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Examining the Relationship Between Manning's Roughness Coefficient and Stage

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INTRODUCTION

Streamflow, also referred to as stream discharge, is the volume of water passing a point within a stream over a given period of time and is an important piece of information for many reasons. Streamflow is needed to help inform stakeholders and policy decisions with regard to quantity and quality of available water resources. Water does not heed political boundaries, so accurate streamflow measurement is necessary to ensure maintaining of transboundary agreements. The measurement of stream flows is important for water allocation (Mutiga et al., 2010), flood management (Muste & Hoitink, 2017), water quality monitoring (Murphy & Sprague, 2019), and ecological sustainability (Apse et al., 2008).

The distribution of water supplies, i.e. water allocation, requires accurate predictions of discharge and water quantity. Stakeholders require this information for many uses including irrigation (Chiew et al., 2003), domestic water supply (Latif & Ahmed, 2023), hydropower generation (Ashman et al., 2004), industrial use (Karimi & Ardakanian, 2010), and ecology (Petts, 1996). Those responsible for withdrawing this water must know streamflow information (water quantities) so that they can withdraw responsibly, leaving enough for other usages. Water withdrawal in the United States is regulated via the Riparian Doctrine, the system of prior appropriation, or a combination of the two (The National Agricultural Law Center, n.d.). The Riparian Doctrine allows for reasonable use of water, which requires that a water user not harm or destroy another downstream water user's reasonable use (Benson, 2012). In the system of prior appropriation, water is allocated on a "first in time, first in right" basis, essentially the first claim to the water, is the first served

(Benson, 2012). This water must be put to beneficial use and may not be wasted (Benson, 2012). For either of these systems, water allocation is done through a permitting system, with a state entity controlling who is using water, how much they are using, and when (The National Agricultural Law Center, n.d.). Streamflow information is essential to know the quantity of water that may be diverted. Basin watermasters use this streamflow information to help administer diversions under the applicable water right system (Hester et al., 2006). Streamflow data becomes particularly important during low flows, when water usage may be restricted (Hester et al., 2006). It is also important so that withdrawals are not so excessive from streams and rivers that those aquatic systems can no longer function ecologically.

Streamflow information at the upper end of the hydrograph is also important for flood management. The Federal Emergency Management Agency (FEMA) administers the National Flood Insurance Program (NFIP), whose responsibilities include creating floodplain maps that show areas prone to flooding in a 100-year storm so that they may be properly insured. Long-term streamflow data is used to determine flood flows for this 100-year storm and to then develop water surface profiles in areas at risk of flooding (Normand, 2021). In addition to knowing where flooding may occur, streamflow information is also used to determine how bad a flood may be. The National Weather Service (NWS) provides flood forecasts based on models driven by USGS streamflow data (Carswell Jr. & Lukas, 2018). These forecasts include predictions of flood magnitude and the timing of flooding, allowing appropriate flood watches and warnings to be issued (Carswell Jr. & Lukas, 2018). This information is extremely vital for keeping people safe and informing emergency response to these events. High flows are the portion of the hydrograph that flood forecasters are interested in, and this portion can also contribute the majority contaminant loads into water bodies (Glaser et al., 2020).

Streamflow information is also important for the proper evaluation of water quality. The Federal Clean Water Act requires in Section 303(d) that states identify streams and rivers that are not meeting water quality standards, and requires Total Maximum Daily Loads (TMDLs) be developed for those impaired streams and rivers (Birkeland, 2001). TMDLs refer to the amount of a constituent that is allowable in a stream while still meeting water quality standards. These constituent loads are calculated as a function of streamflow (Haggard et al., 2003). In other words, without stream discharge, a constituent load cannot be calculated. Without streamflow information, TMDL compliance cannot be verified, and stream water quality can be put in jeopardy. In addition, concentrations of many non point source (NPS) pollutants have a strong association with discharge amount (Meals & Dressing, 2008). Thus, knowledge of high flow events is important for understanding NPS pollution, as well as pollution loads in a watershed.

Water withdrawals, depending on their magnitude, can drastically alter flow regimes of rivers (Jackson et al., 2001). Rivers must still be able to maintain environmental flows during periods of low flow. An environmental flow refers to the flow of water necessary to sustain a freshwater or estuarine ecosystem in addition to the human uses for those water systems (Acreman, 2016). Streamflow information is utilized to determine the impacts of water projects, hydropower operations, and transportation projects so aquatic systems may be properly managed and protected (Hester et al., 2006). Government agencies such as the United States Fish and Wildlife Service (USFWS) use streamflow data to help monitor endangered and threatened species response to flow variations, and to keep these flows within an optimal range (Normand, 2021). Thus, it is important to have good streamflow data on the low end of the hydrograph to protect the ecology of streams.

Manning's equation is a common hydraulic technique for estimating instantaneous discharges. It utilizes measurements of channel geometry and slope along with an estimate of resistance to flow in order to estimate stream velocity (McCuen, 2017). This velocity is multiplied by cross sectional area in order to determine a streamflow rate (Marcus et al., 1992). This yields the following equation:

$$Q = \frac{1.49}{n} AR^{\frac{2}{3}}\sqrt{S}$$

where Q is discharge (cfs), A is area (ft^2), R is hydraulic radius (ft), S is channel slope (ft/ft), and n is Manning's roughness coefficient.

Variation can be introduced by this estimate of resistance to flow, known specifically as Manning's roughness coefficient (Marcus et al., 1992). This report seeks to determine how to account for this variability in Manning's roughness coefficient based on how it changes with increasing stage to be able to better utilize Manning's equation to determine flow.

METHODS

Study Site Description

The data in this thesis was collected in the Brush Creek watershed in Northwest Arkansas. Brush Creek originates in western Madison County west of Huntsville, AR. It then flows westward through a mixture of forest and pasture until it reaches Beaver Lake. The watershed is of interest because it contributes to Beaver Lake, the drinking water supply for the Northwest Arkansas Metropolitan Area. In total, Beaver Lake is the drinking water source for more than half a million people (Beaver Water District n.d.). Brush Creek has been identified by the water management authority for Beaver Lake as an area of high nutrient contribution. This may be a result of the number of poultry farms in the area and the widespread practice of poultry litter spreading on pastureland. Three sites were selected along Brush Creek as it flows to Beaver Lake (Figure 1, Table 1), including BC-7405, BC-295, and BC-45.

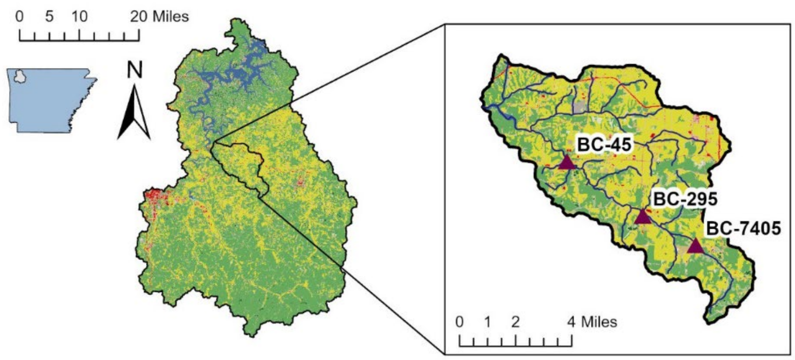


Figure 1. Brush Creek Watershed showing three study sites, BC-45, BC-295, and BC-7405, inset into Beaver Lake Watershed. Land use is also shown.

The most upstream site in the study area was Brush Creek's crossing with Madison County Road 7405 (Figure 1), where watershed area is 4.5 mi^2. The creek crosses underneath the road via a single box culvert (Figure 2). This reach consists of large cobble (2.5 – 10 in across) strata and some gravels (2 mm – 2.5 in) (Table 2) with dense vegetation on either of the banks (Figure 2).

The next study site selected was Brush Creek's crossing with Arkansas Highway 295 (Figure 1), where the watershed area is 11.8 mi^2. The highway crosses the creek as a bridge (Figure 2). At this site, the strata consist of some cobbles but is mostly gravel substrate (Table 2). There is an obvious main channel and lower flood plain. Vegetation is present on the flood plain, and the banks are still heavily vegetated.

Figure 2. Pictures showing BC-7405 bridge (Picture A) and Brush Creek looking upstream (Picture B), BC-295 bridge (Picture C) and Brush Creek looking upstream (Picture D), and BC-45 bridge (Picture E) and Brush Creek looking upstream (Picture F).

The most downstream site is the crossing of Arkansas Highway 45 (Figure 1), where the watershed area is 21.5 mi^2. The creek is crossed over by a bridge (Figure 2). Strata at this site consists of gravels (Table 2). The creek channel is well defined, and vegetation mostly does not encroach within it (Figure 2). There is water at this site most of the time.

