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Spatial variation in drainage area — Runoff relationships and implications for bankfull geometry scaling

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ABSTRACT

Fluvial geomorphic analyses frequently require knowledge of bankfull channel geometries, which are thought to be related to characteristic stream discharges. However, relating bankfull geometry to characteristic discharge is challenged by spatially limited stream discharge measurements, which may also lack extensive temporal records. Because of these limitations, discharge is commonly assumed to scale linearly with watershed drainage area. Here we evaluate the assumption of a linear relationship between discharge and drainage area for watersheds across the United States and Canada with limited anthropogenic disturbance. Using machine-learning to objectively cluster hydrologically similar gauges, we find that discharge scales linearly with drainage area for most of North America. However, regions with low average runoff efficiency tend to have non-linear discharge scaling. In regions with non-linear discharge scaling, bankfull channel dimensions increase more rapidly with drainage area than in regions with linear discharge scaling. These results suggest that the recurrence interval of the characteristic discharge that sets channel geometry may be larger in regions where discharge scales non-linearly with drainage area compared to those regions where linear discharge scaling applies.

1. Introduction

Across diverse environments, landscape surfaces are primarily sculpted by running water (Gilbert, 1877), including relief structures in mountainous regions (Whipple and Tucker, 1999), and floodplains in lowland areas (Wolman and Leopold, 1957; Nanson, 1986). Streamflow also sets stream channel hydraulic geometry (Wolman and Miller, 1960; Leopold and Maddock, 1953). This relationship between channel form and flow is integral to landscape evolution modeling (Dietrich et al., 2003; Lague, 2014) and has even been applied to other planetary surfaces (Morgan and Craddock, 2019).

The relationship between channel form and flow is also important for geomorphic management of watersheds. The flow that transports the most sediment, the effective discharge, is frequently used as a reference in stream restoration. Typically corresponding to the bankfull flow (Wolman and Leopold, 1957), the effective discharge can be used to estimate recovery timescales and to approximate stable channel dimensions (Wolman and Miller, 1960; Fields et al., 2021; Renshaw et al., 2019). Because of its use as an indicator in many systems, stream restoration commonly relies on predictions of the effective discharge (Tranmer et al., 2022).

While these applications depend on knowing the recurrence interval of different stream discharge magnitudes, measurements of stream discharge are limited in time and space, leading to various methods of extrapolating discharge from a measured site to another location (Kirby and Moss, 1987). Often measurements are extrapolated from nearby stream gauges by relating discharge to basin drainage area as:

$$Q = \alpha(A)A \tag{1}$$

where Q is a volumetric discharge rate, A is the basin drainage area, and $\alpha(A)$ is the average specific yield of the catchment as a function of the drainage area. Specific yield – defined as the ratio of discharge to drainage area (with units of length per time) – measures how much each unit area of the watershed contributes, on average, to the given discharge. If the specific yield is scale independent, then $\alpha(A)$ is constant such that, for example, a doubling of watershed area results in a doubling in discharge.

Scaling relationships such as Eq. (1) have been fundamental to our understanding of broader geomorphic processes. Early geomorphic work, for example, during the quantitative turn in the 1950s by Luna Leopold (Leopold et al., 1964), John Hack (Hack, 1957), and others,

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established empirical power law relationships between stream discharge and hydraulic geometry (e.g., cross-sectional width, depth, velocity) (Leopold and Maddock, 1953). Since then, others have sought to establish the physical bases for these hydraulic geometry relationships (Parker, 1979; Bray, 1982; Julien and Wargadalam, 1995; Dade and Friend, 1998; Lee and Julien, 2006; Parker et al., 2007; Dunne and Jerolmack, 2020; Phillips et al., 2022). To the extent that discharge scales with watershed area (Eq. (1)), these relationships imply hydraulic geometry should also scale with watershed area.

With respect to discharge scaling (Eq. (1)), in some cases, the specific yield is scale dependent because the efficiency of runoff generation R_e – defined as the dimensionless ratio of mean annual discharge to mean annual precipitation – varies with watershed area. For example, small headwater basins at high elevation with cool temperatures might lose proportionally less water to evapotranspiration compared to larger basins at lower elevations. In the higher, cooler basins this reduced water loss results in higher runoff efficiencies and subsequently higher average specific yields. Although there is uncertainty in how average specific yield varies with watershed area, specific yield can be related to drainage area as a power law of the form:

$$\alpha(A) = kA^{\beta} \tag{2}$$

where k and β are empirical constants. A scale independent specific yield corresponds to $\beta = 0$, while $\beta < 0$ corresponds to decreasing average specific yields with increasing watershed area. Combining Eq. (1) and Eq. (2):

$$Q = kA^{c} \tag{3}$$

$$c = \beta + 1 \tag{4}$$

Empirically, the constants k and c are observed to vary both with location and with the magnitude of flow being approximated (Benson, 1962; Cathcart, 2001; Eaton et al., 2002). Numerous regional studies report c values ranging from 0.4 to 1.0 (see sources in Dooge, 1986; Knighton, 1987; Cathcart, 2001), with Winston and Criss (2016) observing that higher values of c occur in cool regions with low sunshine and low evapotranspiration. Others contend that c should be equal to 0.75 through Froude number scaling (Johnstone and Cross, 1949; Dooge, 1986). Galster et al. (2006) suggest that c can be as great as 1.8 as a result of land use changes, but Criss and Winston (2007) argue that values of c greatly exceeding one are likely the result of measurement inaccuracies or inappropriate data analysis methods.

