Abstract

THE MOST COMMON STREAM WIDTH IS REMARKABLY INVARIANT WITH CHANGES IN HYDROLOGIC CONDITIONS
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Headwater streams, despite being a significant natural resource, and a critical element of the hydrosphere, remain an understudied system. Anyone who has observed small creeks and rivers closely will know that stream width is highly variable, and depends on the hydrological conditions in the catchment. Stream width (and by extension, surface area) is a critical parameter for a number of important hydrological and biogeochemical processes. Even so, to date there is no consistent study of dynamic stream widths throughout an entire headwater catchment. Here are presented data and observations documenting the spatial and temporal variability of stream width in a single 0.484 km$^2$ headwater catchment in central North Carolina, USA. The frequency distribution of stream widths in the catchment follows a lognormal distribution. Two opposing processes that scale with discharge impact the width distribution. One is at-a-point stream widening, and the other is dynamic network expansion. Despite high spatial and temporal width heterogeneity, the width distribution is remarkably stable with discharge, with a mode width that lies in a narrow range. These results suggest that at-a-point widening and network expansion are roughly in balance, and the relative impacts of each are analyzed.
Dedication

This is for my friends and family, who support me on all my kooky adventures.
Acknowledgements

First and foremost, I could not have done this without my advisor, Dr. Tamlin Pavelsky, who has mentored me for two years through this project and supervised my academic growth. George Allen was instrumental in the continuing development of this project and the ideas herein. I could not have done this work without my field assistants: Madelyn Percy, Michelle Gavel, Elizabeth Henry, Alex Brooks, Justin McNabb, and Harvey Burton. A special thanks goes out to Margaret Zimmer and Brian McGlynn at Duke University who so generously lended us their field site. I also want to recognize Drew Coleman and Kevin Stewart who inspired me to look at rocks in the first place. Finally, I would like to recognize the Morehead-Cain Foundation for all their support and guidance.
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Chapter 1

Introduction

Headwater streams are a critical natural resource. They are unique environments where different ecological, hydrologic, and biogeochemical regimes interact. Estimated to comprise nearly 66-89% of total stream length in the United States [Leopold and Maddock Jr., 1953, Allen et al., in prep., Downing et al., 2012], intermittent and ephemeral headwater streams control vital natural processes at both the watershed scale and across the entire river network [Alexander et al., 2007]. Stream width (and by extension, surface area) is an important driver of the hydrologic, biogeochemical, and ecological processes at work in these small systems.

Low order streams, typically defined as streams of order 1-3 [Alexander et al., 2007, Allen et al., in prep.], are closely coupled to groundwater. The dynamics of low order stream widths has potential to shed light on the dynamics of surface water-groundwater interactions. Stream width scales with discharge [Leopold and Maddock Jr., 1953], and therefore we expect it to be an effective measure of hydrologic conditions in headwater catchments. As such, the dynamic expansion and contraction of small ephemeral streams is a good representation of hydrologic conditions both regionally and at smaller scales [Godsey and Kirchner, 2014, Winter, 2007]. In particular, small streams reveal important characteristics of the substrate on which they flow such as hydraulic conductivity [Winter, 2007].

Furthermore, stream width is important for understanding feedbacks between hydrology and geomorphology through time. At short time scales, width is largely controlled by the combined effects
of changing hydrologic conditions superimposed on essentially static channel morphology. Long-term, however, water flow in the channel will alter and modify the channel geometry, feeding back onto the morphology [Rinaldo et al., 1998, Montgomery and Dietrich, 1992].

In terms of biogeochemical cycling, small headwater streams, being more tightly coupled to groundwater sources than large rivers, have a larger efflux of greenhouse gases to the environment [Allen et al., in prep., Raymond et al., 2013, Butman and Raymond, 2011]. This is largely due to the higher concentrations of CO\textsubscript{2} in headwaters, combined with the fact that these streams are usually steeper and more turbulent than large rivers. The stream surface is an important biogeochemical interface, through which gas exchange between the hydrosphere and the atmosphere takes place. [Hynes, 1970] The speed and magnitude of that exchange is, in part, controlled by the surface area of this interface. Stream width, therefore, is an important parameter to consider when estimating CO\textsubscript{2} efflux into the atmosphere from rivers.

