to lower the *c* value here, including the travel time of water in a watershed with a glacially caused poorly integrated channel network (Gupta and Waymire, 1998).

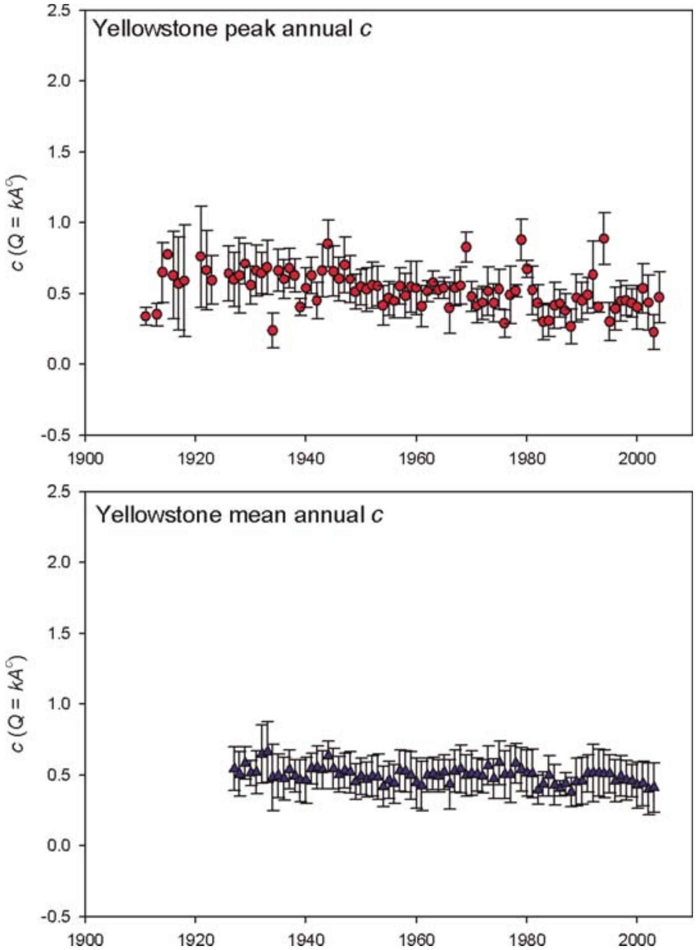


Figure 12. The c (scaling power dependency) values for peak and mean annual discharges on the Yellowstone River.

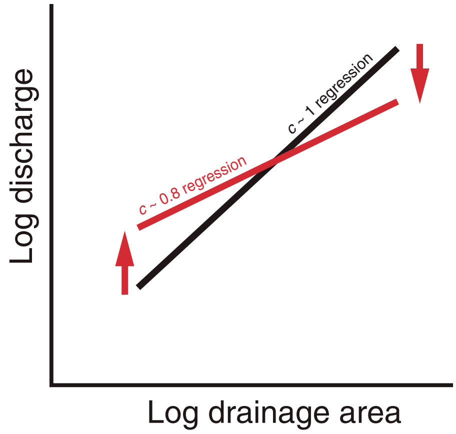


Figure 13. Differences in slope, elevation, and evapotranspiration between upstream and downstream sections of the watershed act to tilt the theoretical geometric regression value (i.e., *c* value) of 1 and decrease the value closer to 0.8. The three variables act to relatively increase upstream discharges (where a river has a small total drainage area) and relatively decrease those discharges at larger drainage areas. It is proposed that this spatial disparity influencing discharges causes *c* values to be ~0.8 rather than 1, as seen in the discharge records from the John Day, Salmon, Wabash, and Greenbrier Rivers.

Yellowstone River: *c* ~0.5

The Yellowstone watershed is unique because of its secular trend in its c values as well as the lower average c values when compared to the other four undammed rivers (Table 1; Fig. 12). The Yellowstone watershed would also have the same processes (slope, elevation, ET) operating within it that serve to reduce the value of c by proportionally increasing the discharges upstream and decreasing them downstream. However, there are temporal and spatial changes in the hydrologic characteristics of the Yellowstone watershed that uniquely affect the scaling of the discharge and act to decrease c below 0.8. The spatial component is the variation in precipitation across the watershed, whereas the temporal aspects are the changes in precipitation, fire frequency, and land use over the 90 year length of the discharge record. Both of these influences change the scaling in a distinct way when compared to the other rivers in this study.