Determining the appropriate values for the empirical constants is complicated by relatively few sets of nested stream gauges, i.e., multiple gauges on the same watershed. Furthermore, gauge records are increasingly likely to be affected by anthropogenic factors as watershed area increases, making it difficult to parse natural effects from anthropogenic effects on runoff efficiency. Consequently, the empirical constants are usually determined by comparing runoff within regional groupings of gauging stations. Here we constrain variability in c values at a continental scale using stream discharge records from 941 watersheds across the United States and Canada. We expand on similar studies (e.g., Eaton et al., 2002; Winston and Criss, 2016) in two respects. First, to limit anthropogenic effects, we restrict our analyses to gauging sites with limited anthropogenic disturbance. Second, we use unsupervised machine learning to objectively cluster the stream gauges into hydrologically similar regions. Our goal is to develop regional discharge-drainage area relationships useful for geomorphic modeling and also for watershed management. In particular, we seek to identify those regions where the specific yield is scale independent ($\beta = 0$) versus those regions where discharge scales non-linearly with watershed area ($\beta \neq 0$). Because hydraulic geometry should also scale with watershed area, we also compare the scaling of bankfull channel geometry with drainage area between regions with linear and non-linear discharge scaling.

2. Methods

2.1. Discharge

We compiled discharge measurements from the United States Geological Survey (USGS) and from the Water Survey of Canada (WSC). We prioritized using gauging sites that experience minimal anthropogenic disturbance, resulting in 941 sites used for analysis. These sites are distinguished by being part of the USGS Hydro-Climatic Drainage Network (Lins, 2012). We also include sites designated as Unregulated Stations by the WSC. To calculate the discharge for a given recurrence interval, we log-transformed the annual maxima of each site and fit a Pearson Type III distribution using the smwrBase library in the R programming language.

2.2. Clustering

Because locations with different drainage areas are needed to relate Q and A, we clustered hydrologically similar gauging sites together to create hydro-region clusters as in Dethier et al. (2020). This approach uses k-means clustering to create a similar number of clusters as the number of input variables. This number of clusters also corresponds with the highest Dunn Index value for the data set (Fig. S1), which indicates better clustering (Dunn, 1974). The variables used include the peak flow for each month normalized by the peak annual flow of record for each site, elevation, latitude, and longitude. We scaled each of these variables to have equal weight for the clustering algorithm. We split two clusters manually because each contained geographically distinct sub-regions. As a result, the clustering process produced 16 clusters.

2.3. Scaling

We determined the coefficients k and c in Eq. (3) for each hydro-region cluster using a least squares best linear fit to the log-transformed discharge versus drainage area data. We repeated this for six different flow discharges: mean annual discharge, two-year flood, five-year flood, ten-year flood, fifty-year flood, and one-hundred-year flood.

We quantified uncertainty in c using the standard error of the slope in a linear best fit to the discharge and drainage area data in log-log space. Where $c \approx 1$ within the uncertainty of the analysis, we set site c values equal to one, for later interpolation, since the scaling exponent should approach unity (Criss and Winston, 2007). In those hydro-regions where c was significantly less than unity, we applied empirical trends to the c values from those clusters to estimate c values for each stream gauge within those clusters. We then used these trends to map the spatial variation in c values. To determine the empirical trends, we noted that regions with low values of c generally correspond to regions of low runoff efficiency and thus regressed c values against the hydro-region average runoff efficiency. Runoff efficiency values were calculated as the mean annual discharge (m^3) divided by the average precipitation over the watershed area (m^3). Precipitations measurements were averaged over the upstream watershed area at gauging stations in the United States using the gridded Parameter-elevation Relationships on Independent Slopes Model (PRISM) climate data (https://prism.oregonstate.edu). PRISM interpolates historical records from climate stations across the conterminous United States with a record since 1950 (Daly et al., 2008). For gauging stations in Canada, we used the gridded North American Regional Reanalysis (NARR) data set (https://psl.noaa.gov/data/gridded/data.narr.html), with a record since 1981. Where the data sets overlapped spatially, we prioritized using PRISM instead of NARR because of its longer record.

2.4. Kriging

To generate maps of c values, we used ordinary kriging with the modeled c values for each site. We used the gstat library in the R programming language to fit a variogram and interpolate over a grid of North America. We used the best model for c values determined at each recurrence interval. We determined the best model by allowing the nugget to be fit to exponential and spherical models until the model with the lowest residual sum of squares was found. We limited the interpolation to a maximum radius of 300 *km* from a gauging station.

2.5. Channel area

To evaluate the effects of non-linear scaling on stream morphology, we assigned stream bankfull geometry measurements compiled by Trampush et al. (2014) to a hydro-region based on geographic proximity. We then grouped streams in hydro-regions with linear scaling together and fit a linear least squares trendline to the cross-sectional area of the channel at bankfull versus drainage area data. We repeated this for streams in hydro-regions with non-linear scaling. We conducted a two-sample *t*-test on the slopes of the trendlines from the non-linear discharge scaling group and the linear discharge scaling group to test whether the difference was statistically significant.

3. Results

3.1. Clusters

The clusters of hydrologically similar regions are comparable to those identified by Dethier et al. (2020) despite using slightly different clustering criteria. The Southeast hydro-region was manually split from the Southwest hydro-region and the Great Lakes hydro-region was manually split from the Rocky Lowlands hydro-region (Fig. 1). The average length of record and the number of sites in each cluster are summarized in Table S1 in the supporting information.

3.2. Discharge Scaling and Regression Groupings

Discharge scaling divides hydro-region clusters into two groups: one where $c \approx 1$ and one where $c < 1$. Where c values are less than one, the discharge–drainage area data are more variable and demonstrate weaker trends than in regions where c is approximately one (Fig. 2; Tables S2–S6). The r^2 values for regions where $c > 0.85$ are generally >0.8, while r^2 values for regions where $c < 0.85$ are generally <0.5. Hydro-region c values for each discharge are given in the Supplemental Information (Tables S2–S6). Across all discharges, for the majority of