In addition to gas exchange, width in small streams plays a key role in controlling water quality and solute transport to downstream reaches. Ephemeral and intermittent streams control water and solute residence times and transport across entire landscapes, modulating nutrient cycling and contaminant spread. On average, they contribute 55% of water volume and 40% of nitrogen flux into fourth and higher order streams [Alexander et al., 2007]. As such, headwaters are important potential sources and conduits for pollution to contaminate downstream reaches. This is particularly salient because in the United States, a large fraction of drinking water supplies depend on water that originates in headwater streams. In fact, nearly 58% of streams where drinking water supplies originate are intermittent streams [EPA, 2009]. Understanding the spatial and temporal variation of stream width in small headwaters catchments will help address important questions about how solutes move through these systems.

Headwater streams are also hotspots for biodiversity. Low order streams, by virtue of their ubiquity throughout the river network, host a diverse suite of environments with a variety of substrates, light, and temperature regimes. [Meyer et al., 2007] Small streams are the most varied running-water habitats, and as such provide a habitat for species that are often found nowhere else in a river network. The role that intermittent streams play in supporting biodiversity locally scales to the entire network because headwaters are the feeding and spawning grounds for many species.
living in larger streams (e.g. salmon [Geist and Dauble, 1998]). Width and inundation area, as a measure of hydrologic connectivity and discharge throughout a catchment, can inform assessments of the suitability of a stream as a habitat, and can contribute to our understanding of the sorts of ecosystems that develop there.

Understanding the distribution of widths in small headwaters streams is critical for addressing a wide variety of questions with ecological, hydrologic, geomorphic and biogeochemical importance. The spatial distributions of width and surface area have been examined in the largest rivers [Allen and Pavelsky, 2015, Yamazaki et al., 2014] and the smallest headwater streams [Allen et al., in prep.]. At the scale of continents, river widths appear to be distributed according a power-law, and small stream widths are often characterized using similar scaling relationships. However, these simple relationships do not capture the real variability of width in time or space. Rather, recent measurement of stream widths by Allen et al. [in prep.] suggests that the frequency of widths can be modeled using log-normal distributions. Furthermore, the basic characteristics of these distributions appear to vary little across a range of mid-latitude catchments.

Despite these new findings, the variability of width and inundation extent within the smallest headwaters catchments remains poorly understood. In particular, changes in the width distribution with hydrologic conditions remain unobserved. To date, there are no consistent and complete measurements of width and surface area variability in headwater catchments. We hypothesize that changes in width distributions are driven by two factors, both increasing with discharge: lengthening of the active drainage network and widening of existing streams. Classical hydraulic geometry theory predicts that stream width will scale as a power-law function of discharge:

\[ w = a Q^b \]  

(1.1)

Applied across a river network, this relationship implies that with increased discharge, at-a-point stream widths will increase. In the absence of other forces, these widening effects will act to \textit{shift the lognormal width distribution to the right}, \textbf{increasing the mode width}. However, small headwaters networks also expand in response to increased discharge, and we hypothesize that on average, new stream segments will be narrower than the mode width, consistent with classical
downstream hydraulic geometry [Leopold and Maddock Jr., 1953]. This pattern implies that with increased discharge, these network expansion effects will shift the width distribution to the left, decreasing the mode width. We predict that a balance between these factors results in relatively little change in the mode or variability of width with discharge.

Figure 1.1: Idealized curves showing our hypotheses for dynamic stream width distributions. From an initial distribution (grey), our null hypothesis (H₀) is shown in blue, our first alternative (H₁) is shown in red, and our second alternative (H₂) is shown in yellow.

From an initial distribution of stream widths A, we hypothesize (H₀) that with increased discharge the total magnitude (total surface area) of the distribution will increase, but the overall shape and position of the distribution will remain unchanged. This will reflect a balance between the effects of at-a-point stream widening and network expansion. For illustration of this, see the blue curve in Figure 1.1. Our first alternative hypothesis (H₁) is that with increased discharge, the total magnitude of the distribution will increase, and additionally the distribution will shift to the right, most clearly shown by an increase in mode width. For illustration of this, see the red curve in Figure 1.1. This would suggest that at-a-point widening effects are stronger on average than network expansion effects. Inversely, our second alternate hypothesis (H₂) is that increased
discharge will increase the total surface area in the stream network, but that network expansion effects will predominate, which on average will shift the distribution to the left, accompanied by a decrease in mode width. For illustration of this, see the yellow curve in Figure 1.1. Here, we test these hypotheses using 13 spatially dense surveys of stream width and length at Stony Creek, a 0.484 km² watershed in central North Carolina, USA.
Chapter 2