The precipitation gradient in the Yellowstone watershed is strongly oriented from southwest to northeast, roughly parallel to the major axis of the watershed (Fig. 6). The higher precipitation in the headwaters produces more runoff per unit drainage area and consequently higher discharges in the headwaters; the opposite occurs in the downstream, drier climate section of the river (Zelt et al., 1999). The rate at which the discharges increase downstream declines, and reduces the regression values for both mean and peak discharges to an average of ~0.5 over the length of the record (Fig. 12). This trend has also been observed for other rivers in semiarid conditions (Gupta and Waymire, 1998). The relationship between discharge and drainage area also becomes more nonlinear for the Yellowstone peak annual discharges with increasing drainage area (Fig. 14), a trend that has been documented for semiarid watersheds (Goodrich et al., 1997). Such a trend suggests that a power law relationship (equation 1) may not be appropriate for semiarid watersheds.

The annual peak discharge on the Yellowstone River typically occurs in June or July (Zelt et al., 1999), often as a result of snowmelt at higher elevations. At this point in the season the lower elevations downstream have lost all or a majority of their winter snowpack, creating a gradient in the amount of runoff generated by snowmelt at the time of the annual peak discharge (Animation 1[1]). The snowier, higher-elevation headwaters generate more runoff than in the lower, warmer, and drier downstream sections of the watershed, creating a peak discharge that slowly increases in size moving downstream, resulting in the low c values for the discharges (Arora and Boer, 2001).

The annual mean and peak discharges are also affected by human influences within the Yellowstone watershed. Of the water used in the watershed, 98% comes from surficial sources, and 99% of that use is agricultural (Zelt et al., 1999). There are also >4000 km^2 of agricultural land within the watershed, the majority of it

[1]If you are viewing the PDF of this paper, or if you are reading this offline, please visit http://dx.doi.org/10.1130/GES00065.S1 or the full-text article at www.gsajournals.org to view the animation.

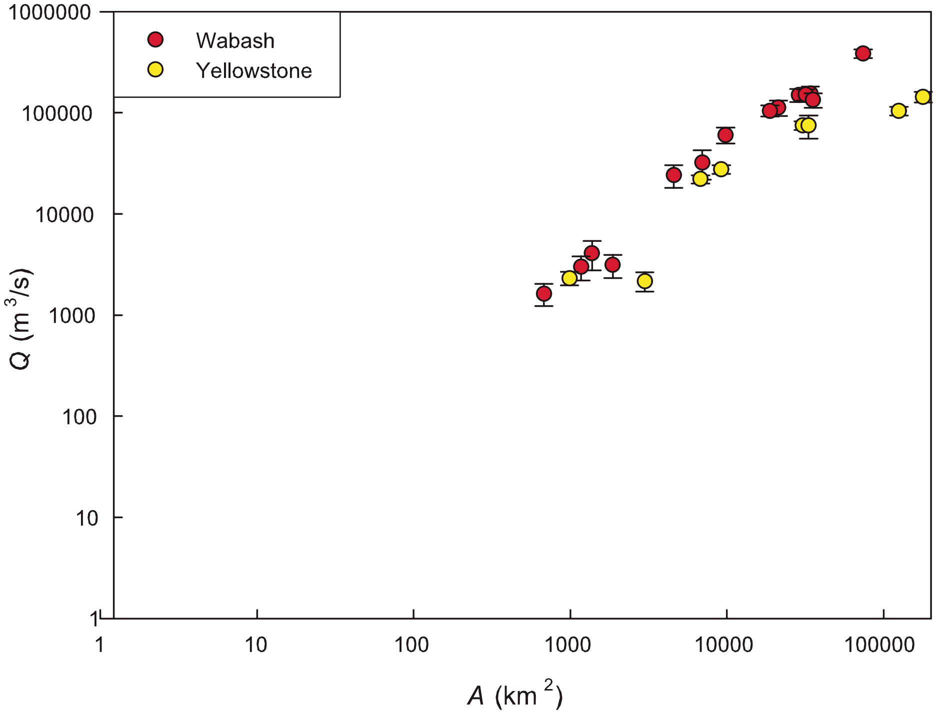


Figure 14. The peak annual discharges from the Wabash and Yellowstone Rivers averaged over the length of each record. Discharges in the Wabash River (red circles), with its equal distribution of precipitation throughout the watershed, increase at an approximately constant rate with increasing drainage areas. In contrast, the average peak annual discharge in the Yellowstone River does not increase downstream at a constant rate. The large contribution of snowmelt upstream to the peak annual discharge and the lower precipitation and large irrigation withdrawals in the downstream sections of the watershed create a nonlinear increase in discharge moving downstream. The error bars are the 95% confidence intervals.

being concentrated along the rivers as well as in the downstream section (Zelt et al., 1999). This consumptive water use is estimated to average 300 m^3/s across the watershed. The construction of several large reservoirs has also affected the discharge characteristics of the Yellowstone watershed. The three largest reservoirs in the watershed (Boysen, built 1951, capacity 0.989 km^3; Buffalo Bill, built 1909, capacity 0.857 km^3; Bighorn Lake, built 1967, capacity 1.695 km^3; Zelt et al., 1999) are located on downstream tributaries to the Yellowstone (Fig. 6). These reservoirs, through consumptive use and storage capacity, would decrease the mean and peak annual discharges that these downstream tributaries contribute to the Yellowstone River. The concentration of these human influences on the downstream tributaries decreases the downstream peak and mean discharges for the Yellowstone River, which subsequently decreases the *c* values for both the peak and mean annual discharges.