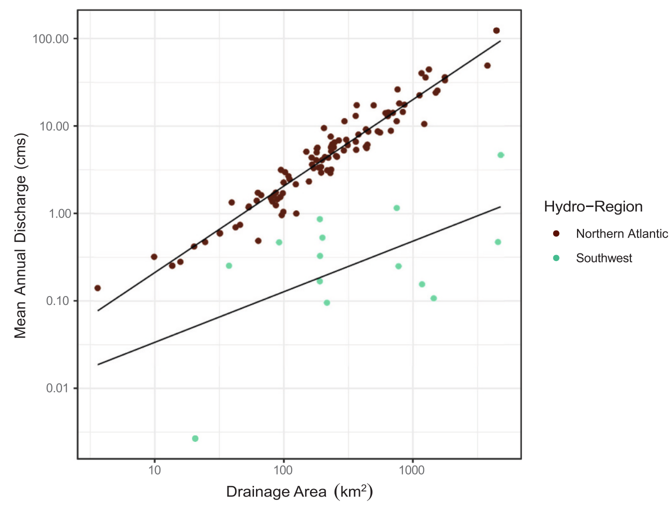

Fig. 2. Example of the data used to calculate the scaling exponent, c, for the linearly scaling Northern Atlantic hydro-region ($c = 0.99 \pm 0.03$) and the non-linearly scaling Southwest hydro-region ($c = 0.58 \pm 0.2$) for the mean annual discharge. Other non-linearly scaling hydro-regions similarly plot below the Northern Atlantic, demonstrating watersheds yield less discharge than watersheds of the same size but with linear discharge scaling.

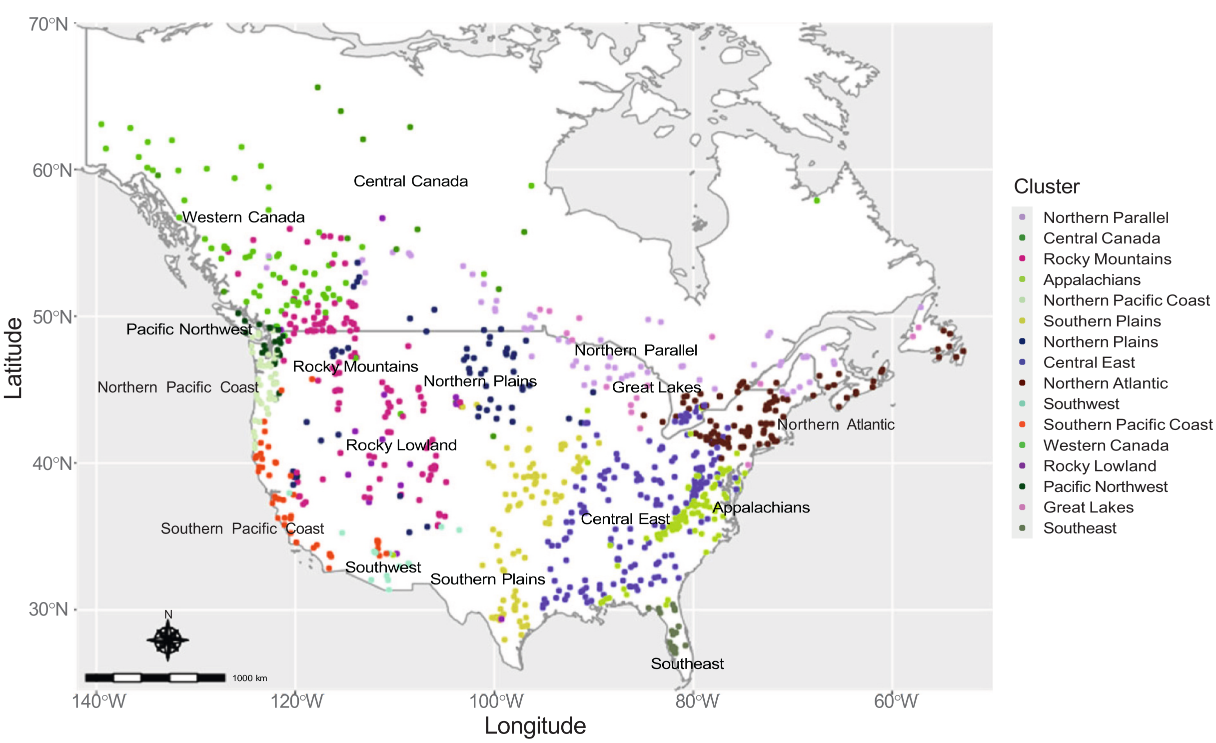

Fig. 1. Sites with measured discharge data clustered into sixteen hydro-regions.

clusters, c is equal to one within uncertainty (Fig. 3). This is true for all recurrence intervals for the Southeast, Rocky Lowland, Southern Pacific Coast, Central East, Great Lakes, Northern Pacific Coast, and Northern Atlantic hydro-regions. The c value of the Pacific Northwest is equal to one within uncertainty using the five-year flood and is otherwise slightly above one. The c value for the Rocky Mountains is equal to one within uncertainty for all but the one-hundred-year flood, where it is less than one. All other hydro-regions have c values less than one.

For all hydro-regions where $c < 1 - \sigma$, where σ is the uncertainty, regressing cluster c values versus runoff efficiency led to two distinct empirical trendlines. The first group includes the Southern Plains, Northern Parallel, and Western Canada (Group A). The second group of clusters (Group B) includes the Southwest, Northern Plains, Central Canada, and Appalachians hydro-regions. For each discharge recurrence interval, the trendlines exhibited strong ($r^2 > 0.9$) relationships with runoff efficiency. The regressions against runoff efficiency are qualitatively similar across all discharge types and the regression coefficients are summarized in Table 1. In general, the regression coefficients for Group A are nearly independent of discharge magnitude, while, for Group B, the slope increases and the intercept decreases with increasing discharge recurrence interval.

3.3. Kriged maps

The spatial variation of c values for the mean annual flow is shown in Fig. 4 and is similar for all discharge recurrence intervals. The c values are generally near one in coastal regions and remain high moving inland until the mid-continent. In the continental interior, c values are lowest across a region from the American Southwest to central Canada. Values of c are intermediate around the Canadian Shield and in Northwest Canada. Kriged maps for the other discharges are in the supplemental information (Figs. S2–S6).

