

**Response of Small Stream Morphology to  
Urbanization and Intense Storms in  
Suburban Maryland**

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## **Abstract**

This goal of this study is to analyze the relationship between urbanization and stream dynamic equilibrium in the Northwest Branch of the Anacostia River watershed. Previous work suggests that urban streams will adjust channel dimensions to both increased discharge and changes in sediment characteristics. Additions of sand from construction or other sources, however, can significantly affect critical dimensionless shear stress, which increases gravel bed mobility, and alter threshold channel conditions. The first hypothesis being tested is that the urban streams with percentages of bed sand greater than 15% are mobile at bankfull stage, they are not threshold channels, and their  $\tau_{BF}^*/\tau_{crit}^*$  ratios will be greater than one. The streams with low percentages of sand in the stream bed will be threshold channels. Threshold channels have dimensionless shear stress ratios ( $\tau_{BF}^*/\tau_{crit}^*$ ) near one. Urban streams that have not been supplied with sand and have had extended channel adjustment periods will be threshold channels. The second hypothesis being tested is that the urban streams that have near-threshold channel forms may still be more mobile due to the number of bankfull or higher events that occur each year. This may be affected by increases in storm intensity that selectively impact small basins.

Geomorphic and hydraulic measurements were made at urban stream sites, and the data was used to determine dimensionless shear stress ratios to determine the stability of the channel for streams with varying sand contents and amounts of impervious cover (urbanization). The sites are gauged by Dr. Prestegard's research group, and channel depth and gradient data was used to determine how frequent critical depth is reached (shear stress ratios greater than 1) for streams with different bed sand percentages. The combination of these results and analyses can provide restoration guidelines and hazard assessments in urbanized areas.

## **Plain Text Abstract**

The goal of this project is to evaluate whether sand, supplied by construction and other disturbances to urban streams, increases channel erosion and affects channel stability in urban streams. These disturbances might increase the time for channel adjustment and complicate the prediction of channel stability before or after restoration projects. The project focuses on small streams in the Northwest Branch of the Anacostia River watershed. Previous studies have shown that an increase in urbanization through an increase in impervious cover (surfaces that prevent water from saturating into the ground, such as pavement, buildings, etc.) causes instability in stream channels. Through a collection of field geomorphic measurements and stream gauge data, calculations of threshold stresses are performed and provide for comparison of channel stabilities and urbanization effects. Analysis of these conditions can provide insight on channel restoration guidelines as well as hazard (floods, erosion, etc.) assessment in urban systems. Additionally, this study analyzes the effects of storms on these small, urbanized streams. Flow gauge data was collected to track streams' responses to summer storm events, and how the urbanization and bed composition can affect this.

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## **Introduction**

### **Statement of the Problem**

Urbanization results in buildings, roads, and other structures that increase impervious cover, and modify soil permeability. Urban areas also have storm sewer systems that efficiently deliver storm runoff to streams. An increase in impervious cover causes an increase in storm runoff to stream systems and a decrease in infiltration and groundwater recharge. This increase in runoff increases the discharge of a stream, which can lead to increased flooding events and erosion of the channel (Doyle & Shields, 2000). Higher storm discharge for a given storm event increases the magnitude of floods. These changes particularly affect the low recurrence interval floods (e.g., 1.5 – 2 years), which are typically the floods that build and maintain channel morphology (Leopold and Maddock, 1953; Leopold, 1968). Streams respond to changes in discharge by adjusting channel morphology (often channel widening) to decrease the depth and thus shear stress during flood events. But discharge changes are not the only variables affected by urbanization. Construction, upstream bank erosion and other processes can also increase the amount of sand in river systems or alter the grain size of sediment delivered to a point in a river. Changes in both discharge and sediment characteristics may cause multiple phases of channel adjustment as they are pushed out of and return to steady-state conditions.

Understanding the factors that influence channel stability in urban streams could increase predictions of channel adjustments and channel erosion and other hazards. Understanding how changes in the supply of sediment affects bed material mobility may improve our understanding of urban stream urban morphological adjustment. These types of assessments may be useful in determining whether observed instabilities are likely to be temporary or will increase at a site. This information is important for the assessment and guidance of restoration efforts in urbanized areas.

### **Motivation**

Increases in impervious cover leads to higher flow peaks and shorter lag times from peak rainfall to bankfull discharge, and smaller basins respond greater to these short-duration, intense storm events (Yang et al., 2016). Shorter lag times and higher peak flow increases the frequency that bankfull stage is reached from 1.5 – 2 years (Edwards et al., 2019). Understanding how small, urbanized streams respond to intense storm events can give insight into the effects of urbanization in these watersheds.

### **Previous Research**

Graded rivers that have smooth, concave-up longitudinal profiles are often in equilibrium, which is defined by no net deposition nor net erosion in the channel (Hoover Mackin, 1948). Streams in this quasi-equilibrium state tend to have stable channel morphology. Channel form may migrate across the floodplain, but the channel characteristics (width, depth, velocity, gradient, grain size) remain similar over time. In gravel-bed streams, bed particles have an organized structure and break up when the  $D_{84}$  grains are mobilized by bankfull flow. Bankfull flow is defined as the flow that builds and maintains the active channel. The flow fills the channel to the top of the bank and tends to have a recurrence interval of 1.5 to 2 years (Leopold et al. 1964). In gravel-bed streams, surface particles maintain the stability of channel beds, which become mobile at bankfull stage in

threshold channels. The size fraction,  $D_{84}$  (one standard deviation above the mean) is used in analyzing threshold conditions in gravel-bed streams because it is the grain size that determines channel morphology: the channel bed breaks apart when the  $D_{84}$  grains are mobilized from bankfull flow (Ferguson, 2003, MacKenzie et al., 2018). The shear stress required to act on the bed is:

$$\tau = \rho g d S \quad (1)$$

where  $\rho$  is water density,  $g$  is the acceleration due to gravity,  $d$  is average channel depth, and  $S$  is the stream gradient (slope). Bankfull shear stress ( $\tau_{bf}$ ) is the shear force exerted by water when a river or creek is at the bankfull stage, calculated by Eq. 1 and using bankfull depth for  $d$ . To define bed mobility, the ratio of bed shear stress to grain resisting forces (weight of sediment on the bed) is used. This dimensionless shear stress is:

$$\tau^* = \frac{\tau}{(\rho_s - \rho) g D} \quad (2)$$

where  $\rho_s$  = sediment density,  $D$  is grain size, taken to be  $D_{84}$ .