There is also a secular decreasing trend in the *c* values for the annual discharges for Yellowstone River over the past 75 years, especially for the peak discharges. The decrease in *c* means that there is slower rate of increase in discharges moving downstream, from ~0.6 at the beginning of the twentieth century to ~0.4 at the end (Fig. 12). This secular decrease in *c* values corresponds with climatic and land use changes in the Yellowstone watershed.

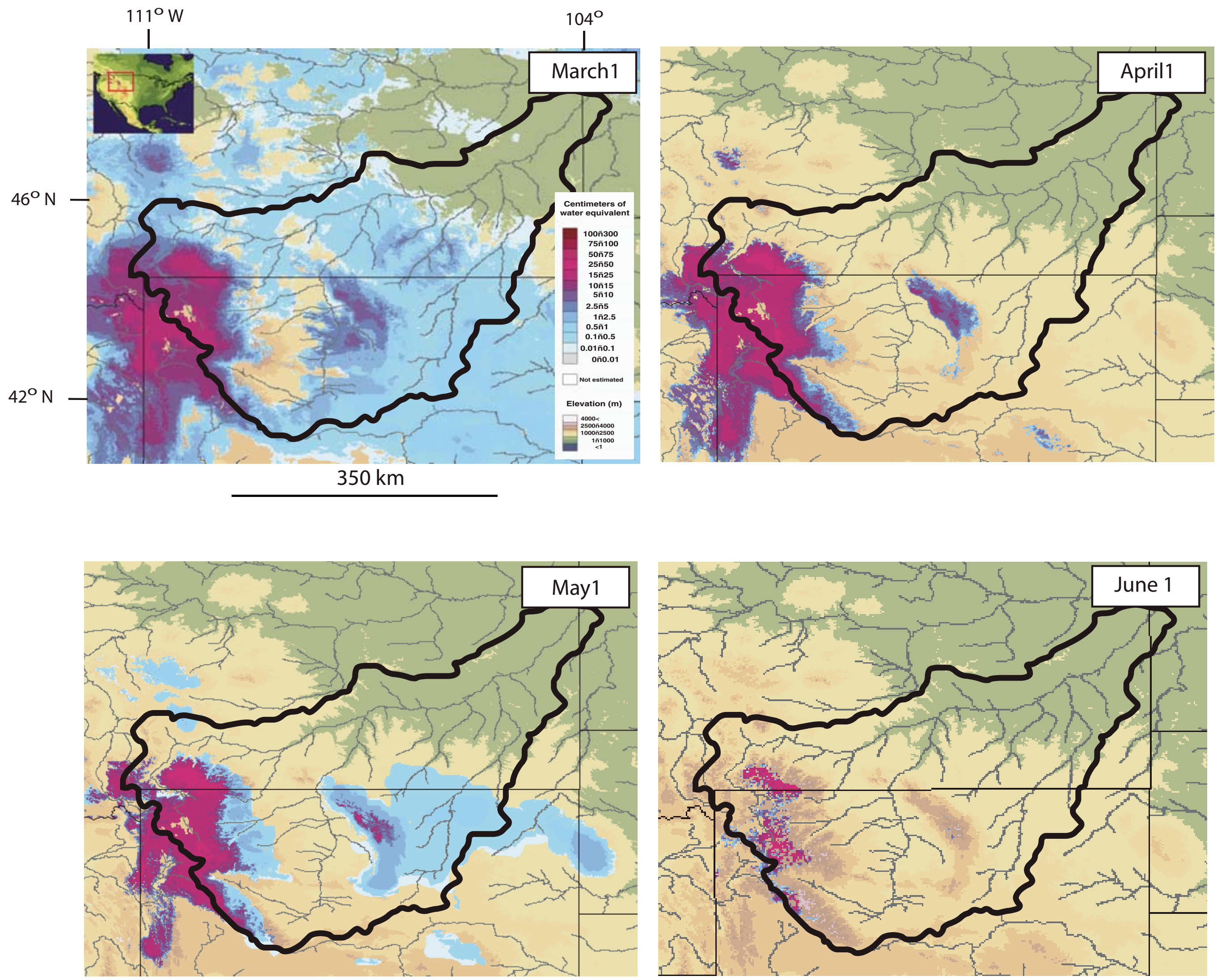
Climatic data that overlap with the discharge record during the twentieth century indicate that the headwaters became progressively warmer during the summer months and that the January–June precipitation there decreased (Balling et al., 1992; Service, 2004). The average peak annual discharge for the Yellowstone River has decreased at the largest drainage area (Zelt et al. 1999); however, at smaller drainage areas the average peak annual discharges have increased for the Yellowstone River (Fig. 7) as well as for the Lamar River (Slack et al., 1993), a headwater tributary of the Yellowstone River. Two possible explanations for these higher discharges in the headwaters are the higher temperatures causing faster melting of the snowpack and increased discharges (Singh et al., 1997; Zappa et al., 2004; Dankers and Christensen, 2005) and the increased frequency and intensity of forest fires increasing the amount of runoff generated (Helvey, 1980; Inbar et al., 1998; Iroume et al., 2005).