Table 1. Site information for the monitoring locations in the Brush Creek Watershed. The watershed land use/land cover information is adapted from the National Land Cover Database, 2019 and was obtained using modelmywatershed.com adapted from Austin et al., 2024.

Site	Latitude	Longitude	Watershed Area (mi^2)	Channel Slope (ft/ft)	% Urban[1]	% Forest[2]	% Pasture[3]
BC-45	36.1339	-93.9514	21.5	0.003	6.5	46.4	47.1
BC-295	36.1062	-93.9027	11.8	0.016	5.5	49.7	44.8
BC-7405	36.0913	-93.8688	4.5	0.025	6.1	59.1	34.9

[1] % Urban is the sum of all developed land categories, as well as barren land
[2] % Forest is the sum of all forest categories, as well as shrub/scrub
[3] % Pasture is the sum of the pasture/hay and grassland/herbaceous categories

Table 2. Wentworth Particle Sizes (Bunte & Abt, 2001)

Particle Size	**Diameter**
Boulder	256-4096 mm
Cobble	64-256 mm
Gravel	2-64 mm
Sand	0.063-2 mm

Data Collection:

In order to compare stage to Manning's n, stage was collected. To do so, a HOBO pressure transducer (Onset Computer Corporation, Bourne, Massachusetts) suspended within a polyvinyl chloride (PVC) pipe was attached to a bridge pier at each of the sites. Pressure would be measured every 15 minutes and were used to determine the change in stage. In order to account for meteorological changes in atmospheric pressure, a HOBO barometric pressure transducer was attached to a tree outside of the stream channel at BC-45. This installation was within 10 km of the other sample sites and was thus assumed to accurately reflect atmospheric pressure at all of the sites. Data was retrieved from the pressure transducers on a monthly basis, and data was measured from March of 2021 to September of 2023.

Cross-section geometry was necessary for calculating area and wetted perimeter based on stage. Cross-sections were collected in two ways. For BC-45 and BC-295, geometry was collected as follows. A string was stretched from the highest point on the lower side of the stream channel, to the spot across the stream of corresponding elevation. The string was checked for level using a line level. A measuring tape was also stretched across the stream. This measuring tape was used to define measurement intervals for stream depth. Elevation difference was measured between the level string and the stream bottom, with measurements occurring at minimum every one meter. Where topography appeared to be more variable within the stream, more narrow intervals were utilized (0.25 to 0.5 m). For BC-7405, culvert geometry was measured utilizing a measuring tape. These cross-sections were then built in Autodesk AutoCAD using field measurements. The Quick Measure function was used to determine areas and wetted perimeters for every stage.

Discharge measurements were necessary to insert into Manning's equation to back calculate for n. A variety of methods were utilized to determine flow. SonTek-IQ acoustic Doppler instruments (SonTek/Xylem Inc., San Diego, CA) were utilized for measuring discharge in high flow events. Water velocity is measured utilizing the Doppler shift, and discharge is calculated internally using the channel geometry uploaded to the SonTek. Roving discharge monitoring stations were installed at all of the sites so that the SonTek could be rotated among the sites. They were installed following procedures outlined in Lasater and Haggard (2021) and Lasater et al. (2022). The SonTek unfortunately could not be utilized for BC-7405 due to extensive vandalism, but results were used for BC-45 and BC-295. Discharge was also measured for low flow conditions using the velocity-area method. A Marsh-McBirney Flo-Mate 2000 (HACH Company, Frederick, MD) was used to measure stream velocity at intervals across the stream cross-section, and this was multiplied by the incremental area and summed to get a discharge. Discharge was only measured in this manner during wadable conditions. For more additional guidance on these methods, consult the US Forest Service's Stream Inventory Handbook Chapter 4 (United States Forest Service, 2016). In addition to the two previous methods, a USGS gaging station (USGS ID#07048890) was operated at BC-45 from December 2006 to September 2011, providing historic discharge measurements.

To determine channel slope, change in elevation was determined using an Exterior Rotary Laser NRL800 Laser Level (Northwest Instrument, Timneth, Colorado) and a 16' Aluminum Grade Rod. Elevations were measured at the sampling location, and 100 feet upstream, which was located using a survey tape. The difference in elevations over 100 feet yields the slope for each site. Technically, slopes should be calculated from one hydrologic control to another, e.g. from one riffle to the next.

Manning's n values can be selected by matching channel surface characteristics to values in a book (McCuen, 2017). Pictures were taken at each site looking upstream and I subjectively selected Manning's n values from the Fayetteville Drainage Criteria Manual, which uses Manning's n values selected from Chow's Open Channel Hydraulics (1959).

Manning's roughness coefficient (n) was calculated by inserting the rearranged Manning's equation for flow into Microsoft Excel to solve for n.

$$Q = \frac{1.49}{n} AR^{\frac{2}{3}}\sqrt{S}$$

$$n = \frac{1.49AR^{\frac{2}{3}}\sqrt{S}}{Q}$$

$$R = \frac{A}{WP}$$

Where A is area (ft^2), WP is wetted perimeter (ft), R is hydraulic radius (ft), S is channel slope (ft/ft), and Q is discharge/streamflow (cfs).

To map trends in the stage versus roughness relationship, a LOESS regression was utilized. LOESS refers to a Locally Estimated Scatterplot Smoothing regression, and it attempts to capture general patterns in related variables, but also reduce noise and make minimal assumptions about relationships between variables. For this project, the Microsoft Excel 'Real Statistics Resource Pack' Add-In (https://real-statistics.com/free-download/real-statistics-resource-pack/) was used. In particular, the '=LOESS' function. The LOESS function takes inputs for x data values as an array, y data values as an array, a column array for number of x values, the number of points in the span, and the degree of the regression. The x-axis data values selected for each site were the stages, the y-axis values were back-calculated Manning's Roughness coefficient values, the number of x values was left blank (the function defaults it to values in the x array), number of points was left blank, with the function calculating it as the number of terms plus the degree divided by three, and degree was left blank, with it defaulting to a degree of one, using a linear LOESS regression.

To compare trends in the data and make the best recommendation, various discharge vs. stage relationships derived with different roughness coefficients were plotted. First, a curve using book values to calculate Q was generated; selection of book values is included in the results. Next, a curve was plotted using the roughness coefficients derived from the LOESS regression. Next, roughness coefficients were selected for low flow and high flow situations by looking at the stage vs. roughness relationship, where there were two distinct regions of roughness coefficients. A low flow roughness and high flow roughness discharge curve were both plotted.

Results:

BC-45:

Manning's roughness coefficient was selected out of the list provided in Chow's Open-Channel Hydraulics (1959) based on the channel's surface conditions. Brush Creek at BC-45 was classified as a natural, minor stream on plain that is clean, winding, and has some pools and shoals based on observations made in the field. This corresponded to a book-value Manning's roughness coefficient of 0.040 (Type A3, Table 3).

For BC-45, bankfull depth was found to be 6 feet in stage. There are 58 measured discharges below bankfull depth and 5 measured discharges above bankfull depth.

For BC-45 an interesting pattern emerged when calculated Manning's roughness coefficient (n) was graphed against stage (Figure 3). At stages less than 4 feet, calculated n varies from 0.029 to as high as 8.91; these roughness values were classified as low flow n's. Low flow n was selected to be 0.51 by calculating the geometric mean of all n values for stages beneath 4 feet. After 4 feet, a more defined trend occurs, with roughness values bottoming out around 0.03 and climbing to near 0.06; these roughness values are classified as high flow n's. High flow n was selected to be 0.044 using the geometric mean of all n values 4 feet or above in stage. This estimated high flow n was within 10% of the book value (n=0.04). The LOESS line shows a decline from the 2 feet stage to the 4 feet stage, and then the curve appears to flatten out as stage increases to 10 feet. When put in log space, though, there was an obvious downward trend from 4 to 6 feet, then an upward trend from 6 to 10 feet.

Table 3. Manning's roughness coefficients (n) for natural channels, adapted from Chow (1959).