Critical dimensionless shear stress,  $\tau^*_{crit}$ , is the fluid shear stress required to initiate bedload transport. This has been determined in field and laboratory studies. For gravel-bed streams without significant sand in the bed, the critical dimensionless shear stress is typically 0.045. Sand content, however, significantly decreases critical dimensionless shear stress (it drops to 0.03 with 15% sand and to values near 0.015 with 30% or more bed sand). These changes in critical dimensionless shear stress would significantly decrease bed mobility (Wilcock and Southard, 1989). The changes are unlikely to be permanent, however, unless the sand supply continues. The increase in bed mobility is likely to decrease if the sand is depleted over time.

Therefore, changes in grain sizes alter the sediment moved at bankfull flow. Looking at the ratio of  $\tau_{BF}$  to  $\tau^*_{crit}$  values can give an operational definition of channel stability, which is when channel grain size is at the threshold of motion.

Urbanization can cause disruptions to steady-state or dynamic equilibrium streams. Bankfull flows are frequent events, usually with a recurrence interval between 1.5 to 2 years. Urbanization increases the frequency of these flows, allowing for more sediment to be moved downstream. Suspended load is finer sediment that is carried downstream suspended in the water of a stream without settling to the bed. Sand-sized material can be suspended during major storms but can also move as bedload in streams with moderate gradients. Sand supplies can increase during bank widening, which is local to the stream, but this supply tends to decrease over a short period of time (30 years). Sand is also supplied during construction by storm runoff. Construction can be regional, but it is short in duration. Streams that are pushed out of threshold conditions from urbanization often widen to accommodate the changes and reach a new equilibrium in about 30 years (Hammer, 1972).

Sand supply and stream hydraulics are the main controls of stream gradient and the amount of sand in the bed. If the shear velocity is too high, the sand will be moved in suspension. This is indicated by the fall velocity to shear velocity ratio from the Rouse equation (Rouse, 1937).

Previous research by Harris (2024) focused on the Northwest Branch (NWB) of the Anacostia, particularly the steep tributary streams in the lower portion of the watershed. These sites have been urbanized for about 60 years, although infill urbanization and stream restoration projects have been conducted. The lower NWB channels include both concave and convex stream profiles and a wide range of channel steepness indices. The steepness index of a stream is determined from the stream gradient-basin area relationship. Harris (2024) found that streams with a higher steepness index had higher bankfull discharges and had shear stress ratios significantly greater than one, while channels with lower steepness indices had shear stress ratios near one. This suggests that streams with high steepness indices may not have been in dynamic equilibrium prior to urbanization but are clearly not adjusting to increases in discharges after urbanization (Harris, 2024). The streams with concave profiles and lower stream gradients were in dynamic equilibrium, suggesting that streams with moderate to low gradients in other portions of the watershed might be adjusted to urbanization. Lower gradient streams, however, can transport sand as bedload rather than suspended load, which may affect channel stability. Therefore, streams with a supply of sand might be more unstable due to the effects of sand on critical shear stress. This study is in the same watershed in the Harris study, but the focus here is on whether the amounts and/or variability of sand in bed in the stream beds affect stream stability.

## **Hypotheses**

Null hypothesis: All the stream sites are threshold channels, with dimensionless bankfull shear stress equal to the critical dimensionless shear stress to move the sediment.

Alternative hypothesis: All the stream sites are not threshold channels. Urban streams with percentages of bed sand greater than 15% are mobile at bankfull stage, they are not threshold channels, and their  $\tau_{BF}^*/\tau_{crit}^*$  ratios will be greater than one. The streams with low percentages of sand in the stream bed will be threshold channels.

Null hypothesis: Urban stream channels have adjusted their bankfull form to increased discharge and bankfull discharge is reached approximately annually or less (avg R.I. = 1.5 - 2 years).

Alternative hypothesis: Urban streams may be threshold channels, but they might experience multiple bankfull or higher events each year due to increases in storm intensity that contribute to flood events in small basins.

## **Experimental Design**

### **Study Sites**

This study focuses on the small tributaries of the Anacostia River and Rock Creek. Some of the selected sites were previously studied in the 1970s before a period of construction and suburban expansion (Yorke and Herb, 1978). This study includes these same sites after a recent period of construction including the construction of major roads, such as the Inter-County connector (ICC) which has multiple stream crossings. Gauging stations have been re-established at these sites by Dr. Prestegaard and Jennie-Jin Mullen. The study sites are listed below (Table I) and shown on the map in Fig. 1. These sites have a range of impervious surface covers and variable locations relative