Methods

2.1 Study Area

To address these hypotheses, we worked at the Stony Creek research watershed. Located south of Hillsborough, NC (see Figure 2.1, map inset) and situated on US Forest Service Land, the site is heavily monitored, and its hydrological properties have been under investigation for over two years. [pers. comm. M. Zimmer] The watershed is located in a humid subtropical climate, was formerly cultivated as cropland, and relict structures such as building foundations and irrigation ditches remain. Such anthropogenic disturbances – especially irrigation ditches – have since become identifiable hydrologic features. Since the time when the land was acquired by the Forest Service, the site has been allowed to reforest, and is now predominantly pine, oak, and hickory. The site of several forestry experiments, the land has been subject to multiple controlled burns and partial clear-cut harvests.
2.2 Methods

To quantify patterns of stream width in response to variable discharge, we established a set of sampling locations marked by survey flags along the entire stream network at Stony Creek (740 points). This is shown in the red inset in Figure 2.1. We mapped the centerlines of the streams manually using optical imagery and GPS track data, corroborated with field observations. We placed survey flags at five meter intervals along the channel thalweg, and each flag was given a unique identifier.

We surveyed wetted stream widths at a range of discharge percentiles from September 2015 to March 2016. During each survey, we measured the wetted width orthogonal to the thalweg of the stream with a standard tape measure at every survey flag. We defined a stream as flowing water in
a channel, including ephemeral channel features formed in leaf litter [Allen et al., in prep.]. When a stream divided into multiple channels, we visually estimated the percentage of the stream that was dry, to capture both the overall width and an index of channel braiding [Allen and Pavelsky, 2015]. When a sample location had no flowing water, a width of 0 was recorded. On occasion, new flow conditions filled channels that were previously not flagged, in which case the 5 m sampling interval was estimated by pacing. In such circumstances, we assumed that the stream segment was dry in the previous surveys. Flowing segments under five meters long, which were rare, were not mapped or recorded. Each independent event has 732 - 740 measurements, and each survey was completed in under four hours to avoid averaging over large temporal variations in discharge. Sometimes a survey flag was completely inundated, buried by sediment during large events, or washed downstream. In such cases, we recorded the width as a missing value, and later replaced the lost flag. These errors comprise a small proportion (0.00 to 0.81%) of the total number of measurements. Actual measurement error was estimated by taking the root mean squared error of paired measurements between the 12th and the 13th surveys, which occurred within 2 hours of each other. Our root mean squared error between these surveys was 11 cm. We surveyed the stream network 13 times (n = 13) throughout the season, seeking to capture a wide range of flow conditions and seasonal variability.

For each survey, width data were paired with discharge information. Stage was measured at a 5-minute interval at the downstream-most point in the network. Discharge was then calculated from a rating curve with n = 22 points. Percentiles of flow were calculated from the long-term stage record (since September 2013). Mean discharge for each survey was then calculated from the 5-minute discharge data during the time when the survey took place. We collected surveys at a wide range of discharges spanning the 11th to 98th flow percentiles, calculated from nearly 2 years of discharge data. This range, 0.03 to 128.08 L s⁻¹, represents flows that differ by a factor of almost 4500.

To assess whether the width distributions in our study were comparable to the findings in Allen et al. [in prep.], we fitted a lognormal distribution to each width dataset using a maximum likelihood estimation and calculated the goodness-of-fit using a Kolmogrov-Smirnov test [Massey, 1951] to determine whether our distributions were statistically distinguishable from a lognormal distribution.
Mode stream width was initially calculated from the lognormal fits. However, we preferred a different method that fits a smoothing spline interpolation (smoothing parameter 0.3) to histograms of the binned width data (bin size = 10 cm). This method produces PDFs that more convincingly match the overall shape and peak of the width distribution.