Type of channel and description	Manning's Roughness Coefficient n		
D. NATURAL STREAMS			
1. Minor Streams			
a. Streams on Plain	Minimum	Normal	Maximum
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4, but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150

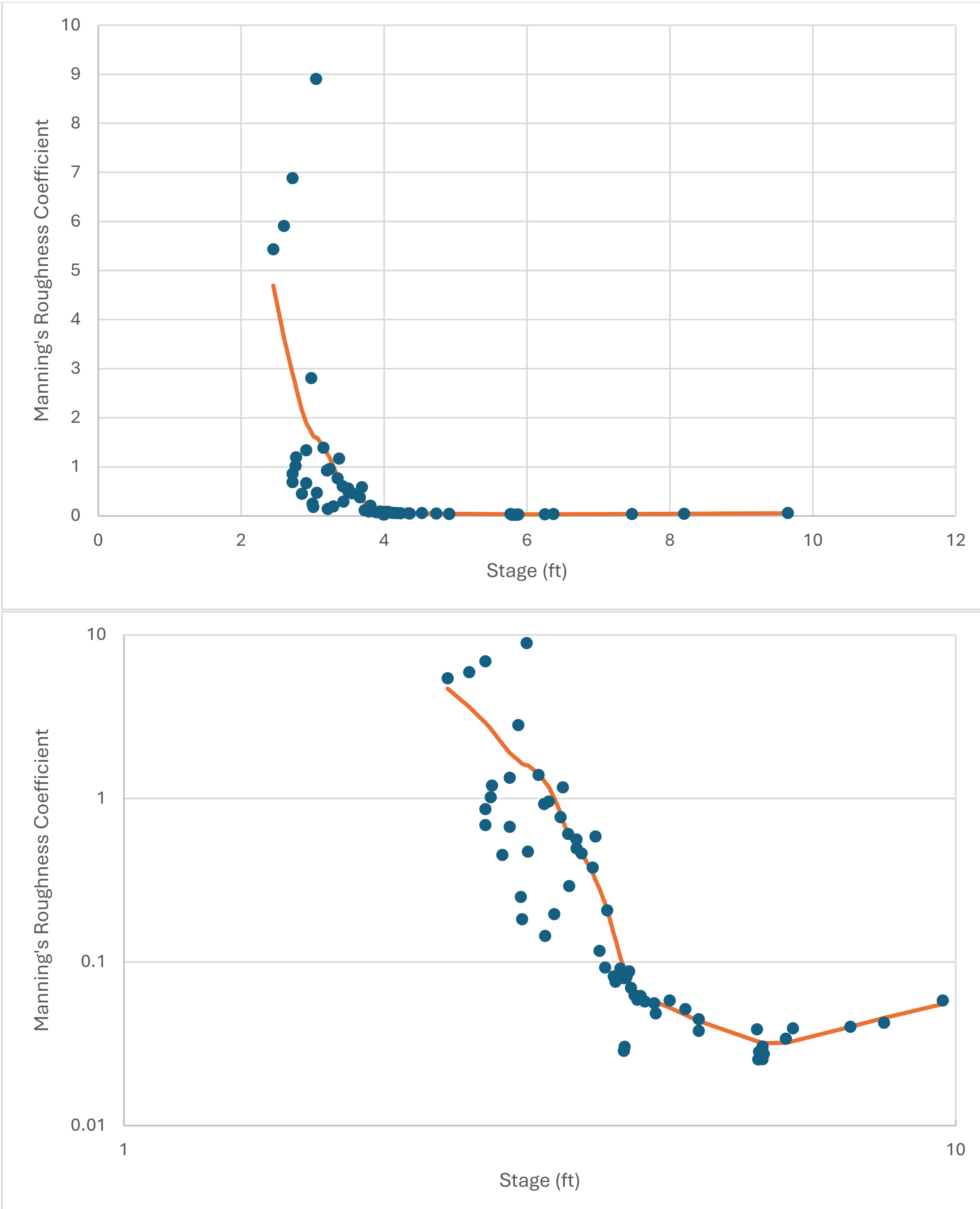


Figure 3. Calculated Manning's roughness coefficient (n) at various stages for Brush Creek near Highway 45 (BC-45) including the locally estimated scatterplot smoothing (LOESS) line used to predict n across the range of stages with axes shown in normal scale and log scale, respectively.

The generated discharges using LOESS predicted n correspond well with the actual discharges, showing a good fit for the regression. The LOESS generated n's created a discharge curve that climbs slowly until below a 4 feet stage, where it begins to climb steeper until discharge reaches around 1250 cfs at 6 feet stage, and the curve begins to flatten out slightly until it reaches a discharge of around 2900 cfs at 9 feet stage (Figure 4).

The discharge curve using the low flow matches the LOESS discharge curve until approximately 4 feet where it begins to lag behind the other curves severely, terminating with a maximum discharge of about 250 cfs at a stage of about 10 feet. The discharge curve using the low flow n corresponds well to measured Q data until slightly below 4 feet in stage. After this, measured Q climbs drastically away from this discharge curve, and by the maximum stage, this discharge curve predicts discharges more than ten times less than those that were measured.

The discharge curve estimated using high flow n exceeded the LOESS discharge curve until approximately 4 feet, and then began to climb more in line with the LOESS discharge curve, until over 8 feet, where the LOESS discharge curve was less. The discharge curve using high flow n also exceeded measured Q values until around 4 feet where the curve more accurately predicts measured Q. This discharge curve generally estimates flow well until around 8 feet, where it begins to overestimate again, based upon one measured discharge at a stage of 9.65 feet.

The discharge curve using the book value n resembles the high flow curve relatively well, because the n values were within 10% of each other. Both curves overestimate flow through 4 feet, at which they begin to be more consistent with measured flow values through 8 feet in stage, where they begin to overestimate. The discharge curve using the book value n climbs slightly higher than the curve using the estimated high flow n, so the book value even more drastically overestimates flows at the highest measured stages based on one measured discharge.