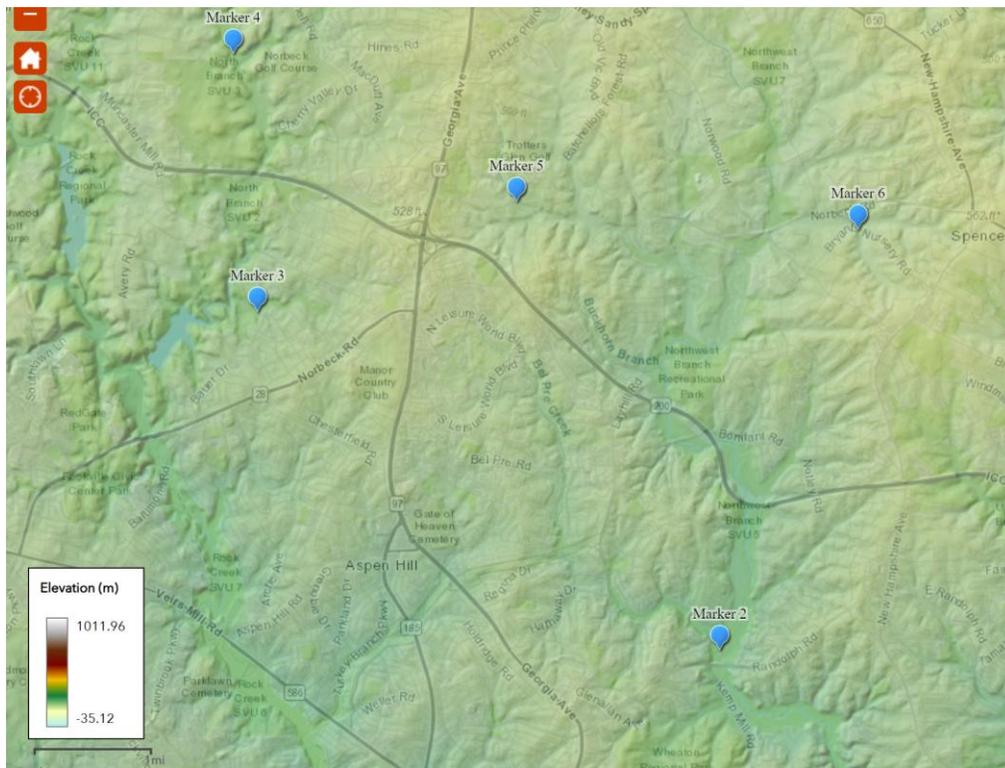
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to major construction sites that, along with channel expansion, might supply sand. Photos of two of the streams are shown in Fig. 2 and 3.

**Table 1: Characteristics of Study Watersheds**

Site Number	Lat / Long	Site Name	Impervious Cover	Basin Area (km <sup>2</sup> )
1	38.981 / -76.947	Guilford Run	21%	0.44
2	39.068 / -77.028	Bel Pre	43%	4.38
3	39.109 / -77.101	Manor Run	24%	2.62
4	39.140 / -77.104	Williamsburg Run	35%	5.83
5	39.123 / -77.060	Batchellors Run	16%	1.22
6	39.120 / -77.007	Nursery Run	16%	0.91
7	39.043 / -77.009	NWB N6	21%	0.75
8	39.042 / -77.007	NWB N5	28%	0.28
9	39.034 / -77.008	NWB N1	28%	0.22
10	39.029 / -77.001	NWB S1	24%	0.11

Percent impervious cover and basin area data from the USGS.



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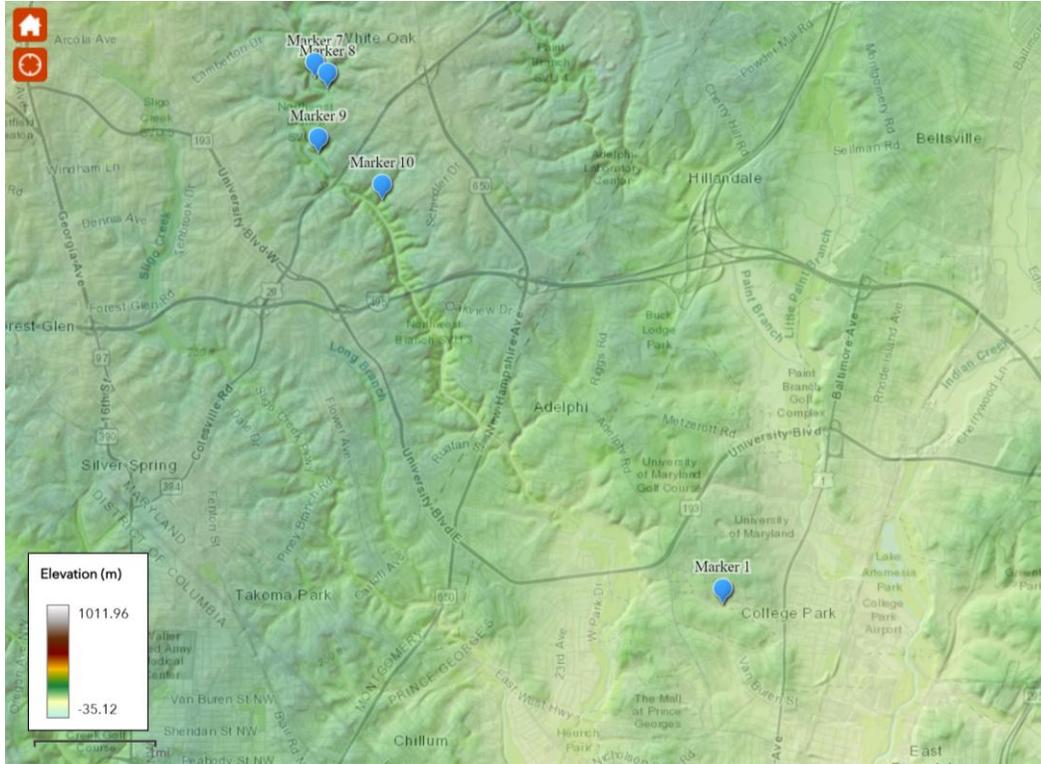


Figure 1 Map of all gauged sites in study. Top: Northern sites Bottom: Lower watershed sites and Guilford Run.