For each survey, we calculated the total stream surface area by summing the products of width and length for the whole network. We assessed the relative magnitude of at-a-point stream widening effects versus network expansion and contraction effects on stream surface area. We selected nine pairs of surveys $A$ and $B$, selected so that $A$ and $B$ are adjacent in time and so that both the surface area and discharge of $B$ are greater than of $A$. For each pair, we calculated the total change in surface area ($\Delta A_T$), then separated $\Delta A_T$ into two parts. One part was the change caused by the conversion of dry locations to wet locations (network expansion or $\Delta A_{ex}$) and the other was the change in width of wet locations (at-a-point widening or $\Delta A_{wi}$). We then compared the relative magnitude of the two effects for each pair of surveys. Furthermore, to address the question of how each effect changes the overall width distribution, we also compared the shape and mode of the distributions generated by each effect.
Chapter 3

Results

3.1 Dynamic network expansion, fragmentation, and widening

Overall, the spatial and temporal distribution of stream widths in the network is quite heterogeneous. Stream widths across all surveys ranged from 2 to 831 cm (mean 82±61 cm), and within individual surveys the smallest range was 231, and the largest was 828. The length of active stream network varied from 800 meters to 3465 meters. Flowing widths of individual points were also highly variable. Some points varied by as much as 787 cm between surveys, while others varied little enough as to be within our root mean squared measurement error.

We find that generally speaking, at-a-point width increases with discharge across the stream network. We calculated the b exponent in Equation 1.1 at every point in the network, with values ranging between -1.02 and 2.19. However, the range of b-values is large, and is spatially quite heterogeneous. Negative b-values are few, and they also generally correspond to low r² values, indicating that they might be an artifact of a poor regression fit. Furthermore, the spatial distribution of stream widths in the network changes dynamically with discharge, (see Figure 3.1). The extent of Figure 3.1 is marked by the blue box in Figure 2.1. Certain reaches are more likely to grow dramatically in width with a small increase in discharge. For example, consider the reach marked by a square in each panel of Figure 3.1. During relatively dry conditions (1, 2, 3, 5, 6, 8, 9, 12, 13) this reach is narrow. During relatively wet conditions (4, 7, 10, 11), however, this
reach becomes quite wide. In contrast, some reaches changed very little in width despite large changes in discharge. Consider the reach marked by a triangle, which shows very little variation in width except during extreme events. Some reaches even went dry from one time to another despite an overall increase in discharge. Additionally we observed some changes in channel morphology throughout the network, for example when log-jams were cleared in large storm events, or trees fell and redirected stream flow.

In addition, our observations confirm the results of Godsey et al. [2014] that the active stream network dynamically expands and contracts in response to changing hydrologic conditions. In general, tributaries contracted from their tips before the trunk stream in the network disappeared. However this was not always the case. For example, Figure 3.1 shows the disappearance of different parts of the main trunk stream in early September, while smaller tributaries remained active. We observed significant fragmentation of the network as individual reaches within a segment went dry, as can be seen throughout Figure 3.1.

### 3.2 Width distribution variation and the mode width

While the spatial and temporal distribution of individual widths in the stream network is quite heterogeneous, the shape and position of the width distribution itself is in fact quite stable, (see Figure 3.2). The width distributions are readily characterized by lognormal distributions ($r^2$ values range between 0.94 and 0.99) and they have a distinctive peak, which approximates the mode of the distribution. Overall, while widths across all surveys range from 2 to 831 cm (mean 82±61), mode stream width varies surprisingly little, from 27 to 71 cm with a mean of 43±11 cm (see Figure 4.1 (a)). The mean and standard deviations of the total distributions vary over similarly narrow ranges (78±16 cm and 55±13 cm respectively). In addition, the interquartile range of the mode widths is smaller than the interquartile range of all widths by nearly a factor of 7 (see Figure 3.2, boxplot inset).
Figure 3.1: Variation in network connectivity and width across all surveys. This figure shows a subset of the basin to highlight fine-scale variations in width. The extent of this section can be seen in Figure 2.1 surrounded by a blue box. Each panel represents a unique survey, and discharge for each is shown on the hydrograph at bottom right. In order of appearance, the surveys took place during the 11th, 12th, 95th, 98th, 84th, 57th, 85th, 62th, 26th, 95th, 98th, 54th, and 56th percentiles of flow.
Although mode stream width does not vary much compared to the overall width variation, it does vary systematically. Mode width covaries positively with discharge \((b = 0.225 \pm 0.052, r^2 = 0.59, p\text{-value} = 0.0012)\), as do the standard deviation of widths \((b = 0.298 \pm 0.044, r^2 = 0.79, p\text{-value} = 2.76 \times 10^{-5})\), and mean width \((b = 0.367 \pm 0.058, r^2 = 0.76, p\text{-value} = 5.71 \times 10^{-5})\).