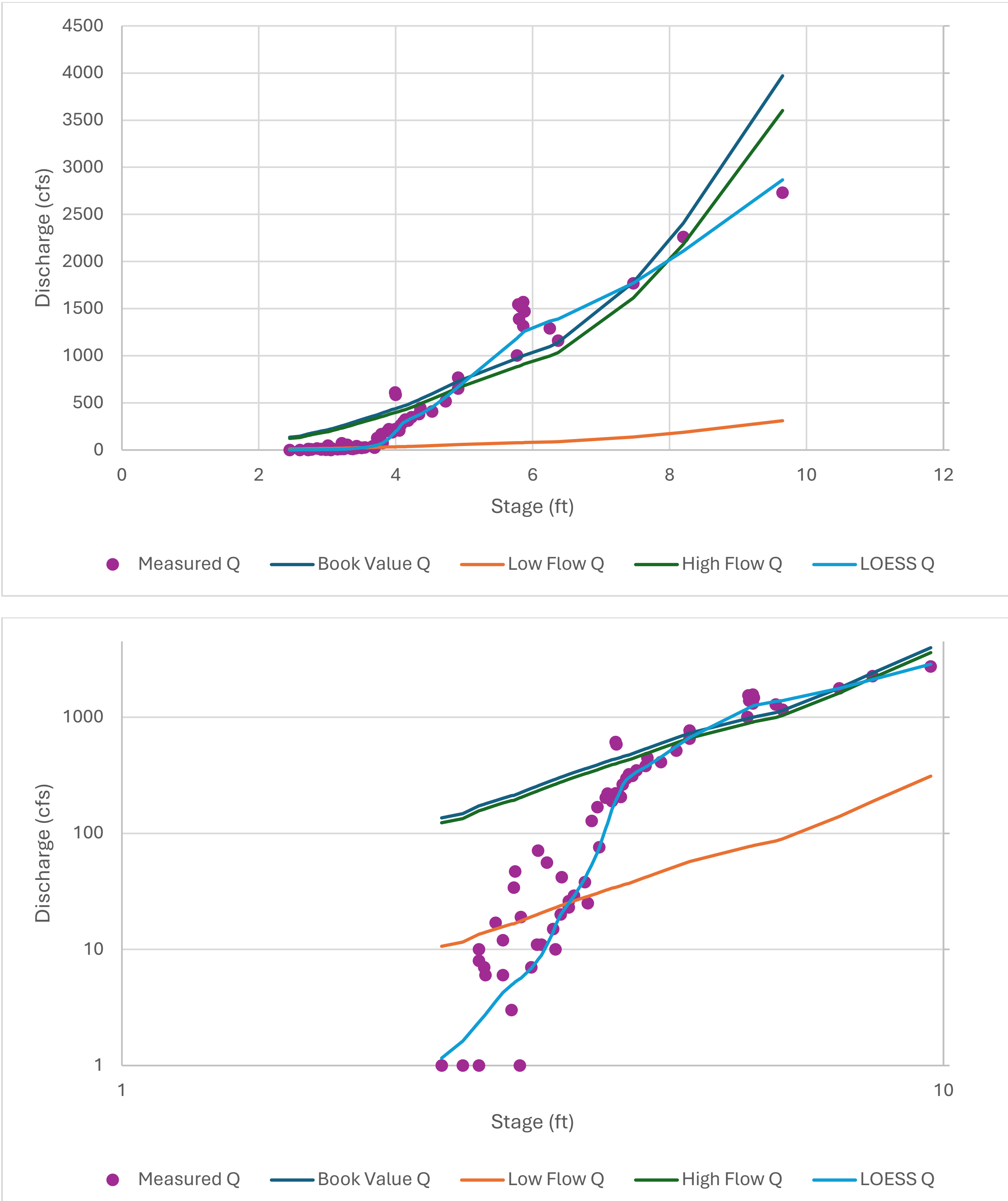


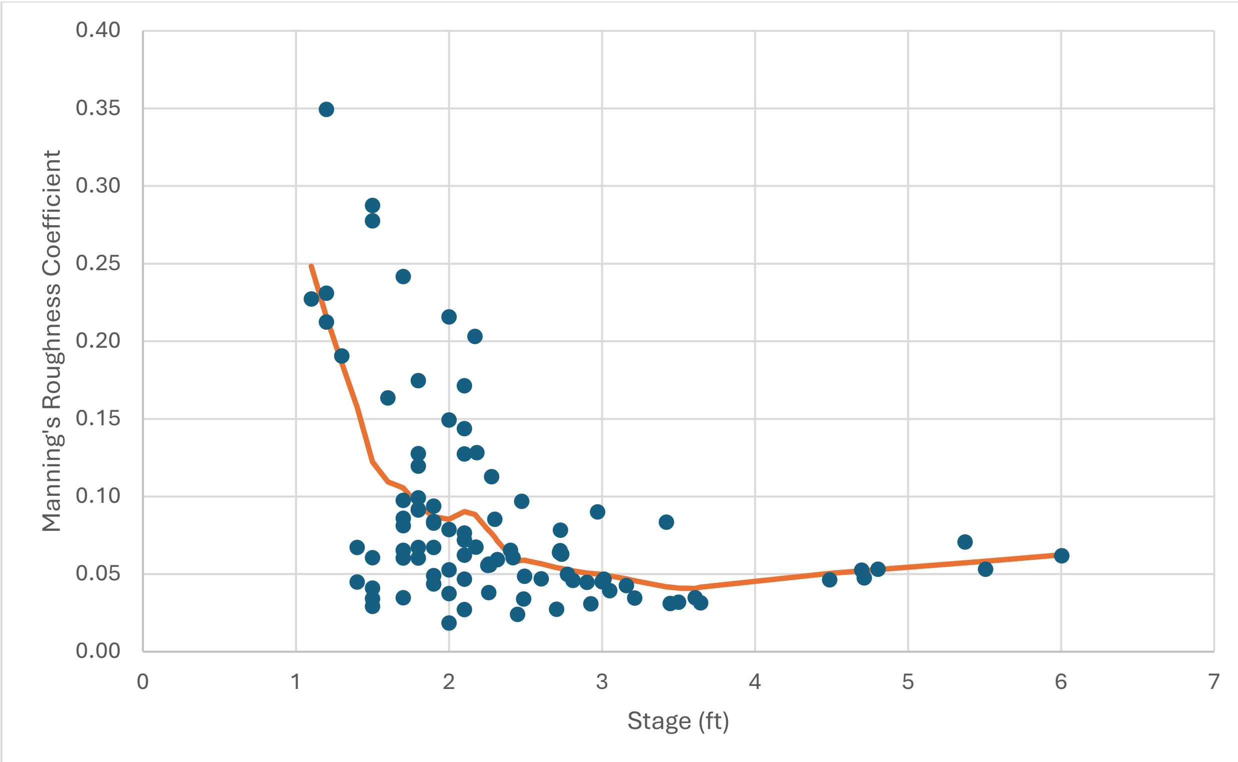
Figure 4. Calculated discharges for low flow, high flow, book value, and LOESS calculated roughness coefficient values plotted against stage for Brush Creek near Highway 45 (BC-45) represented with normal and log scale axes, respectively; the symbols represent measured discharge.

BC-295:

Chow's Open Channel Hydraulics was also used to select a Manning's roughness coefficient for BC-295. Brush Creek at BC-295 was given an n value of 0.045, which corresponds to a natural, minor stream on plain that is clean and winding with some pools and shoals and some weeds and stones (Type A4, Table 3). This value was chosen because there is an enhanced vegetation presence at BC-295 as compared to BC-45.

Bankfull depth at BC-295 was found to be 4.3 feet. There were 86 measured discharges below bankfull depth and 7 measured discharges above bankfull depth.

At BC-295, the LOESS line showed a similar pattern to the LOESS line at BC-45 (Figure 5). At stages less than 2.5 feet, calculated n ranges from 0.018 to 0.349, with these n's being classified as low flow. The geometric mean of n's below 2.5 feet was found to be 0.083 and was chosen as the n to represent low flow. At stages above 2.5 feet, n's were variable, ranging from 0.027 to 0.090, and n was calculated to be 0.062 at 6 feet in stage (at the greatest measured discharge). The high flow n was selected as the geometric mean of the n's above 2.5 feet which was 0.049. This estimated high flow n was also within 10% of the respective book value (n=0.045). The LOESS line representing n generally declines until 3.5 feet, where it begins to climb again. At this site back-calculated n's show an order of magnitude in difference for the same stream stage. This is attributed to low flow discharge not always being measured at the exact same cross-section.