Table 1
Empirical trendline equations for the regression of c against runoff efficiency for each discharge.

Group	Slope	Intercept	Flow Magnitude	r^2
A	0.55	0.46	Mean Annual	0.96
A	0.60	0.41	Q2	0.94
A	0.59	0.44	Q5	1.0
A	0.58	0.46	Q10	1.0
A	0.54	0.49	Q50	0.98
A	0.53	0.51	Q100	0.97
B	1.0	0.49	Mean annual	0.99
B	0.82	0.55	Q2	0.98
B	1.1	0.47	Q5	0.99
B	1.2	0.44	Q10	0.97
B	1.4	0.40	Q50	0.93
B	1.4	0.39	Q100	0.92

Regression equations are of the form $c = (\text{Slope} * R_e) + \text{Intercept}$. Group A includes Northern Parallel, Southern Plains, and Western Canada. Group B includes Appalachians, Central Canada, Northern Plains, and Southwest.

3.4. Channel area

Bankfull channel areas are similar for hydro-regions with both linear and non-linear discharge scaling (Fig. 5). However, streams in small drainage basins that are located in hydro-regions with non-linear discharge scaling have smaller bankfull channels than streams in similarly sized basins in hydro-regions with linear discharge scaling (Fig. 5). The slopes of the regression lines for each scaling group are statistically different from each other ($p < 0.001$). In regions with non-linear discharge scaling, bankfull geometry increases more quickly with drainage area than in regions with linear discharge scaling.

4. Discussion

Consistent with previous studies (Galster, 2007; Winston and Criss,

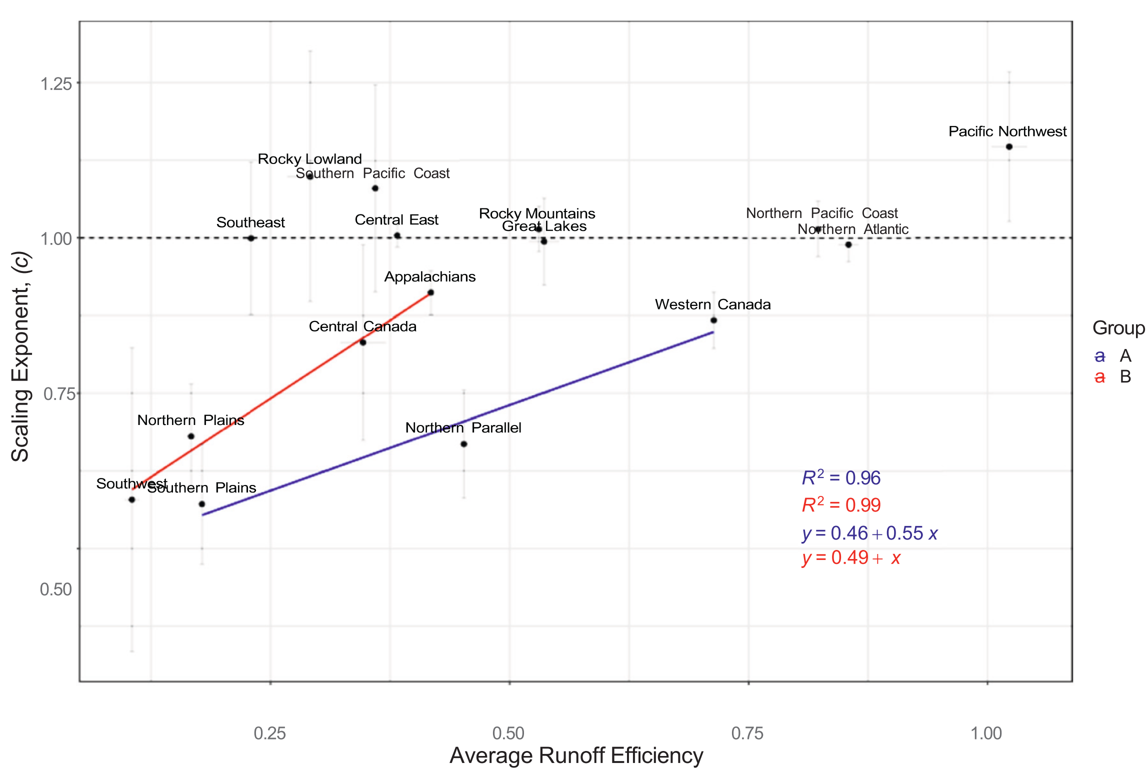

Fig. 3. Cluster c values plotted against average runoff efficiency for mean annual flow. Two empirical trendlines are fitted for clusters where c is less than one within uncertainty.

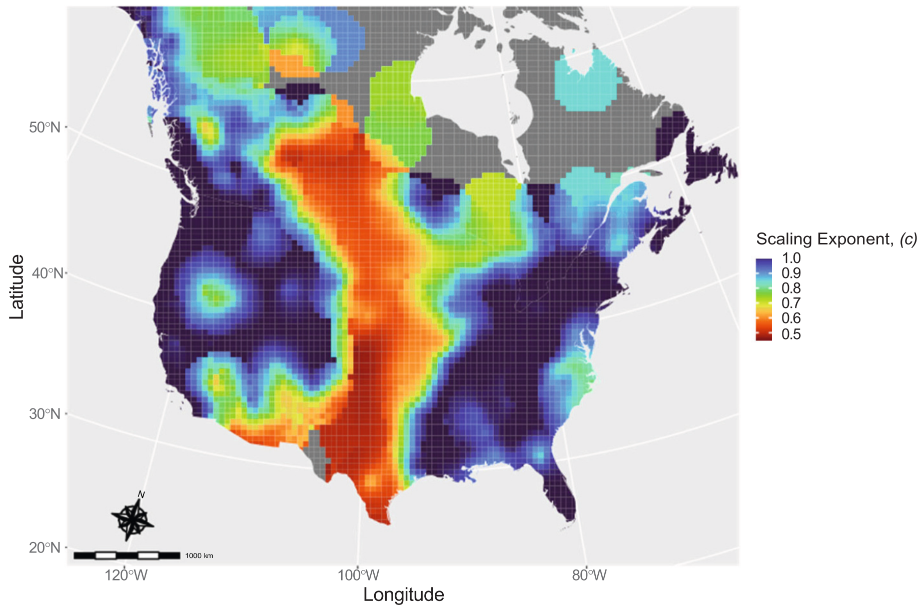

Fig. 4. Kriged scaling parameter values using the mean annual discharge. Gray areas do not have interpolated values.