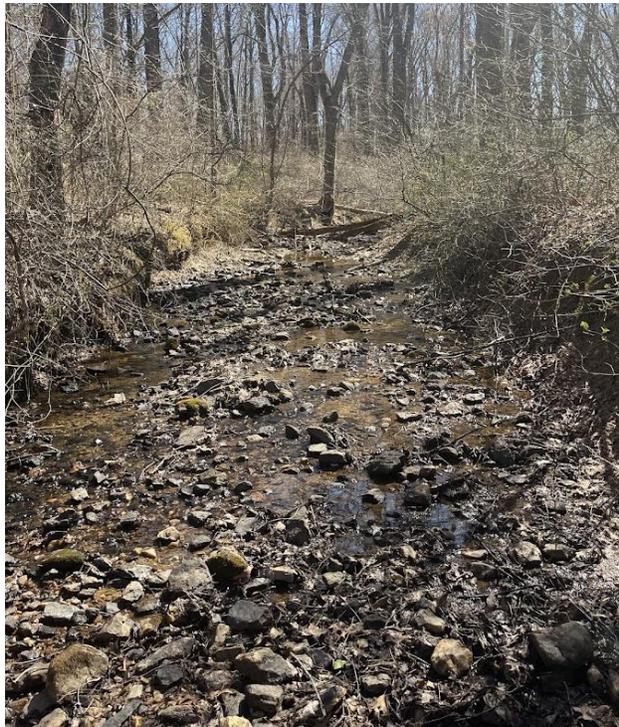


Figure 2 Nursery Run channel on March 18, 2025.



Figure 3 Riffle-pool sequence of Manor Run on March 18, 2025.

## Methods

I measured channel morphology, grain size characteristics, and stream gradient in the field. The study sites are gauged by Dr. Prestegaard's research group, and these data will be used to determine variations in channel depth, shear stress, and dimensionless shear stress ratios. This data will be used to evaluate channel stability and the frequency of bedload transport events.

### Channel Morphology Measurements

#### *Channel Cross Sections*

I measured and constructed channel cross-sections. At each cross-section, I use a measuring tape, surveying level (or level string), and stadia rod to determine the channel cross-section. I attached the measuring tape to a stake that I then placed at bankfull stage of the stream. I also noted a backsight elevation as a reference. Then, I stopped every 0.25 m to measure and record the value off the rod, noting where the edge of the channel and water surface was on both sides of the bank. This group of foresight data was then subtracted from the height of the surveying level to convert them to depths and plotted in Excel (Fig. 4).

For other sites, I used a measuring tape, a leveled baseline and stadia rod. I attached the measuring tape and stake at bankfull stage of the stream to create a horizontal level line across the channel. Again, I stopped every 0.25 m to measure the distance from the bed to bankfull stage, as well as the water depth. I plotted these as a function of distance across the channel.

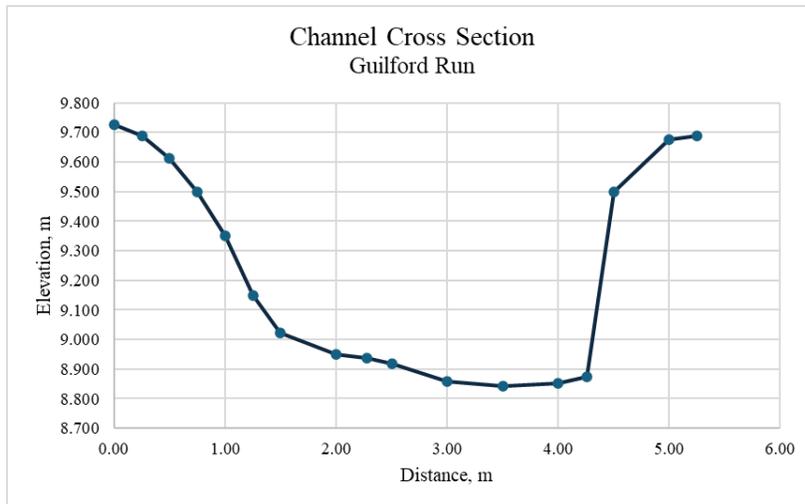


Figure 4 Guilford Run cross-section.

#### *Longitudinal Stream Profile*

To create the longitudinal stream profile, a survey level was set up, and a benchmark height was identified. Then, the bed and water surface elevations were recorded every 2 m along the channel. Elevations were determined by subtracting the foresight from the height of the survey level. The elevations were plotted against cumulative distance along the channel, and a best-fit line was taken to determine water surface slope. Fig. 5 shows the survey of the bed topography for a pool-riffle

sequence in Guilford Run. The average water surface gradient (0.0041 m/m) is used as an estimate of the bankfull water surface gradient.

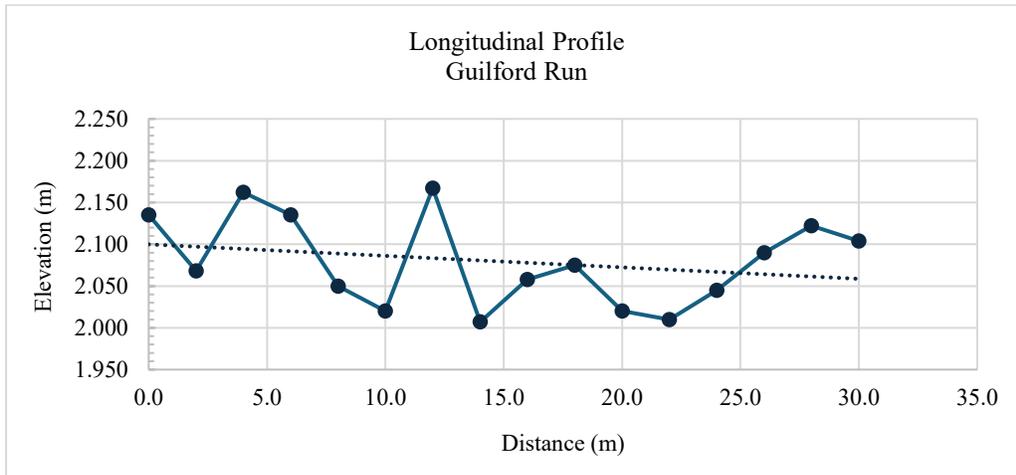


Figure 5 Longitudinal profile of Guilford Run.