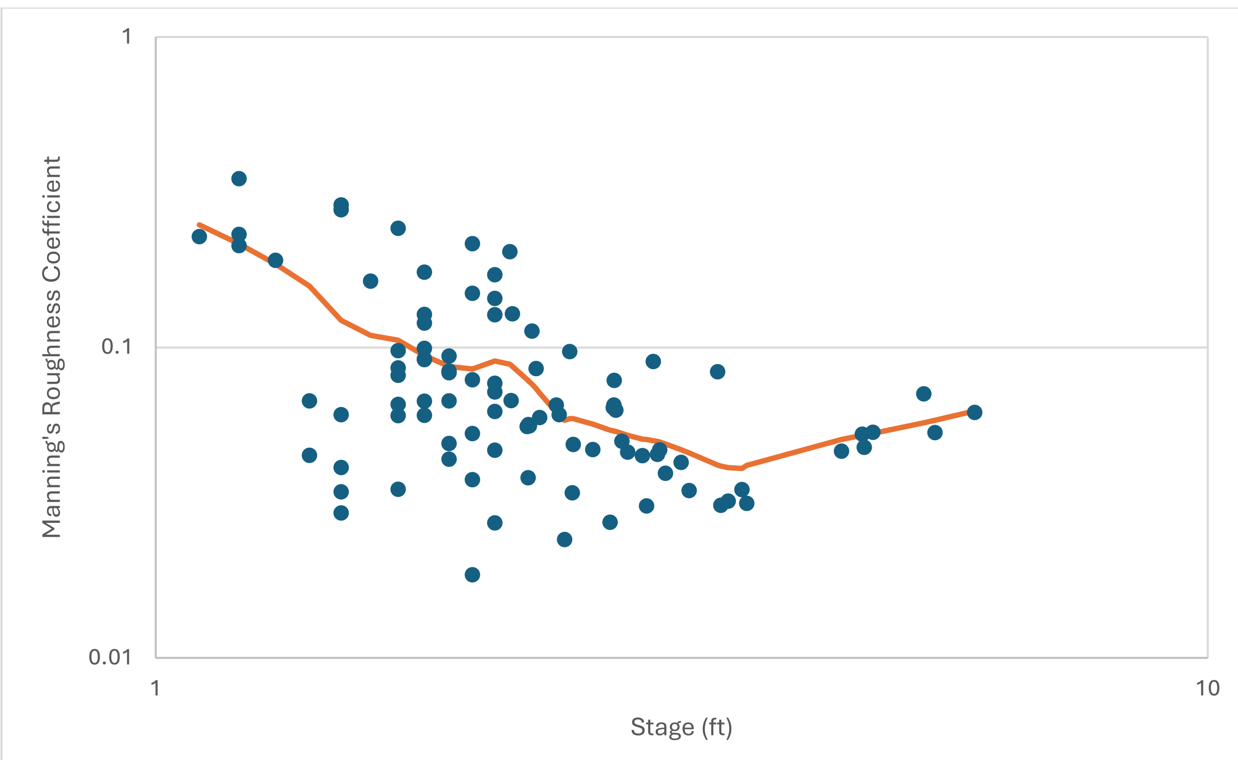


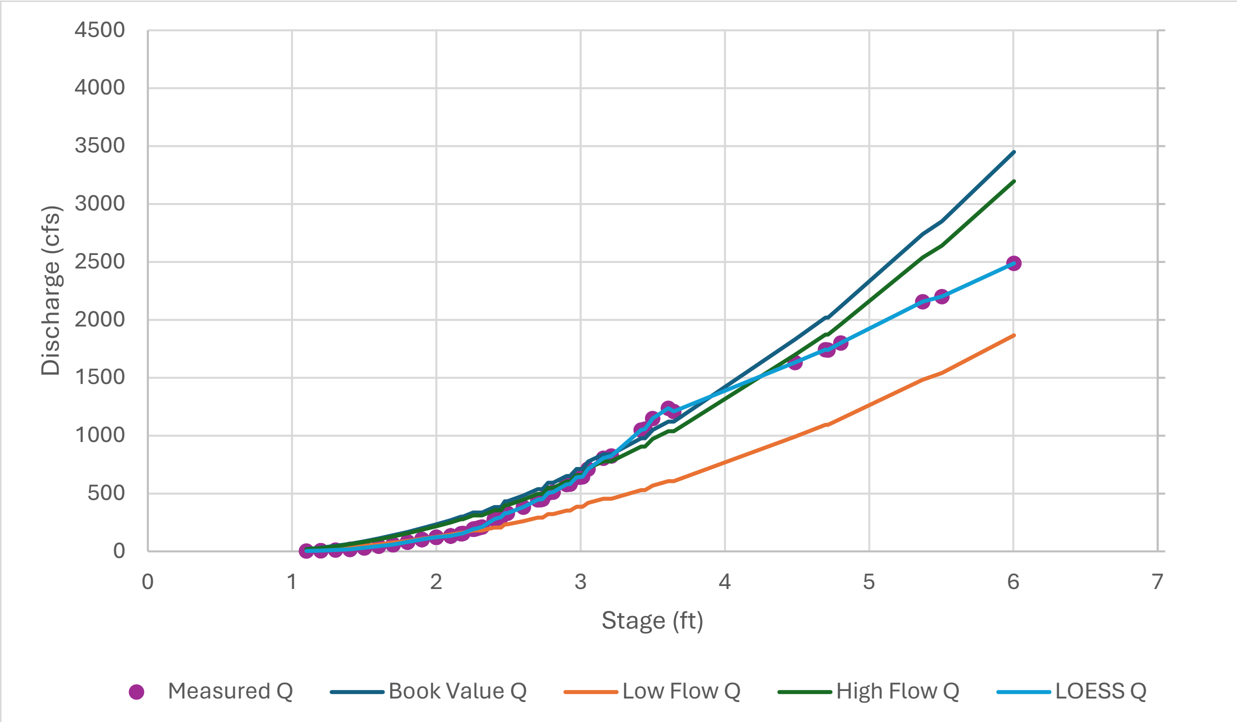
Figure 5. Calculated Manning's roughness coefficient (n) at various stages for Brush Creek near Highway 295 (BC-295) including the locally estimated scatterplot smoothing (LOESS) line used to predict n across the range of stages with axes shown in normal scale and log scale, respectively.

The discharge curve generated with LOESS predicted n fits the measured discharges very well as expected. The LOESS predicted curve climbs slowly until 2.5 feet at the transition from low flow to high flow where it begins to climb steeper up to a discharge of 1250 cfs at 3.5 feet in stage (Figure 6). Here, there is an inflection point where n increases from slightly less than 3.5 to 6 feet.

The discharge curve using low flow n follows the LOESS curve well until 2.5 feet where it begins to underestimate flow. However, when the relationship is viewed on log-scale, the low flow n overestimates discharge up to a stage of 2 feet, where it matches the LOESS prediction. It continues to climb to a discharge of 1800 cfs at the six ft stage. As the low flow curve progresses it begins to get closer to the LOESS curve again and the underestimation of flows becomes less dramatic.

The discharge curve using high flow n was greater than the LOESS curve until 2.5 feet, where it converges with the discharge curve estimated by the LOESS generated n until approximately 4.5 feet in stage where the high flow curve begins to overestimate again, climbing to about 3200 cfs by the 6 feet stage. At this point, the high flow curve overestimates discharges as much as the low flow curve underestimates discharges.

The book value curve was a good match to the high flow curve. Both curves overestimate flow until 2.5 feet, at which point the curves begin to match up better with LOESS. The book value curve again diverges from the LOESS curve at 4 feet in stage and continues to overestimate. The book value curve terminates slightly higher than the high flow curve at 3500 cfs at 6 feet in stage.



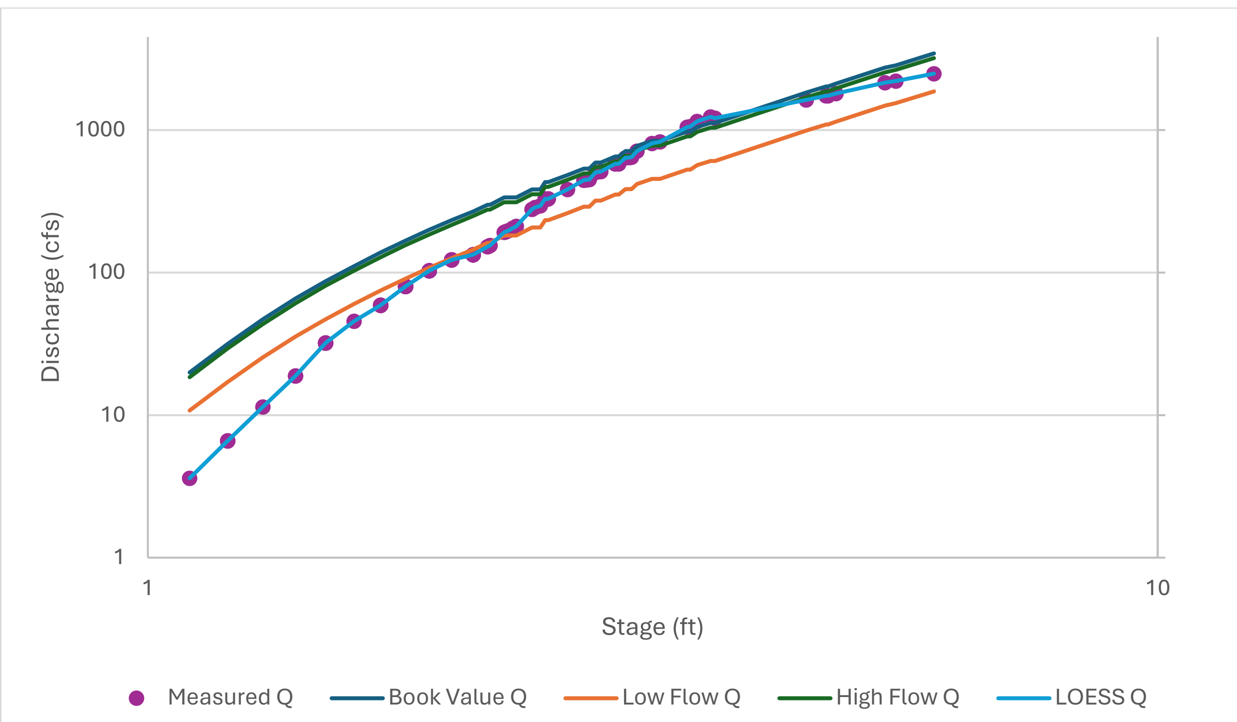
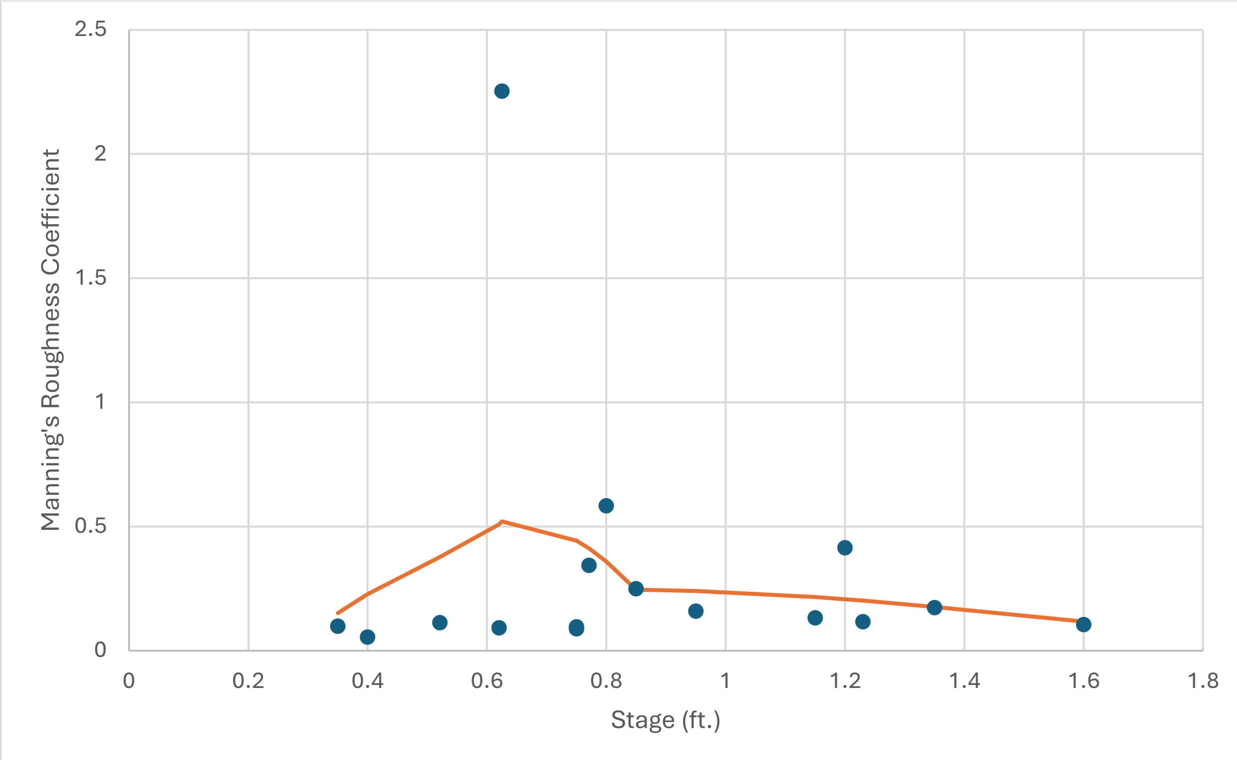