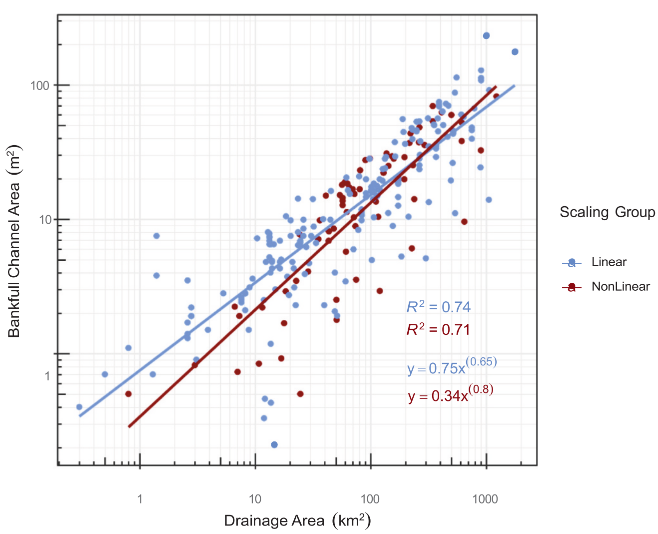

Fig. 5. Cross-sectional channel area at bankfull flow for streams of varying drainage areas. Measurements were compiled by Trampush et al. (2014). Streams geographically located in hydro-regions with linear scaling are separated from streams geographically located in hydro-regions with non-linear scaling.

2016), the assumption that discharge scales linearly with drainage area is supported by the results for most watersheds in North America. While c values may partially depend on climate (Cathcart, 2001) and topography (Benson, 1962), explaining some of the variability between hydrologically similar clusters, setting c equal to one is a reasonable approximation for most regions outside the interior of North America. Fig. 4 shows the continental interior is characterized by low values of the scaling exponent ($c < 1$), similar to that found by Winston and Criss (2016). In these locations, relative to smaller watersheds, larger watersheds are less efficient at delivering precipitation to streams (i.e., their average specific yield decreases with watershed size) and a scaling exponent less than one should be used for the spatial extrapolation of discharge. We note that our analyses are limited to watersheds with limited anthropogenic influence and hence caution should be used in applying empirical formulations, particularly in urban areas, where anthropogenic activity may impact c values (Galster, 2007). Also, the lower r^2 values describing the relationship between discharge and drainage area in hydro-regions with low c values indicates greater variation in how discharge scales among different watersheds in these regions (Fig. 2). In these regions discharge may scale linearly within individual watersheds, even while discharge scales non-linearly across different watersheds.

By limiting our analyses to watersheds minimally affected by anthropogenic effects and using unsupervised machine learning to cluster hydrologically similar watersheds, our results primarily reflect natural variations in average specific yields with watershed area. While c values may change slightly with larger discharge recurrence intervals (Thomas and Benson, 1970; Kölla, 1986; Winston and Criss, 2016), we find that broad spatial patterns in c values are largely independent of discharge recurrence intervals; the same general patterns are present for the mean flow as the one-hundred-year flood. We note that some of the variation in c could arise from differences in gauge record lengths, which alters the recurrence interval assigned to large discharges, in particular.

The correlation between runoff efficiency and c values (Fig. 3) suggests that similar factors may influence both. Runoff efficiency tends to decrease with decreasing annual precipitation (McCabe and Wolock, 2016) and the lowest c values occur where both the runoff efficiency and annual precipitation are low; Winston and Criss (2016) note that c values less than unity are generally restricted to regions where the annual precipitation is <75 cm/yr. Runoff efficiency is also sensitive to temperature in much of the continental interior, making temperature a likely limitation on the scaling of discharge with drainage area in this region (Williams, 1940). Furthermore, the presence of large aquifers in large basins – allowing proportionally more precipitation to exit the catchment as subsurface flow – may decrease runoff efficiency in larger basins and result in low c values (Wu et al., 2021). Larger aquifers also allow for the temporary storage of precipitation as groundwater, which delays the transition to streamflow, lengthening the time for evapotranspiration (Almanaseer and Sankarasubramanian, 2012; Peterson et al., 2021). Winston and Criss (2016) further emphasize the importance of meteorology to low c values in the continental interior, where small storms cause spatially irregular delivery of precipitation to watersheds. Similarly, Ayalew et al. (2014) suggest short, intense storms lower the c value for a watershed in the American Mid-west, which falls in the range of our results for the Northern Plains hydro-region. Intense thunderstorms are also responsible for extreme floods that cause high ratios of the peak flood to the ten-year flood in some watersheds in this region (Smith et al., 2018).