### Surface Grain Size Distribution

Surface grain size distributions were collected using the Wolman pebble count method at the cross-section location. To do this, I walked across the stream in a grid pattern, picking up a grain and measuring with a ruler in millimeters its intermediate axis (Fig. 7). I continued walking in this grid pattern across the stream until 80 to 100 grain sizes were collected (Wolman, 1954). The distributions for each site were then plotted as a cumulative percentage (Fig. 6), and I calculated two values:  $D_{50}$ , the median diameter, and  $D_{84}$ , the diameter that is one standard deviation above the mean.  $D_{84}$  values are used in channel stability calculations.

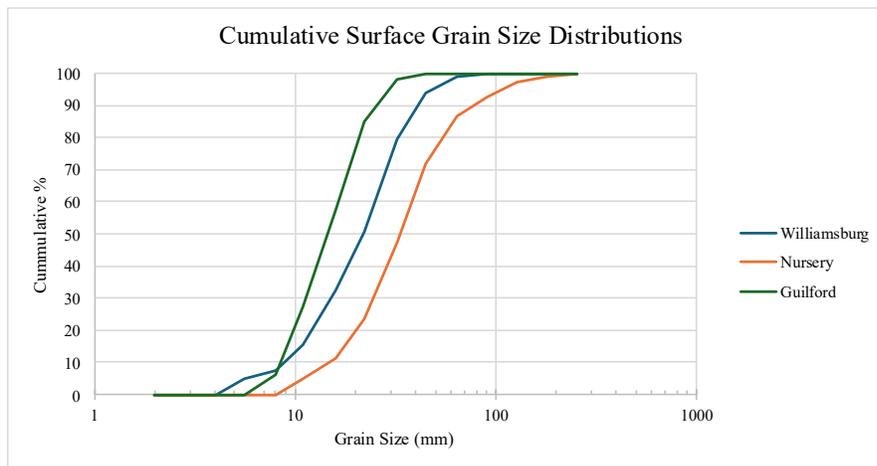


Figure 6 Surface grain size distributions of Guilford Run, Nursery Run, and Williamsburg Run.



Figure 7 Sample collection at Williamsburg Run.

### *Subsurface Percent Sand*

To determine the amount of sand in the bed, I removed the surface layer of bed particles and sampled the subsurface material. Samples of subsurface grains were collected and dried to be sieved to measure for percent sand ( $< 2$  mm) in the bed. The samples were sorted into coarse and sand-sized material using a 2 mm sieve to separate the sand-sized particles from the coarser grains (Fig. 8). The particles larger than 2 mm and finer than 2 mm were weighed separately. The percent sand was calculated as the ratio of the sand-sized sediment to the total subsurface sediment to determine the percentage of sand in the sample. This measurement provides the amount of sand in the subsurface.



Figure 8 Left: Samples before sieving. Right: Guilford Run sample in 2 mm sieve.

## Gauge Data to Determine Depth and Shear Stress Frequency Distributions

All study sites are gauged by workers at the University of Maryland (Prestegaard, Mullen). These data provide time series of gauge height, which combined with the channel cross-section data, provides a time series of water depth that can be used to determine shear stress and shear stress frequency. A two-and-a-half-month series for Guilford Run is shown in Fig. 9. This data will be collected for the duration of the study, providing records of events throughout the year. In each time series, water depth is shown in green and can be used with the field morphology measurements to determine instantaneous shear stress values and dimensionless shear stress can be calculated.

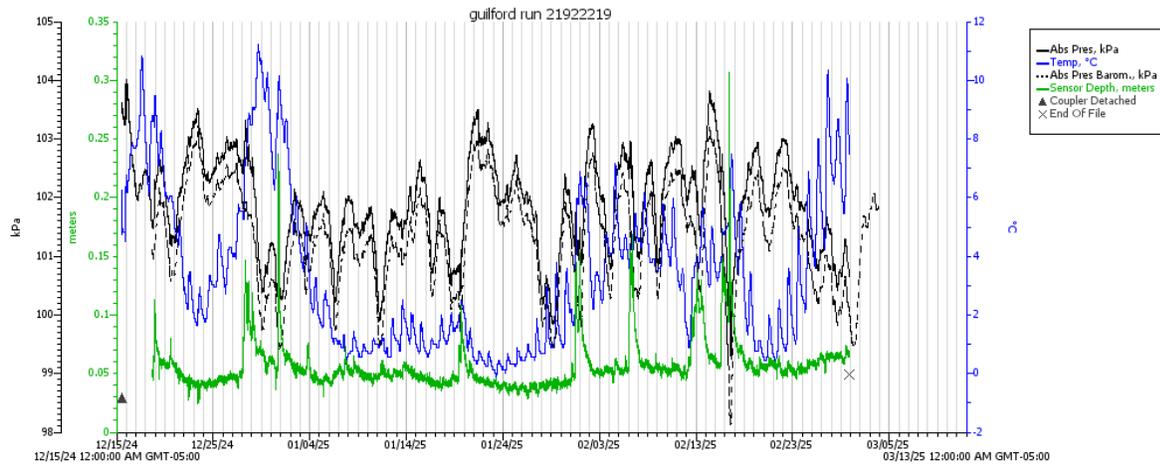


Figure 9 Gauge data time series for Guilford Run from December 2024 to March 2025.