Figure 6. Calculated discharges for low flow, high flow, book value, and LOESS calculated roughness coefficient values plotted against stage for Brush Creek near Highway 295 (BC-295) represented with normal and log scale axes, respectively; the symbols represent measured discharge.

BC-7405:

For BC-7405, Chow's Open Channel Hydraulics was used to determine a Manning's roughness coefficient. A value of 0.050 was selected, which corresponds to a natural, minor stream on plain that is clean and winding with some pools and shoals, some weeds, and stones (Type A6, Table 3). This value was selected because BC-7405 is as weedy as BC-295 but has a larger number of stones.

At BC-7405, only low flow calculated n's are available, so LOESS was only fit to those values. For this reason, the LOESS line lacks consistency with the other two sites. For BC -7405, the LOESS line climbs slowly from stages of 0.35 feet to about 0.70 feet, then decreases from 0.70 feet to 0.85 feet, where it begins to decline less rapidly through a stage of 1.6 feet. With the exception of a single outlying n, the n values for BC-7405 remained consistently low from a stage of 0.35 feet to 1.60 feet (Figure 7). Roughness coefficient values, excluding the one high n, ranged from 0.055 to 0.584 across the range of stages with most on the smaller end of n values. This one data point likely influences the LOESS line, but when viewed in log-space it fits the pattern with the inflection point. All of these n's were classified as low flow n's. The geometric mean of these n's was 0.178, which was selected as the low flow n used to generate a discharge curve.



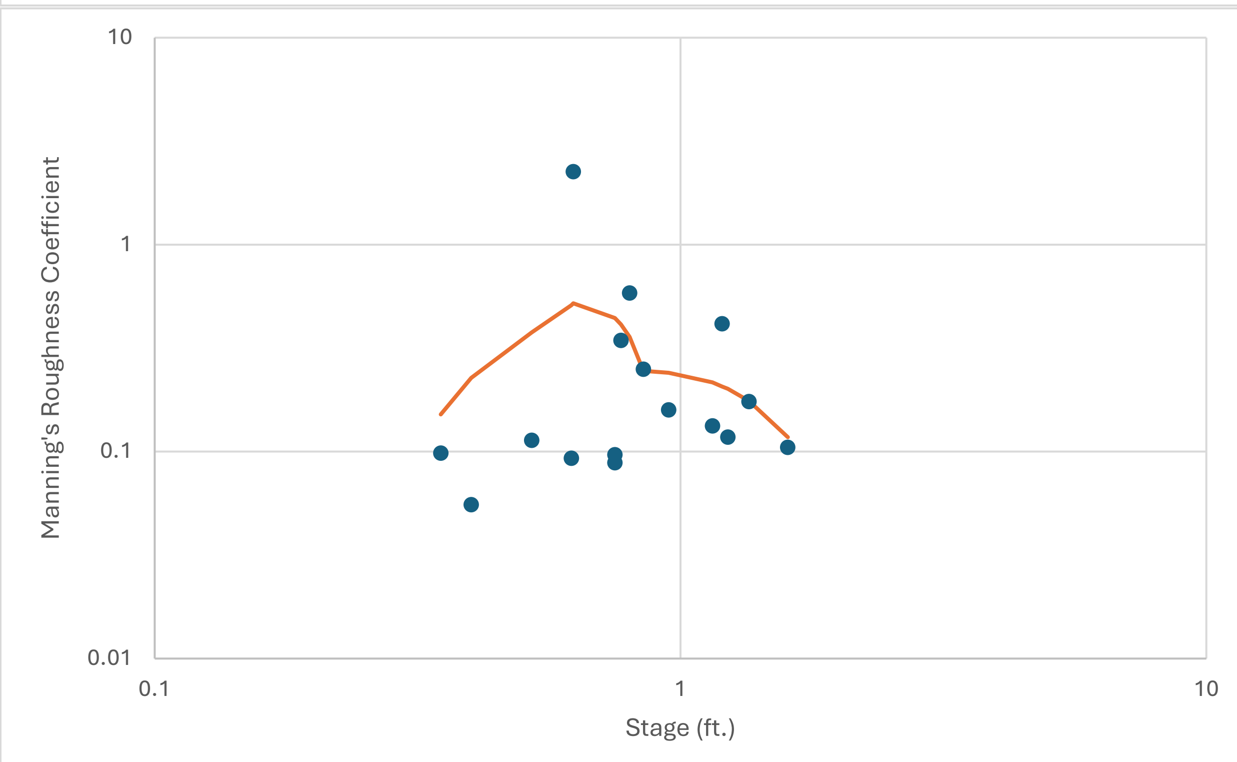


Figure 7. Calculated Manning's roughness coefficient (n) at various stages for Brush Creek near County Road 7405 (BC-7405) including the locally estimated scatterplot smoothing (LOESS) line used to predict n across the range of available stages with axes shown in normal scale and log scale, respectively.

Due to the nature of discharge data availability at BC-7405, a different approach was necessary to develop and compare discharge curves. There was no high flow data available to calculate n values and then fit with LOESS. To overcome this, a new predicted discharge curve was generated using relationships with BC-295, the closest of the other two sites to BC-7405, since all data are available for BC-295. Each LOESS curve at the two downstream sites (BC-45 and BC-295) was observed to exhibit a trend where LOESS would go down until it reach a certain point, which was deemed the inflection point, where it begins to rise again. It was assumed that BC-7405 would show a similar inflection point to BC-295. The inflection point for the LOESS curve at BC-295 was estimated by graphing the LOESS curve and observing where the curve transitions from a negative slope to a positive slope. This inflection point was observed to occur at a stage of 3.5 feet, and an n value of 0.04. The inflection point at BC-295 occurs at approximately 50% of the full surveyed channel area. It was assumed that this inflection point would occur at the same percentage of the channel area for BC-7405. The stage at which BC-7405 has an inflection point was calculated to be 2 feet by multiplying BC-7405's full stage by 50%, where the inflection point occurs in BC-295. Roughness values were assumed to follow a line from the last LOESS point, which had a stage of 1.6 feet, and a n of 0.117 on the LOESS line. The last LOESS point and the inflection point were put into a Microsoft Excel chart, and the linear trendline between the two was found to be

$$n = -0.0627 \times Stage + 0.2177$$

The next trend observed in the LOESS lines at the upstream sites was a climb to an end point after the inflection point. This end point is calculated in a similar manner to the inflection point. The LOESS curve for BC-295 terminates at a stage of 6 feet and a n value of 0.063. The end point for BC-295 occurs at 85% of the full surveyed channel area. For BC-7405, 85% of the full channel area is 4.73 feet in stage. An additional line was created in Excel between the inflection point n and the end point n. The linear equation for the trendline was found to be

$$n = 0.0129 \times Stage + 0.0087$$

The first equation was used to calculate n values from stages of 1.60 feet to 2.70 feet. The second equation was used to calculate n values from stages of 2.80 feet to 4.73 feet. These n's were then used to calculate corresponding discharges, and were plotted with the book value discharge curve, the low flow n discharge curve, the LOESS curve for low flows, and measured discharges (Figure 8).