Low runoff efficiency in regions with non-linear discharge scaling also explains the occurrence there of smaller bankfull channel areas in smaller watersheds (Fig. 5). Where runoff efficiency is low, there is less discharge, so channel area remains small. More challenging to explain is why, for larger watersheds, bankfull channel areas are similar regardless of the scaling of discharge. For watersheds with non-linear scaling, discharges accumulate less quickly with drainage area, as is the case for the Southwest hydro-region relative to the Northern Atlantic hydro-region in Fig. 2. If the same characteristic discharge (e.g., the two-year recurrence interval discharge) dictates channel form in both large and small watersheds, where discharge scales non-linearly ($c < 1$), channel area should grow less rapidly with drainage area. Instead, Fig. 5 shows the opposite; channel dimensions increase more rapidly with drainage area in regions with non-linear discharge scaling. A possible explanation for this discrepancy is that, in regions with non-linear discharge scaling, the recurrence interval of the channel forming discharge varies with drainage area. For example, while channels in small watersheds might be primarily shaped by the one to two-year flow, channel geometries in large watersheds might be shaped by less frequent flow events. The difference in recurrence interval of the channel forming flow fits with observations in the American Southwest where the ordinary high water mark – a proxy for bankfull flow – is set by the six to eleven-year flow for channels in large drainage areas ($> 1000\ \text{km}^2$) compared to the one to two-year flow for channels in smaller drainage areas (Hamill and David, 2021). The possibility of channels being shaped by less frequent flows is also consistent with the observations of Wolman and Gerson (1978), who found that channels in arid to semi-arid regions were often larger than channels of the same drainage area in humid regions despite experiencing high water loss. Because discharge increases relatively less rapidly with watershed area in arid and semi-arid regions (Fig. 2), it may be that larger basins require greater magnitude, less frequent precipitation events to generate sufficient discharge to shape the channel. These less frequent, channel-shaping events correspond to larger recurrence intervals. It is possible that this arises from hydrometeorological differences across watershed scales (Robinson et al., 1995; Ayalew et al., 2014).

5. Conclusion

We clustered gauges across the United States and Canada to identify regional scaling relationships between discharge and drainage area. For most of the continent, the assumption that the average specific yield is scale independent is valid within uncertainty. This implies that the assumption of discharge scaling linearly with drainage area is also valid. However, in the continental interior and in the American Southwest, the scaling exponent is less than one and instead demonstrates strong empirical relationships with regional runoff efficiency. These relationships can be used to estimate discharge where direct measurements are limited.

Non-linear discharge scaling also has implications for bankfull channel geometry. Bankfull geometry increases more per unit increase in drainage area in regions with low average runoff efficiency and non-linear discharge scaling. Relatedly, small watersheds have reduced bankfull geometry, while larger watersheds have similar bankfull geometry to watersheds of the same size in regions with linear discharge scaling. The consistency of large watershed bankfull geometry across regions with different discharge scaling may be because large channels in non-linearly scaling regions are primarily shaped by larger recurrence interval discharges.

CRediT authorship contribution statement

Christian M. Erikson: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Carl E. Renshaw:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Francis J. Magilligan:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used are publicly available or are available from the referenced sources. The code used for analysis is available at https://github.com/cmerikson/Runoff_Scaling.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2023.108998.

References

Almanaseer, N., Sankarasubramanian, A., 2012. Role of climate variability in modulating the surface water and groundwater interaction over the southeast United States. J. Hydrol. Eng. 17, 1001–1010. URL: https://ascelibrary.org/doi/10.1061/%28ASCE%29HE.1943-5584.0000536 https://doi.org/10.1061/(ASCE)HE.1943-5584.0000536. Publisher: American Society of Civil Engineers.

Ayalew, T.B., Krajewski, W.F., Mantilla, R., 2014. Connecting the power-law scaling structure of peak-discharges to spatially variable rainfall and catchment physical properties. Adv. Water Resour. 71, 32–43. https://www.sciencedirect.com/science/article/pii/S0309170814001031. https://doi.org/10.1016/j.advwatres.2014.05.009.

Benson, M.A., 1962. Evolution of Methods for Evaluating the Occurrence of Floods. Technical Report 1580. USGS. https://pubs.er.usgs.gov/publication/wsp1580A.

Bray, D.I., 1982. Regime relations for gravel-bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers. John Wiley, Chichester, U.K., pp. 517–542

Cathcart, J.G., 2001. The Effects of Scale and Storm Severity on the Linearity of Watershed Response Revealed through the Regional L-Moment Analysis of Annual Peak Flows. Ph.D. thesis. University of British Columbia. https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/831/items/1.0090768. 10.14288/1.0090768.

Criss, R.E., Winston, W.E., 2007. Effects of urbanization on watershed hydrology: the scaling of discharge with drainage area: Comment and reply: Comment. Geology 35, e126–e127. https://doi.org/10.1130/G23380C.1.

Dade, W., Friend, P., 1998. Grain-size, sediment-transport regime, and channel slope in alluvial rivers. J. Geol. 106, 661–676. https://www.journals.uchicago.edu/doi/abs/10.1086/516052. https://doi.org/10.1086/516052. Number: 6 Publisher: The University of Chicago Press.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., Pasteris, P.P., 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. Int. J. Climatol. 28, 2031–2064. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.1688 https://doi.org/10.1002/joc.1688. Number: 15 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/joc.1688.

Dethier, E.N., Sartain, S.L., Renshaw, C.E., Magilligan, F.J., 2020. Spatially coherent regional changes in seasonal extreme streamflow events in the United States and Canada since 1950. Sci. Adv. 6, eaba5939. URL: https://www.science.org/doi/full/10.1126/sciadv.aba5939 https://doi.org/10.1126/sciadv.aba5939. Number: 49 Publisher: American Association for the Advancement of Science.

Dietrich, W.E., Bellugi, D.G., Sklar, L.S., Stock, J.D., Heimsath, A.M., Roering, J.J., 2003. Geomorphic transport laws for predicting landscape form and dynamics. In: Iverson, R.M., Wilcock, P.R. (Eds.), Prediction in Geomorphology, Geophysical Monograph Series. Blackwell Publishing Ltd., pp. 103–132. http://www.scopus.com/inward/record.url?scp=85028911875&partnerID=8YFLogxK. https://doi.org/10.1029/135GM09

Dooge, J.C.I., 1986. Looking for hydrologic laws. Water Resour. Res. 22, 46S–58S. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/WR022i09Sp0046S https://doi.org/10.1029/WR022i09Sp0046S._eprint.