Figure 3.2: Using the same color scheme, we show a smoothed spline estimation of the frequency distribution of widths during each event. Each unique event is connected to its location in the hydrograph. Additionally, we show the total variation in width as compared to the variation in modal width on the same scale as the distributions.

### 3.3 Analyzing stream surface area dynamics

Stream surface area ranged from 519 to 3456 m\(^2\), which comprises 0.04 to 0.27\% of the total catchment area. Total stream surface area varies as an approximate power function of discharge \((\beta = 0.332 \pm 0.071, r^2 = 0.68, p\text{-value} = 0.0011)\). This relationship is shown below in Equation 2. (see Figure 4.1 (a) and (b)) The first survey was discarded from analyses involving discharge because discharge was effectively zero at the gauge.
\[ A = \alpha Q^\beta \]  
(3.1)

When comparing a pair of surveys \( A \) and \( B \), the relative magnitudes of \( \Delta A_{ex} \) and \( \Delta A_{wi} \) are approximately evenly distributed. In Figure 4.1 (c), points above the 1:1 line represent transitions between events where \( \Delta A_{ex} \) had a larger magnitude than \( \Delta A_{wi} \). Further, the size of the symbol is proportional to the surface area of event \( A \). In general, if the surface area of event \( A \) is small, network expansion effects will be dominant, and if the surface area of event \( A \) is large, at-a-point widening will be dominant.

Figure 4.1 (d) shows an example analysis of two such events, which are indicated in Figure 4.1 (a), (b), and (c) by circles around the relevant data points. The total change in area from the orange curve to the light blue is the total area of newly inundated reaches as added to the marginal increase in width at every point. In this case, the \( \Delta A_{ex} \) was 888.3 m\(^2\) and \( \Delta A_{wi} \) was 810.6 m\(^2\).

The width distribution from survey \( B \) can be separated into two distributions, one for \( \Delta A_{ex} \), and one for \( \Delta A_{wi} \), which in Figure 4.1 (d) are plotted alongside the two distributions for \( A \) and \( B \). In general, the distribution for \( \Delta A_{ex} \) forms a smaller lognormal distribution close to the lower end of the width distribution. This is represented by a dark grey line in Figure 4.1 (d). In contrast, the distribution for \( \Delta A_{wi} \) forms a very different distribution. Essentially, at-a-point widening shifts the distribution of survey \( A \) towards higher width values and increases the spread, as in the grey curve in Figure 4.1 (d).

If the mode widths from each of these distributions \((A, B, \Delta A_{ex}, \Delta A_{wi})\) is compared across nine selected survey pairs, a pattern emerges. On the whole, the mode width of \( \Delta A_{ex} \) is slightly narrower than mode of \( A \), the difference is statistically significant at 95% confidence. The mode width of \( \Delta A_{wi} \), in contrast, is significantly wider on average than the mode of \( A \). The mode of \( B \) is also significantly wider than the mode of \( A \) and the mode of \( \Delta A_{ex} \) (see Figure 4.1 (e))
Chapter 4

Discussion

4.1 Variation of width distributions with discharge

While the discharge and surface area in Stony Creek during our study varied across a large range of flow conditions, the distribution of stream widths remained comparatively stable both in location and shape. We used the mode width as our primary tool for assessing whether the distributions moved relative to each other. The mode width is much less variable compared to the total variation in width at individual points and also throughout the catchment. The total range in mode widths is smaller than the median range of at-a-point widths. In addition, the interquartile range of mode widths is almost seven times smaller than the interquartile range of all stream widths (see Figure 3.2).