## Testing for Threshold Channel Conditions

A threshold stream is defined as a stream in which the bankfull shear stress is equal to the critical dimensionless fluid shear stress ( $\tau_{crit}^*$ ). The critical dimensionless fluid shear stress is the shear stress required for the bed particles in a channel to begin to move. Critical dimensionless fluid shear stress varies with grain size:

$$\tau_{crit}^* = \frac{\tau_{crit}}{(\rho_s - \rho_w)gD_{84}} \quad (3)$$

where  $\tau_{crit}$  is the critical fluid shear stress,  $\rho_s$  is sediment density,  $\rho_w$  is water density,  $g$  is the acceleration due to gravity, and  $D_{84}$  is the keystone grain size (the grain size that determines channel morphology). Critical fluid shear stress is 0.045 for gravel-bed streams but can vary with the percentage of sand in the bed (Fig. 11). A higher percentage of sand in the stream bed, which is defined by  $< 2$  mm grains in the subsurface, decreases the value of  $\tau_{crit}^*$  (Wilcock, 2005).

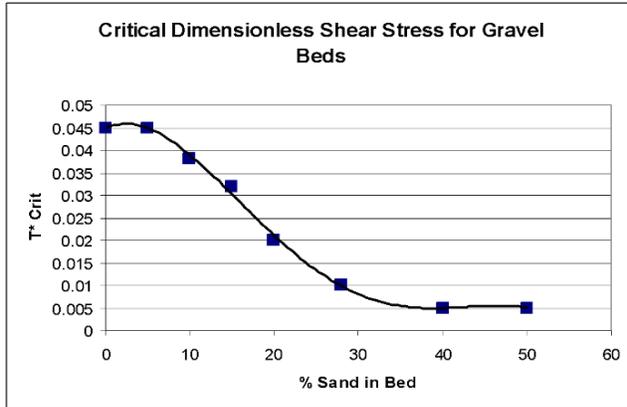


Figure 10 Relationship between critical dimensionless shear stress and percent sand in the bed (from Wilcock, 2005).

I will also calculate the bankfull shear stress, which is the shear force exerted the water on the bed when a river is at the bankfull stage, from depth and stream slope:

$$\tau_{bf} = \rho g d S \quad (4)$$

where  $\rho_w$  is water density,  $g$  is the acceleration due to gravity,  $d$  is the bankfull channel depth, and  $S$  is the stream gradient (slope).

### Frequency of Threshold Conditions

Finally, I calculated the shear stress ratio,  $\tau_{BF}/\tau_{crit}$  for bankfull events and used stream gauge data to evaluate the frequency of events that can mobilize sediment in the different reaches. Previous field experiments in the lower portion of the NW Anacostia by Matt Kraham in 2021 indicate that predicted bed mobility from flume experiments overestimated bed mobility in urbanized gravel-bed streams. The study found that dimensionless shear stresses were not significantly lower than 0.035, even with higher sand contents (Kraham, 2021). This might be due to the flashy flow regime in urban streams, where peak flows are relatively short periods but are high.

### Time Series Data: Gauge Height (flow depth), Shear Stress, and $\tau/\tau^*_{crit}$

Flow depth data from the gauges at each site along with the stream gradient data was used to calculate a continuous time series of shear stress. Flow depth data was used to determine how often the streams reach bankfull flow levels. Shear stress data, dimensionless shear stress values, and shear stress ratios were calculated using the gauge data at each site. This data was used to evaluate the mobility of the channel bed and will be compared to field mobility indicators to determine whether the Wilcock critical dimensionless shear stress estimates are applicable for these flashy, urban channels.

Dimensionless shear stress was calculated using the grain size and flow hydraulic data for the bankfull stage. For Guilford Run, bankfull dimensionless shear stress was 0.047, which is the threshold criterion for gravel-bed streams. This suggests that the channel is stable. The amount of sand in the bed is estimated to be 14%, which would reduce the critical shear stress to near 0.035. Therefore, the time series of dimensionless shear stress ratios were constructed using critical

dimensionless shear stress values of 0.045 (typical for gravel bed streams) and 0.035 (calculated value from bed sampling) (Fig. 11). Field studies of bed mobility and re-sampling bed grain size will be conducted to determine sand contents in the bed and bed mobility changes over time.

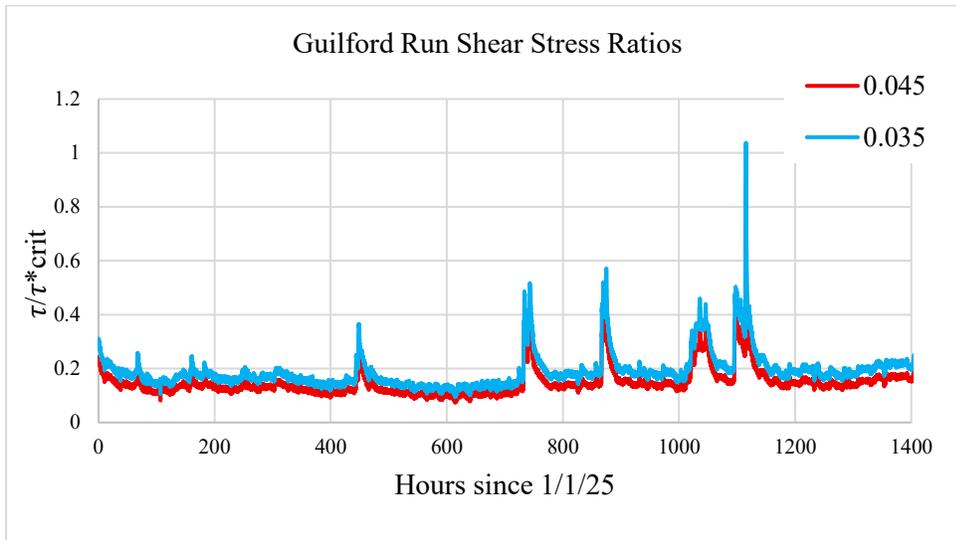


Figure 11 Dimensionless shear stress ratios based on varying sand contents.