Dunn, J.C., 1974. Well-separated clusters and optimal fuzzy partitions. J. Cybern. 4, 95–104. https://doi.org/10.1080/01969727408546059 publisher: Taylor & Francis.

Dunne, K.B.J., Jerolmack, D.J., 2020. What sets river width? Sci. Adv. 6, eabc1505. https://www.science.org/doi/full/10.1126/sciadv.abc1505. https://doi.org/10.1126/sciadv.abc1505. number: 41 Publisher: American Association for the Advancement of Science.

Eaton, B., Church, M., Ham, D., 2002. Scaling and regionalization of flood flows in British Columbia, Canada. Hydrol. Process. 16, 3245–3263. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.1100 https://doi.org/10.1002/hyp.1100. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/hyp.1100.

Fields, J., Renshaw, C., Magilligan, F., Dethier, E., Rossi, R., 2021. A mechanistic understanding of channel evolution following dam removal. Geomorphology 395, 107971. https://www.sciencedirect.com/science/article/pii/S0169555X21003792. https://doi.org/10.1016/j.geomorph.2021.107971.

Galster, J.C., 2007. Natural and anthropogenic influences on the scaling of discharge with drainage area for multiple watersheds. Geosphere 3, 260–271. URL: https://doi.org/10.1130/GES00065.1. https://doi.org/10.1130/GES00065.1. number: 4.

Galster, J.C., Pazzaglia, F.J., Hargreaves, B.R., Morris, D.P., Peters, S.C., Weisman, R.N., 2006. Effects of urbanization on watershed hydrology: The scaling of discharge with drainage area. Geology 34, 713–716. URL: https://doi.org/10.1130/G22633.1. https://doi.org/10.1130/G22633.1. number: 9.

Gilbert, G.K., 1877. Report on the Geology of the Henry Mountains. Technical Report. U.S. Government Printing Office. https://pubs.er.usgs.gov/publication/70039916. https://doi.org/10.3133/70039916. publication Title: Monograph.

Hack, J., 1957. Studies of Longitudinal Stream Profiles in Virginia and Maryland. USGS Numbered Series 294-B. Washington, D.C. URL: https://pubs.er.usgs.gov/publication/pp294B.

Hamill, D.D., David, G.C.L., 2021. Hydrologic analysis of field delineated ordinary high water marks for rivers and streams. In: Report. Cold Regions Research and Engineering Laboratory (U.S.). URL: https://erdc-library.erdc.dren.mil/jspui/handle/11681/41681, doi: 10.21079/11681/41681. Accepted: 2021-08-25T18:09:11Z Artwork Medium: PDF Interview Medium: PDF Publication Title: this Digital Resource was created in Microsoft Word and Adobe Acrobat.

Johnstone, D., Cross, W.P., 1949. Elements of Applied Hydrology. Ronald Press Company, New York.

Julien, P.Y., Wargadalam, J., 1995. Alluvial channel geometry: theory and applications. J. Hydraul. Eng. 121, 312–325. https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9429%281995%29121%3A4%28312%29. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:4(312). publisher: American Society of Civil Engineers.

Kirby, W.H., Moss, M.E., 1987. Summary of flood-frequency analysis in the United States. J. Hydrol. 96, 5–14. https://www.sciencedirect.com/science/article/pii/0022169487901399. https://doi.org/10.1016/0022-1694(87)90139-9.

Knighton, A.D., 1987. River channel adjustment — the downstream dimension. In: Richards, K.S. (Ed.), River Channels: Environment and Process. B, The Institute of British Geographers Special Publications Series. Blackwell, Oxford, UK, pp. 95–129. Number 18.

Kölla, E., 1986. Zur Abschätzung von Hochwassern in Fliessgewässern an Stellen ohne Direktmessung: eine Untersuchung über Zusammenhänge zwischen Gebietsparametern und Spitzenabflüssen kleiner natürlicher Einzugsgebiete. Doctoral Thesis. ETH Zurich. https://www.research-collection.ethz.ch/handle/20.500.11850/139247. https://doi.org/10.3929/ethz-a-000415348. accepted: 2017-06-13T00:22:49Z.

Lague, D., 2014. The stream power river incision model: evidence, theory and beyond. Earth Surf. Process. Landf. 39, 38–61. https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.3462. https://doi.org/10.1002/esp.3462. Number: 1 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/esp.3462.

Lee, J.S., Julien, P.Y., 2006. Downstream hydraulic geometry of alluvial channels. J. Hydraul. Eng. 132, 1347–1352. https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9429%282006%29132%3A12%281347%29. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:12(1347). publisher: American Society of Civil Engineers.

Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and Some physiographic implications. USGS Numbered Series 252. Washington, D.C. URL: https://pubs.er.usgs.gov/publication/pp252.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial processes in geomorphology. URL. https://pubs.er.usgs.gov/publication/70185663.

Lins, H.F., 2012. Fact Sheet 2012-3047: USGS Hydro-Climatic Data Network 2009 (HCDN-2009). URL. https://pubs.usgs.gov/fs/2012/3047/.

McCabe, G.J., Wolock, D.M., 2016. Variability and trends in runoff efficiency in the conterminous United States. J. Am. Water Resour. Assoc. 52, 1046–1055. http://onlinelibrary.wiley.com/doi/abs/10.1111/1752-1688.12431. https://doi.org/10.1111/1752-1688.12431. Number: 5 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1752-1688.12431.

Morgan, A.M., Craddock, R.A., 2019. Assessing the accuracy of paleodischarge estimates for rivers on Mars. Geophys. Res. Lett. 46, 11738–11746. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2019GL084921 https://doi.org/10.1029/2019GL084921. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL084921.

Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood-plain development. GSA Bull. 97, 1467–1475. https://doi.org/10.1130/0016-7606(1986)97<1467:EOVAAC>2.0.CO;2.