The discharge curve using the LOESS estimated n's and the inflection point n and end point n produced a stage-discharge curve not different from the other sites (BC-45 and BC-295). This discharge curve climbs slowly matching measured discharges until it begins to diverge from the low flow curve at 1.6 feet in stage where discharge increases at a greater rate with stage. It climbs increasingly steeply towards the inflection point at 2.78 feet. At the inflection point, the discharge curve begins to climb much slower, terminating at 4.7 feet with a discharge of nearly 300 cfs.

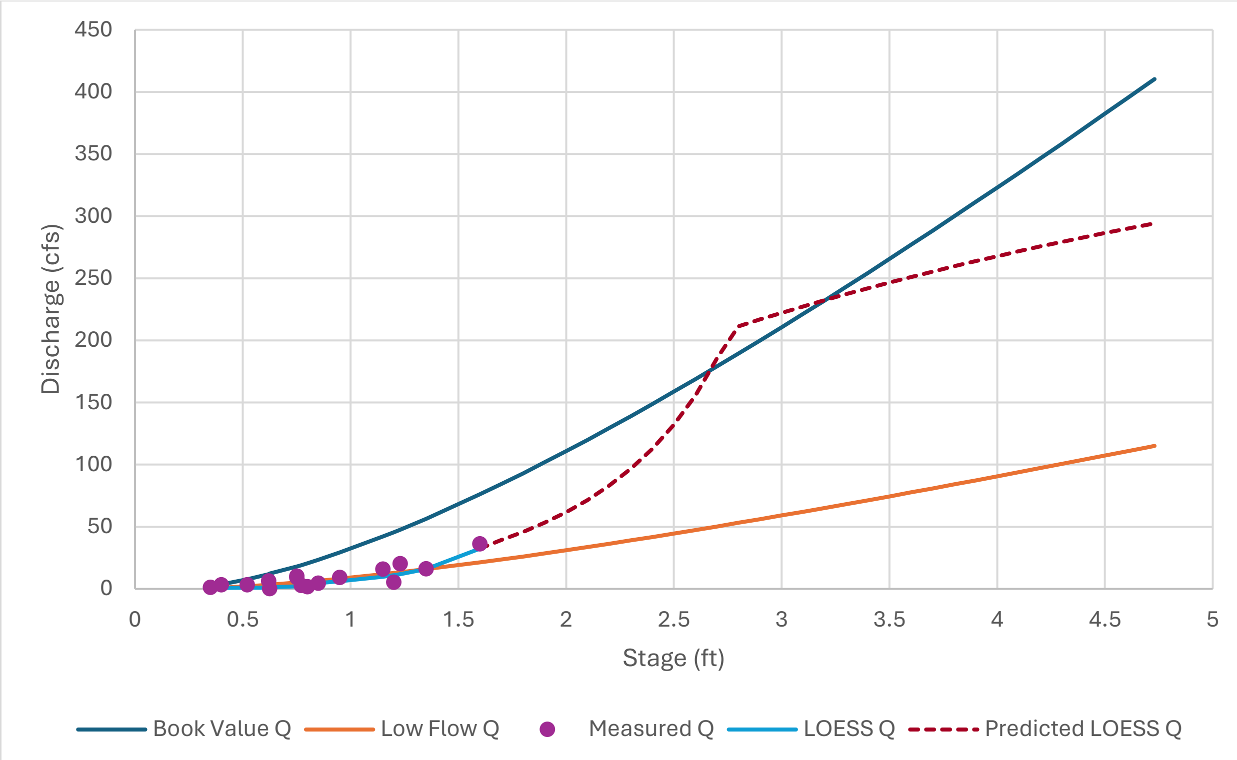


Figure 8. Calculated discharges for low flow, book value, and LOESS, along with a calculated discharge predicting LOESS where high flows were unavailable plotted against stage for Brush Creek near County Road 7405 (BC-7405) represented with normal and log scale axes, respectively; the symbols represent measured discharge.

The discharge curve using low flow n was consistent with the LOESS curve through slightly less than 1.5 feet in stage, where it begins to underestimate flow. It terminates at 4.7 feet at a discharge of around 120 cfs and is about 180 cfs underneath the maximum predicted discharge using the developed n relationship with stage.

The discharge curve using the book value n's overestimates all measured discharge values and is greater than the predicted discharges using the developed n relationship with stage until around 2.6 feet. The discharge curve using the book value n continued to overestimate flows as it approached its end near 420 cfs at a stage of 4.7 feet.

Discussion

Low Flow Discharge Estimation:

For all of the sites, generating discharge curves using Manning's book value roughness failed to properly represent actual discharge, based on measured discharges at Brush Creek. The equation using book values consistently overestimated low flow discharges by as much as 1000%. The failure of book value n generated discharge curves has many implications for using Manning's equation to calculate low flow discharges, and thus the selection of n values is very important to the accuracy of calculated discharges.

Choosing a proper Manning's n value is very important for accuracy of discharge calculations. For example, in water allocation, if water managers overpredict the amount of water available, then withdrawals will not be properly apportioned, and water will be overdrawn. If book value n's were utilized for low flow discharge estimation, the results of this thesis suggest that discharge would be greatly overestimated. In the worst case, there will be no more water to distribute, no more flow downstream, and some water users will have to go without the water needed for designated uses like irrigation and domestic water supply.

Water allocation calculation methods must also be robust in order to leave enough water in streams and rivers for environmental flows. Humanity is beginning to realize that our hydrologic systems need to maintain some amount of water to allow for proper habitation and to enable ecosystem functioning (Gopal, 2016). Functioning ecosystems also benefit humanity by providing an array of ecosystem services (Yang et al., 2016). If discharge calculations are overestimated from using book values, these systems may not be able to function, reducing ecosystem services, which can be very difficult to reestablish. For that reason, discharge must be properly calculated, utilizing a proper Manning's n value for the situation.

The most accurate method examined in this thesis is to develop a stage vs. discharge relationship and to use this information to back calculate n and use that calculated n to develop a discharge curve. If only low flow information is available for a site, such as in the case of BC-7405, the geometric mean of the back calculated low flow n's may also be used to generate a discharge curve, but only for low flows. Whenever possible it is recommended to get out in to the environment and measure discharge, so that n may be back calculated across a range of discharge and stage.

There are other methods to estimate Manning's n both utilizing measurements and visual estimates (Marcus et al., 1992). Various equations (e.g. Strickler, Keulegan, Limerinos, and Bathurst) use various sediment sizes, including the d50 value, which refers to the diameter of 50^{th} percentile of sediments (Strickler, 1924), the d84 which refers to the diameter of 84^{th} percentile of sediments (Bathurst, 1978), and the d90, which refers to the diameter of 90^{th} percentile sediments (Keulegan, 1938). The Jarrett, Limerinos, and Bathurst equations all utilize the hydraulic radius to help calculate n (Marcus et al., 1992). The Cowan, Chow (used in this thesis), and Benson and Dalrymple methods use visual estimations; the Chow method uses channel characteristic; and the Benson and Dalrymple method uses sediment size (Marcus et al., 1992). Other studies have shown that calculated n and stage can be predicted by energy gradient, hydraulic radius to particle size ratios, stream width, and vegetation (Coon, 1995).

High Flow Discharge Estimation

Within Brush Creek, curves generated using Manning's book value roughness are more representative of measured values for high flow discharge estimation. In particular, the book value n generated curves are reasonably accurate for the lower half of high flow events. After this, book value generated discharges begin to overestimate measured values by as much as 71%, becoming more consistent with the pattern of overestimating low flows. As it is with low flows, this information must be taken into account when selecting n values for flow estimation.

Accurate streamflow information at high flows is crucial for flood management, because streamflow data is used in flood forecasting. If this forecasting is performed on data generated using Manning's equation and book value selected n's, the results of this thesis suggest that flooding would be overestimated. This could be a good thing in terms of being prepared for the worst case scenario, but this also has the potential to divert emergency resources away from other places that may actually need them more. Using book value generated discharge could also generate erroneous flood zones and require many to be insured who are not actually at a significant enough risk of flooding.

Correct discharge information is also important for water quality in rivers and streams, where streamflow is used along with contaminant concentration to calculate constituent loads. If streamflow is overestimated, as they are if book values are utilized, apparent loads will be greater than actual contaminant loads in streams and rivers. Total Maximum Daily Loads (TMDLs, Birkeland, 2001) are developed to regulate these contaminant levels, and they would be much harder to meet if streamflow is being overestimated. Water quality management decisions made based on these loads may also be incorrect due to an excess in apparent contaminant load from an overestimation of flow. High flow events have a strong association with non-point source pollution, so correct streamflow information is vital (Meals & Dressing, 2008).