We interpret the stability of the width distribution to be an indication that at-a-point widening and network expansion effects are largely in balance. This is in favor of our null hypothesis (H0). Indeed, in terms of added stream surface area it does not appear that there is a clear dominance of either at-a-point widening or network expansion effects. In fact, we see that for any given pair of surveys A and B, the ratio of $\Delta A_{ex}$ to $\Delta A_{wi}$ for each of the two effects ranges widely on either side of a 1:1 line. For an illustration of this, see Figure 4.1 (c), which shows a selection of such pairs. It appears that for any given pair, the initial surface area (area of A) is important for determining whether widening or expansion is larger. We conclude from this that when transitioning from low
to high streamflow, expansion is more important, while from high to high streamflow, widening is more important (see Figure 4.1 (c)).

![Figure 4.1](image)

Figure 4.1: (a) Variation of mode width with discharge. (b) Power law relationship between total surface area and discharge. Connect this with Equation 3.1 (c) Selecting nine pairs of events, the increase in area due to at-a-point widening is compared to the increase due to network expansion. The relative importance of network expansion and channel widening is represented by the 1:1 line, above which expansion dominates and below which widening dominates. (d) Examining the relative balance between the two effects, distribution A shown in orange, expands to become distribution B (blue) at a higher discharge and surface area.

However, within its narrow range, mode width covaries positively with discharge and area, such as in Figure 4.1 (a). This is in favor of our first alternative hypothesis (H\textsubscript{1}), which suggests that the most common width will increase with discharge. To understand why this is, we analyzed the impacts of widening and expansion on the mode width between each pair of surveys. Despite the fact that at-a-point widening and network expansion are mostly in balance, at-a-point widening effects have a disproportionate impact on the mode width.

At-a-point widening (\(\Delta A_{ex}\)) increases the mode width (H\textsubscript{1}) by shifting individual measurements towards the tail of the distribution (Figure 4.1 (d) grey curve). Network expansion (\(\Delta A_{wi}\)) adds
points that are narrower (see Figure 4.1 (d), black curve, which decreases the mode width \(H_2\)). Since the distribution of \(B\) (blue curve) is the sum of the distributions \(\Delta A_{ex}\) and \(\Delta A_{wi}\), the mode width of \(B\) can be thought of as a weighted average of the modes of \(\Delta A_{ex}\) and \(\Delta A_{wi}\). The mode of \(\Delta A_{wi}\) is on average much larger than the mode of \(\Delta A_{ex}\), but since the mode of \(\Delta A_{ex}\) is not much narrower than the mode of \(A\), widening effects pull the mode of \(B\) to be wider than that of \(A\). In this way, the two factors (\(\Delta A_{ex}\) and \(\Delta A_{wi}\)) can be equivalent on average, but the mode width will still increase with discharge.

We conclude that overall, surface area change in the catchment is being accommodated by both at-a-point widening and network expansion in approximately equal measure. Even so, at-a-point widening has a slightly larger impact on the distribution than does network expansion, increasing mode width and moving the width distribution slightly to the right. However, there are some practical limits to these results. In general, when discharge increased, the distribution kept the same shape and location while increasing in area. The only time when the distribution did not follow this pattern was at its highest discharge. In that survey (Figure 3.2, dark green curve), the mode width as well as the spread of the distribution increased substantially. And yet, the total area under the curve was not much larger than other surveys with high surface area. During this survey, the stream expanded to fill almost 86% of the geomorphic channel network, and was essentially only experiencing at-a-point widening effects, having very little channel to expand into. Furthermore, based on our observations in the field, this event was close to Stony Creek’s bankfull discharge. Our conceptual framework relying on channel geometry cannot explain width variation at flood stages, and therefore the implications of these findings should be restricted to discharges less than bankfull.

4.2 Spatial variation of stream width and channel geometry

Hitherto undocumented in a rigorous fashion, the spatial and temporal heterogeneity of stream widths we observe in Stony Creek is quite large. We observe some basic trends. For example, higher order streams are wider on average, and there is an overall downstream increase in width and width variability. This issue is discussed in depth in Allen et al. [in prep.]. However, beyond
simple relationships predicted by at-a-station and downstream hydraulic geometry, some reaches are usually dry, and others are often significantly wider than surrounding reaches. On average, individual measurement locations varied by 89 cm, but this variation ranged from as little as 0 cm and as much as 787 cm. The location of anomalous reaches follows no clear spatial pattern, and is not periodic.