There were several large fires in the region during the twentieth century, the largest occurring in 1988 and three of the six largest fires occurring from 1979 to 1988 (Balling et al., 1992). Although the decrease in *c* values and the increase in forest fires are coincident, the degree to which the fires affected the discharges may be limited. Discharges only increased by 4% after the 1988 fire, which was by far the largest of the twentieth century fires in Yellowstone National Park (Farnes et al., 2004). The 1988 fire was large enough that if there was a strong link between forest fires and discharge, we might expect to see a step function in the *c* values, instead of the observed gradual decrease for both peak and mean discharges. However, the sequence of forest fires followed by increased discharge has been documented in other watersheds (Helvey, 1980; Inbar et al., 1998), leaving open the question of the impact of fires on the Yellowstone River's discharges.

The secular trend may also be explained by the increasing human influence on the watershed: as the consumptive use for agriculture increased and large reservoirs were constructed throughout the twentieth century (Zelt et al., 1999), there has been an increasing impact on both the peak and mean annual discharges. The increase in downstream concentration of the human water use in the watershed could also explain the decrease in *c* values observed for the peak and mean annual discharges. The argument for human influence and not climate change is strengthened when the Salmon River is compared to the Yellowstone River. The Salmon River watershed has also undergone increased levels of fire and warmer temperatures during the twentieth century (Pierce, 2004), and has not undergone similar secular changes in its *c* values for either peak or mean discharges (Fig. 9).

CONCLUSIONS

These results have implications for the ability to model landscape evolution through river erosion. Most of these models have the basic assumption built into them that drainage area (*A*) and discharge (*Q*) are scalable geometrically (i.e., *c* ~1). This assumption is made chiefly because of the ease of measuring drainage area and the difficulty of measuring discharge. Four of the rivers in this study (John Day, Salmon, Wabash, and Greenbrier) have *c* values that approximate 1 but are actually closer to 0.8.



Animation 1. Monthly snowpack levels for spring and summer, 2003, for the Yellowstone watershed (outlined in black in the first image). The peak annual discharge for Yellowstone typically occurs in June or July, when the only snow present (pink colors) is in the higher elevations in the headwaters of the watershed. Images obtained from the National Operational Hydrologic Remote Sensing Center of the National Oceanic and Atmospheric Administration.

A c of 0.8 may be a close-enough approximation to 1 that the basic assumption of substitutability between drainage area and discharge is still valid for some rivers. However, as the Yellowstone River illustrates, some streams apparently can have c values closer to 0.5, at which point the simple substitution of A for Q would most likely break down.

The issue of scale is important in the relationship of drainage area and discharge. These rivers have large watersheds; the smallest (Greenbrier) has an area of 4200 km^2. It may be that at these scales there are too many disparities in factors such as bedrock lithology, vegetation, precipitation, evapotranspiration, and slope to accurately model landscape evolution. However, there are also difficulties in using small headwater streams in these landscape erosion models; the discharges are lower and tend to be more strongly influence by heterogeneities in channel armoring, outcrop-scale bedrock differences, and knickpoints (Adams and Spotila, 2005; Bishop et al., 2005). There may be a solution with a watershed that is just the right size: not too big, and not too small. However, more work needs to be done characterizing long-term discharge records at different spatial scales before the issue of scale can be more clearly defined.

It is notable that none of the five studied rivers had scaling relationships significantly >1. A geometric relationship of discharge with drainage area (i.e., a value of c ~1) seems to be the maximum possible in natural settings. For a river to have a c >1, at least one of two processes must occur: (1) the headwaters of a drainage area must be ineffective at delivering its precipitation to the channel as runoff and generate less runoff, or (2) the downstream sections generate disproportionately more runoff. Factors such as slope and relief work against the former, while evapotranspiration and transport time work against the latter, resulting in a natural limit to the values of c. There are exceptional cases, such as in urban watersheds, where the hydrological setting has been significantly altered and c values approach 2 (Galster et al., 2006). However, it does not seem likely that such an increase is possible without anthropogenic intervention.

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