For high flow estimation, Manning's roughness coefficient generated discharge is reasonably accurate for the lower half of high flows, after which it then diverges and overestimates flow. This point has been referred to as the inflection point within this thesis, and it is a sudden change in trend of LOESS n values from decreasing to increasing. This trend is actually corroborated in other studies, including Coon (1995) which cites an increase in n by around 0.01 when a stream's stage reaches the floodplain containing trees, brush, and other debris, which is consistent with the inflection point. Due to the observed inflection point phenomenon, Manning's can be used if only this lower half of flows are needed, but optimally, stage vs. discharge information should be utilized to back calculate n, and that n should be utilized to generate discharge curves to properly account for this inflection.

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This honors thesis focused on the use of Manning's equation to estimate streamflow, and how the roughness coefficient, Manning's n, changes with stream stage. The goal was to provide the AWRC and hydrologists with something to build on when developing stage discharge relationships for local streams. While I worked for the AWRC, I got experience with this project, field work and water sampling, lab practices, and internal quality assurance and quality control practices within the certified lab. This honors thesis represents the culmination of this specific project and all my work experiences with the AWRC.

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Works Cited

Acreman, M. (2016). Environmental flows—Basics for novices. *WIREs Water*, *3*(5), 622–628. https://doi.org/10.1002/wat2.1160

Anna E. Normand. (2021). *U.S. Geological Survey (USGS) Streamgaging Network: Overview and Issues for Congress*. Congressional Research Service. Retrieved from https://crsreports.congress.gov/product/pdf/R/R45695

Apse, C., DePhilip, M., Zimmerman, J., & Smith, M. P. (2008). Developing instream flow criteria to support ecologically sustainable water resource planning and management. *Final Report to the Pennsylvania Instream Flow Technical Advisory Committee*.

Bathurst, J. C. (1978). Flow Resistance of Large-Scale Roughness. *Journal of the Hydraulics Division*, *104*(12), 1587–1603. https://doi.org/10.1061/JYCEAJ.0005114

Benson, R. (2012). Alive but Irrelevant: The Prior Appropriation Doctrine in Today's Western Water Law. *University of Colorado Law Review*, *83*(3), 675–714.

Birkeland, S. (2001). EPA's TMDL Program. *Ecology Law Quarterly*, *28*(2), 297–325.

Bunte, K., & Abt, S. R. (2001). *Sampling surface and subsurface particle-size distributions in wadable gravel-and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring* (No. RMRS-GTR-74; p. RMRS-GTR-74). Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-74

Chiew, F. H. S., Zhou, S. L., & McMahon, T. A. (2003). Use of seasonal streamflow forecasts in water resources management. *Journal of Hydrology*, *270*(1), 135–144. https://doi.org/10.1016/S0022-1694(02)00292-5

Coon, W. F. (1995). *Estimates of roughness coefficients for selected natural stream channels with vegetated banks in New York*. US Geological Survey; Earth Science Information Center, Open-File Reports ….

Donald W. Meals & Steven A. Dressing. (2008). *Surface Water Flow Measurement for Water Quality Monitoring Projects*. USEPA.

Gary Hester, Kim Carsell, & David Ford. (2006). *Benefits of USGS Streamgaging Program*. National Hydrologic Warning Council. Retrieved from https://water.usgs.gov/osw/pubs/nhwc_report.pdf

Glaser, C., Zarfl, C., Rügner, H., Lewis, A., & Schwientek, M. (2020). Analyzing Particle-Associated Pollutant Transport to Identify In-Stream Sediment Processes during a High Flow Event. *Water*, *12*(6), 1794. https://doi.org/10.3390/w12061794

Gopal, B. (2016). A conceptual framework for environmental flows assessment based on ecosystem services and their economic valuation. *Ecosystem Services*, *21*, 53–58. https://doi.org/10.1016/j.ecoser.2016.07.013

Haggard, B. E., Soerens, T. S., Green, W. R., & Richards, R. P. (2003). Using regression methods to estimate stream phosphorus loads at the Illinois River, Arkansas. *Applied Engineering in Agriculture*, *19*(2), 187–194. USGS Publications Warehouse. https://doi.org/10.13031/2013.13110

Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., & Running, S. W. (2001). WATER IN A CHANGING WORLD. *Ecological Applications*, *11*(4), 1027–1045. https://doi.org/10.1890/1051-0761(2001)011[1027:WIACW]2.0.CO;2

Karimi, A., & Ardakanian, R. (2010). Development of a Dynamic Long-Term Water Allocation Model for Agriculture and Industry Water Demands. *Water Resources Management*, *24*(9), 1717–1746. https://doi.org/10.1007/s11269-009-9521-3

Keulegan, G. H. (1938). Laws of turbulent flow in open channels. *Journal of Research of the National Bureau of Standards*, *21*(6), 707. https://doi.org/10.6028/jres.021.039

Latif, S. D., & Ahmed, A. N. (2023). Streamflow Prediction Utilizing Deep Learning and Machine Learning Algorithms for Sustainable Water Supply Management. *Water Resources Management*, *37*(8), 3227–3241. https://doi.org/10.1007/s11269-023-03499-9

Limerinos, J. T. (1970). *Determination of the manning coefficient from measured bed roughness in natural channels* (Report No. 1898B). USGS Publications Warehouse. https://doi.org/10.3133/wsp1898B

Marcus, W. A., Roberts, K., Harvey, L., & Tackman, G. (1992). An Evaluation of Methods for Estimating Manning’s n in Small Mountain Streams. *Mountain Research and Development*, *12*(3), 227–239. JSTOR. https://doi.org/10.2307/3673667

Mary S. Ashman, Roy S. Socolow, & Joseph L. Zanca. (2004). *One Hundred Years of Streamflow Measurements in Massachusetts and Rhode Island*. USGS. Retrieved from https://pubs.usgs.gov/fs/2004/3056/

McCuen, R. H. (2017). *Hydrologic analysis and design* (Fourth edition). Boston Columbus Hoboken Indianapolis New York [und 20 weitere]: Pearson.

Murphy, J., & Sprague, L. (2019). Water-quality trends in US rivers: Exploring effects from streamflow trends and changes in watershed management. *Science of The Total Environment*, *656*, 645–658. https://doi.org/10.1016/j.scitotenv.2018.11.255

Muste, M., & Hoitink, T. (2017). Measuring Flood Discharge. In *Oxford Research Encyclopedia of Natural Hazard Science*. https://doi.org/10.1093/acrefore/9780199389407.013.121

Mutiga, J. K., Mavengano, S. T., Zhongbo, S., Woldai, T., & Becht, R. (2010). Water Allocation as a Planning Tool to Minimise Water Use Conflicts in the Upper Ewaso Ng'iro North Basin, Kenya. *Water Resources Management*, *24*(14), 3939–3959. https://doi.org/10.1007/s11269-010-9641-9

PETTS, G. E. (1996). WATER ALLOCATION TO PROTECT RIVER ECOSYSTEMS. *Regulated Rivers: Research & Management*, *12*(4–5), 353–365. https://doi.org/10.1002/(SICI)1099-1646(199607)12:4/5<353::AID-RRR425>3.0.CO;2-6

Service Area. (n.d.). Retrieved April 28, 2024, from Beaver Water District website: https://www.bwdh2o.org/about/service-area/

Strickler, A. (1924). *Beiträge zur Frage der Geschwindigkeitsformel und der Rauigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen* [Text/html,application/pdf,text/html]. https://doi.org/10.5169/SEALS-82804

Te Chow, V. (1959). *Open-channel Hydraulics*. McGraw-Hill. Retrieved from https://books.google.com/books?id=q0xKvgAACAAJ

The National Agricultural Law Center. (n.d.). *Water Law: An Overview*. Retrieved from https://nationalaglawcenter.org/overview/water-law/#:~:text=Today%2C%20almost%20all%20riparian%20states,when%20they%20can%20use%20it

United States Forest Service. (2016). *Stream Inventory Handbook*. Retrieved from https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd538833.pdf

William J. Carswell Jr. & Vicki Lukas. (2018). *The 3D Elevation Program—Flood risk management*. USGS Publications Warehouse. https://doi.org/10.3133/fs20173081

Yang, W., Sun, T., & Yang, Z. (2016). Does the implementation of environmental flows improve wetland ecosystem services and biodiversity? A literature review. *Restoration Ecology*, *24*(6), 731–742. https://doi.org/10.1111/rec.12435