Figure 4.2: Map of b-values calculated for Equation 1.1 using the downstream discharge for every point in the stream network. Features to note are reaches where b is very large, implying that channels there are wider and not deeply incised.
Width does generally increase with discharge at a point as a power law (Equation 1.1). However, the variation of width with discharge throughout the catchment is unexpectedly heterogeneous. By solving for values of \( b \) across Stony Creek, we can quantify how width varies at every point in the network as a function of discharge. Lower values of \( b \), for example, imply wide, shallow channels with steep walls [Leopold and Maddock Jr., 1953]. These \( b \)-values (mean value: 0.22±0.28) are also spatially heterogeneous. This result suggests that fine-scale stream width variability is being driven by local channel geometry. Remarkably, the mode width, and the width distribution as a whole, are quite stable despite this significant local variability in channel geometry. These results affirm the notion that the mode width is largely an emergent property of a dynamic interaction between streamflow and the geomorphic channel network.

Downstream hydraulic geometry relationships and Horton’s laws imply that in a given channel network, there will be very many narrow channels of low order, and few wide channels of higher order. This is due to the fact that stream networks are fractal in nature [Leopold and Maddock Jr., 1953, Horton, 1945, Rinaldo et al., 1998]. However, streams are not infinitely fractal; there are not streams everywhere and so at some point, the fractal nature breaks. These relationships predict that a frequency distribution of stream widths would appear as a truncated power law (an assumption posed by Allen and Pavelsky [2015]). The lognormal shape of the width distribution we observe in reality is a consequence of superimposing these relationships on a real channel network, in which stochastic processes give rise to local variability in channel geometry [Allen et al., in prep.].

In this study, we build on the results from Allen et al. [in prep.], and highlight that in addition to being confined to a narrow range across different geologic, tectonic and climatic conditions, the mode width of small streams is also constrained to a relatively narrow range across variable hydrologic conditions. A conceptual framework of catchment hydrology involving a mode or most common width is relatively new, and important for a variety of problems related to biogeochemistry, geomorphology, ecology, and hydrology.
4.3 Implications for hydrology and geomorphology

Power laws have long been used to describe hydrological systems [Leopold and Maddock Jr., 1953]. A new framework based on the collapse of fractal characteristics suggests that skewed distributions like lognormal or gamma distributions may be better descriptors than power laws of small scale hydraulic patterns. The occurrence of a similar mode width across wide ranging tectonic, climatic, and geologic settings suggests that it may be a general phenomenon with a general physical explanation [Allen et al., in prep.]. Furthermore, Allen et al. [in prep.] assert that using distributions with mode values implies that there may also be a most common discharge, depth, and velocity. Depth and velocity also vary at a point according to power law functions (Equations 4.1 and 4.2). A new conceptual framework based around lognormal distributions suggests that these mode values of v, d, and Q may be relatively invariant under a range of hydrologic conditions within the same watershed.

\[ d = cQ^f \]  \hspace{1cm} (4.1)

\[ v = kQ^m \]  \hspace{1cm} (4.2)

In addition, since width varies at a point as a function of discharge, (Equation 1.1) higher values of b will constrain the magnitudes of other scaling exponents for at-a-point hydraulic geometry equations (Equations 4.1 and 4.2). In particular, \( b + f + m = 1 \), so changes in width will force changes in depth or velocity. This will have an impact on the shear stress conditions that can exist there. The exponent b is spatially heterogeneous throughout stony creek, and it will force increases in velocity and depth in some areas and not others. This variation in width and shear stress implies that incision will also not be uniform across the catchment, ultimately feeding back on the morphology of the channel.
4.4 Implications for biogeochemical cycling and ecology

In the context of biogeochemical cycling, the heterogeneous spatial and temporal distribution of surface area should have an impact on a number of different chemical transport phenomena. For example, CO\textsubscript{2} exsolution from streams depends on the surface area of the water-air interface. Our results demonstrate that the change in size of that interface varies widely throughout the channel network; i.e. all reaches do not increase in area at the same rate with increasing wetness. However, the width distribution remains relatively stable with increasing surface area, despite a heterogeneous distribution of surface area. Therefore we speculate that while the distribution of $\Delta A_T$ is not homogeneous across the network, the local variability will not have a large impact on the average CO\textsubscript{2} efflux because the surface area is being added in such a way that it is not concentrated in any particular location in the network topology. The stable nature of the width distribution suggests that since widening and expansion balance each other on average, the major factor determining the total surface area will simply be total discharge (see Equation 3.1).