## Results

### Bed Sediment Characteristics

Grain size of the surface and subsurface bed material was measured by field sampling at each site.  $D_{50}$  and  $D_{84}$  values of the surface were determined after each surface sample was sieved, and percentage of sand in the bed was determined after each subsurface sample was sieved (Table 2). Both fluid shear stress and surface grain size were used to calculate bankfull dimensionless shear stress. The percentage of sand in the bed was used to estimate the critical dimensionless shear stress for the initiation of motion from Wilcock (2005) (Fig. 10).

**Table 2: Bed Sediment Characteristics**

Site	Surface $D_{50}$ (mm)	Surface $D_{84}$ (mm)	% Sand in bed	$\tau_{crit}^*$ (Wilcock)
N6	12	37	8	0.043
N5	68	118	7	0.044
N1	8	80	16	0.030
S1	6	58	17	0.027
Batchellors Run	70	240	13	0.033
Bel Pre	36	70	20	0.020
Guilford Run	15	21	14	0.035
Manor Run	95	210	6	0.045
Nursery Run	76	92	11	0.037
Williamsburg	20	35	8	0.042

*Bankfull Hydraulic Characteristics*

Cross section measurements were used to determine bankfull surface width, bankfull area, and average bankfull depth, and longitudinal profile measurements were used to calculate stream gradient, which is used in the bankfull shear stress calculations (Table 3).

**Table 3: Bankfull Hydraulic Characteristics**

Site	BF Width, m	BF Area, m <sup>2</sup>	Avg. Depth, m	Gradient (m/m)
N6	3.04	0.90	0.30	0.0091
N5	5.28	1.28	0.24	0.0332
N1	3.07	0.83	0.27	0.0384
S1	2.47	0.61	0.25	0.0134
Batchellors Run	10.50	4.82	0.46	0.0076
Bel Pre	7.32	6.55	0.90	0.0091
Guilford Run	5.25	2.10	0.40	0.0041
Manor Run	8.4	2.60	0.31	0.0157
Nursery Run	4.90	5.18	1.06	0.0103
Williamsburg	8.3	6.47	0.78	0.0049

**Bankfull Geomorphic and Hydraulic Relationships**

Analysis of geomorphic and hydraulic relationships can determine if the streams have adjusted to discharge and substrate changes. One relationship to look at is discharge (Q) versus basin area, which shows a stream’s response to precipitation and runoff (Fig. 12). Streams with higher basin areas tended to have higher bankfull discharge due to the larger contributing areas. Scatter is likely due to the variations in impervious, but many sites had impervious cover of around 20-25%.

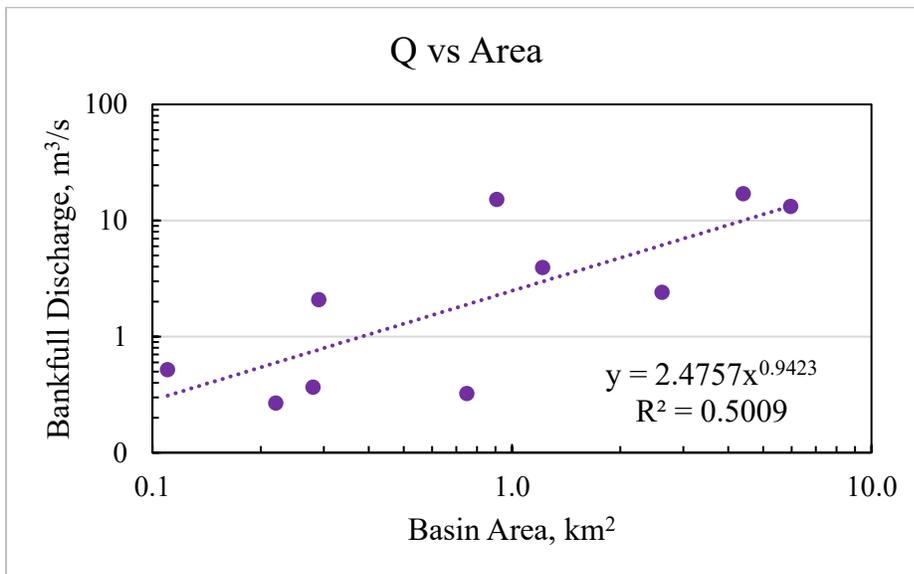


Figure 12 Bankfull discharge compared to basin area.

Small headwater catchments are the steepest, and gradient shallows out downstream (Wood et al., 1990). Sites with larger basin areas have shallower gradients, while the smaller basin sites have higher gradients (Fig. 13).

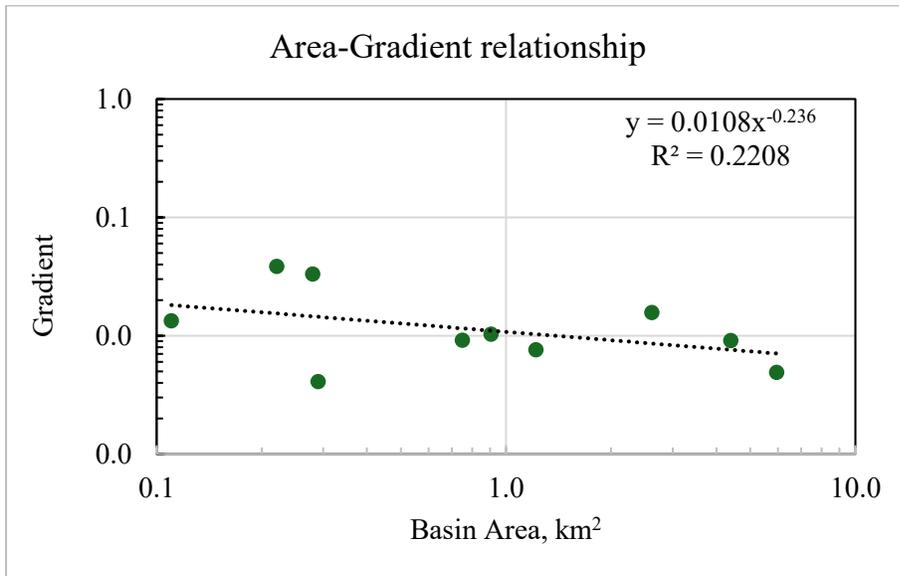


Figure 13 Area-gradient relationship of sites.