Parker, G., 1979. Hydraulic geometry of active gravel rivers. J. Hydraul. Div. 105, 1185–1201. https://ascelibrary.org/doi/10.1061/JYCEAJ.0005275. https://doi.org/10.1061/JYCEAJ.0005275. publisher: American Society of Civil Engineers.

Parker, G., Wilcock, P.R., Paola, C., Dietrich, W.E., Pitlick, J., 2007. Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers. J. Geophys. Res. Earth Surf. 112 https://doi.org/10.1029/2006JF000549 eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2006JF000549.

Peterson, T.J., Saft, M., Peel, M.C., John, A., 2021. Watersheds may not recover from drought. Science 372, 745–749. https://www.science.org/doi/10.1126/science.abd5085. https://doi.org/10.1126/science.abd5085. Publisher: American Association for the Advancement of Science.

Phillips, C.B., Masteller, C.C., Slater, L.J., Dunne, K.B.J., Francalanci, S., Lanzoni, S., Merritts, D.J., Lajeunesse, E., Jerolmack, D.J., 2022. Threshold constraints on the size, shape and stability of alluvial rivers. Nat. Rev. Earth Environ. 3, 406–419. https://www.nature.com/articles/s43017-022-00282-z. https://doi.org/10.1038/s43017-022-00282-z. number: 6 Publisher: Nature Publishing Group.

Renshaw, C.E., Magilligan, F.J., Doyle, H.G., Dethier, E.N., Kantack, K.M., 2019. Rapid response of New England (USA) rivers to shifting boundary conditions: processes, time frames, and pathways to post-flood channel equilibrium. Geology 47, 997–1000. http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DynamicDOIArticle&SrcApp=WOS&KeyAID=10.1130%2FG46702.1&DestApp=DOI&SrcAppSID=8BPDS1vMMGnAAm7rVjX&SrcJTitle=GEOLOGY&DestDOIRegistrantName=Geological+Society+of+America. https://doi.org/10.1130/G46702.1 (number: 10 Place: Boulder Publisher: Geological Soc Amer, Inc WOS:000487674000028).

Robinson, J.S., Sivapalan, M., Snell, J.D., 1995. On the relative roles of hillslope processes, channel routing, and network geomorphology in the hydrologic response of natural catchments. Water Resour. Res. 31, 3089–3101. https://onlinelibrary.wiley.com/doi/abs/10.1029/95WR01948. https://doi.org/10.1029/95WR01948. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/95WR01948.

Smith, J.A., Cox, A.A., Baeck, M.L., Yang, L., Bates, P., 2018. Strange floods: the upper tail of flood peaks in the United States. Water Resour. Res. 54, 6510–6542. https://onlinelibrary.wiley.com/doi/abs/10.1029/2018WR022539. https://doi.org/10.1029/2018WR022539. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018WR022539.

Thomas, D.A., Benson, M.A., 1970. Generalization of streamflow characteristics from drainage-basin characteristics. In: US Geological Survey Water Supply Paper 1975. URL: http://pubs.er.usgs.gov/publication/wsp1975, doi: 10.3133/wsp1975.

Trampush, S.M., Huzurbazar, S., McElroy, B., 2014. Empirical assessment of theory for bankfull characteristics of alluvial channels. Water Resour. Res. 50, 9211–9220. https://onlinelibrary.wiley.com/doi/abs/10.1002/2014WR015597. https://doi.org/10.1002/2014WR015597. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2014WR015597.

Tranmer, A.W., Caamaño, D., Clayton, S.R., Giglou, A.N., Goodwin, P., Buffington, J.M., Tonina, D., 2022. Testing the effective-discharge paradigm in gravel-bed river restoration. Geomorphology 403, 108139. URL: https://www.sciencedirect.com/science/article/pii/S0169555X22000320 https://doi.org/10.1016/j.geomorph.2022.108139.

Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs. J. Geophys. Res. Solid Earth 104, 17661–17674. https://doi.org/10.1029/1999JB900120 number: B8 _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1999JB900120.

Williams, G.R., 1940. Natural water loss in selected drainage basins. In: USGS Numbered Series 846. U.S. G.P.O.. http://pubs.er.usgs.gov/publication/wsp846. https://doi.org/10.3133/wsp846. code Number: 846 Code: Natural water loss in selected drainage basins Publication Title: Natural water loss in selected drainage basins Reporter: Natural water loss in selected drainage basins Series: Water Supply Paper.

Winston, W.E., Criss, R.E., 2016. Dependence of mean and peak streamflow on basin area in the conterminous United States. J. Earth Sci. 27, 83–88. https://doi.org/10.1007/s12583-016-0631-6.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process. Landf. 3, 189–208. In: http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1002%2Fesp.3290030207&DestApp=DOI&SrcAppSID=5Cr2P3nZ6WhNJhbjRpt&SrcJTitle=EARTH+SURFACE+PROCESSES+AND+LANDFORMS&DestDOIRegistrantName=Wiley+%28John+Wiley+%26+Sons%29. https://doi.org/10.1002/esp.3290030207 (number: 2 Place: Hoboken Publisher: Wiley WOS:A1978EX92000006).

Wolman, M.G., Leopold, L.B., 1957. River flood plains: some observations on their formation. In: USGS Numbered Series 282-C. U.S. Government Printing Office, Washington, D.C.. http://pubs.er.usgs.gov/publication/pp282C. https://doi.org/10.3133/pp282C. Issue: 282-C Code Number: 282-C Code: River flood plains: Some observations on their formation Publication Title: River flood plains: Some observations on their formation Reporter: River flood plains: Some observations on their formation Series: Professional Paper.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 68, 54–74. https://doi.org/10.1086/626637. Number: 1. Publisher: The University of Chicago Press.

Wu, S., Zhao, J., Wang, H., Sivapalan, M., 2021. Regional patterns and physical controls of streamflow generation across the conterminous United States. Water Resour. Res. 57, e2020WR028086. https://onlinelibrary.wiley.com/doi/abs/10.1029/2020WR028086. https://doi.org/10.1029/2020WR028086. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2020WR028086.