The intermittent connectivity with changing flow conditions we document implies that when streams become reconnected, they can advect solutes and particulate matter that were previously unsupplied to downstream sections, or were supplied through groundwater flow. We would expect that as a result, some nutrients or contaminants may be transported to downstream reaches as discontinuous pulses rather than a continuous flow. This sort of reconnection is particularly likely to happen during high flow events, when shear stresses are also more likely to be high. Contaminants thus held in a disconnected reach of a headwater might suddenly be released downstream by a high-flow event. This will have impacts for the water quality of downstream reaches [Alexander et al., 2007].

The spatial heterogeneity and dynamic variation of widths also suggests that headwaters contain a variety of microclimates and microecosystems even within the catchment. Such a habitat might exhibit a set of similar flow conditions, and provide a haven to animal species unique to that catchment. This may have implications for understanding the biodiversity of river systems [Freeman et al., 2007].
4.5 Implications for stream surface area estimation

This study is the first to directly measure variations in the total surface area of an entire stream system and relate it to discharge. The total surface area in a stream system can be approximated as a power function of downstream discharge measurements in Equation 3.1 (shown in Figure 4.1 (c)) \( \beta = 0.332 \pm 0.071, r^2 = 0.68, \text{p-value} = 0.0011 \). Because the length of the active channel network is important for the surface area, our rating curve is comparable in nature to the relationship found in Godsey and Kirchner [2014] that describes total active channel length as a function of downstream discharge. Similarly, we would expect to see highly variable \( \beta \) exponents across basins depending on the drainage density.

For the purposes of estimating the global surface area of streams, our study and work of Allen et al. [in prep.] support the conceptual model that using truncated power law distributions, as in Allen and Pavelsky [2015] is an unsatisfactory approach to estimating total surface area. Rather, we suggest that better results could be obtained by fitting a lognormal distribution to the upper end of a distribution such as that obtained in the NARwidth dataset. Additionally, we recommend setting a mode width somewhere in the narrow range of widths we identify in these two papers. This study, along with Allen et al. [in prep.] would suggest that such assumptions are well-founded, because the mode width is relatively insensitive to variation in the scale, area, and discharge of a basin.
Chapter 5

Conclusions

Our results reveal spatial and temporal patterns of width in a headwater stream network. We show that stream width is spatially heterogeneous, and that the variation is a reflection of local channel morphology. Nonetheless, the stream widths in a given watershed follow a lognormal distribution, and while the total area under the curve changes with discharge, the shape and location of the distribution is comparatively stable. The peaks of these distributions, or the mode width, is an important parameter for understanding dynamics in a stream network. While the mode width varies little in comparison to the overall variability in width, it has linear relationship with discharge.

As a result, we find that there is also a scaling relationship between the discharge and upstream surface area of a stream network, and that in general, surface area change in Stony Creek is driven by both at-a-point widening and network expansion. Network expansion seems to be more important at times when the network is dry, i.e. when the surface area of the network is small. The relationship between discharge and the mode width, however, suggests that the dynamic interplay between network expansion and at-a-point widening is not completely in balance.

Building off of work by Allen and Pavelsky [2015], instead of estimating stream surface area with power-law functions, we recommend fitting lognormal distributions with a fixed mode width to remotely sensed river width data (as in the NARwidth dataset) to estimate total river surface area. Allen et al. [in prep.], further suggested that the existence of a most common stream width across tectonic regimes points to the possibility of a most common depth, velocity and discharge. We
extend this notion to hypothesize that these other mode values may be also be stable in relation to hydrologic conditions as well.

What remains unknown are the physical mechanisms at work that locate the peaks of width distributions in a narrow range. In addition, we do not yet know whether other hydraulic parameters also follow lognormal distributions. These questions have importance for understanding small scale systems, which ultimately have large impacts on the ecology, biogeochemistry, and hydrology of large river systems.


George H. Allen, Tamlin M. Pavelsky, and Eric Barefoot. Uniformity of stream hydromorphology across headwater systems. in prep.


Frank J. Massey. The Kolmogorov-Smirnov Test for Goodness of Fit. Journal of the American