Relationship between relative roughness and channel shape is systematic, relative width decreases in finer-grained streams with higher  $d/D_{84}$  ratios (Fig. 14).

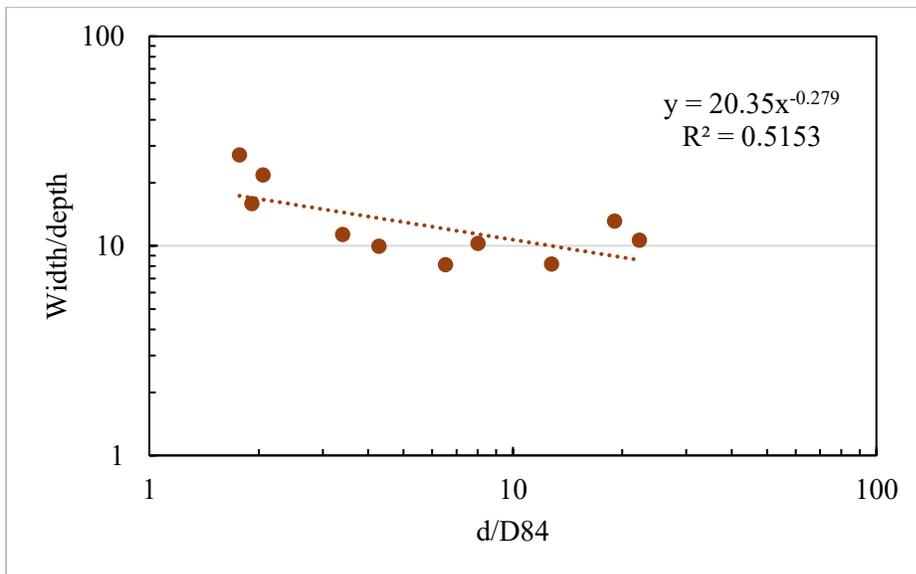


Figure 14 Relative roughness compared to channel shape.

Although there was a range in grain size and flow depths, most of the channels had bankfull depths that were similar to the critical depth (Fig. 15). The exceptions are channels with bedrock and boulders, and thus a much larger critical depth than bankfull depth. The bankfull depth to critical depth ratio compares the required water depth to move bed sediment. When the critical depth is is

higher than the bankfull depth, bed sediment is not moving, and the stream has a low  $d_{BF}/d_{crit}$  ratio; streams where the critical depth is below the bankfull depth are able to move bed sediment. The depth to  $D_{84}$  ratio gives the bed relative resistance to flow: higher  $d/D_{84}$  ratio streams have smaller grains and deeper water (less resistant to flow), while lower ratio streams have coarser grains and shallower water (being more resistant to flow).

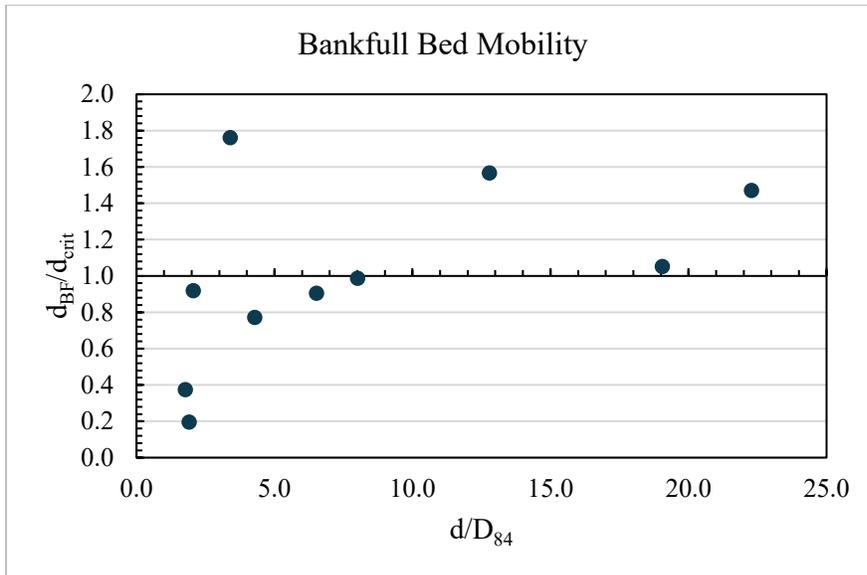


Figure 15 Bankfull depth to critical depth related to depth to  $D_{84}$  ratio.

Sites where bankfull depth exceeds the critical depth are N1, Guilford Run, Bel Pre, and Williamsburg Run. N1 and Guilford Run have over 15% sand in the bed (16% and 17%, respectively), while Bel Pre has 10%, and Williamsburg with 8%. Three of these four sites have some of the largest  $d/D_{84}$  ratios, with N1 having one of the lowest.

### Frequency of Threshold Events

The geomorphic data were used to determine critical (threshold) depth ( $d_{crit}$ ):

$$d_{crit} = \frac{\tau_{crit}^* (\rho_s - \rho_w) g D}{\rho_w g S} \tag{5}$$

Critical depth is the flow depth where streams exceed threshold conditions ( $\tau_{BF}^*/\tau_{crit}^* > 1$ ), and the number of exceedances can be counted to obtain seasonal frequency. Frequency of exceeding critical depth can be compared to geomorphic characteristics to determine channel stability. Data was collected for the summer months (May – September), as these include the heaviest storms of the past year.

Small storms cause response in small streams but are not always seen in larger streams. Increase in impervious cover results in an increase in runoff, which gets to smaller streams quicker, causing larger responses. The three sites that had a much larger number of exceedances had moderate impervious cover, but three of the smallest basin areas (Figs. 16 and 17).

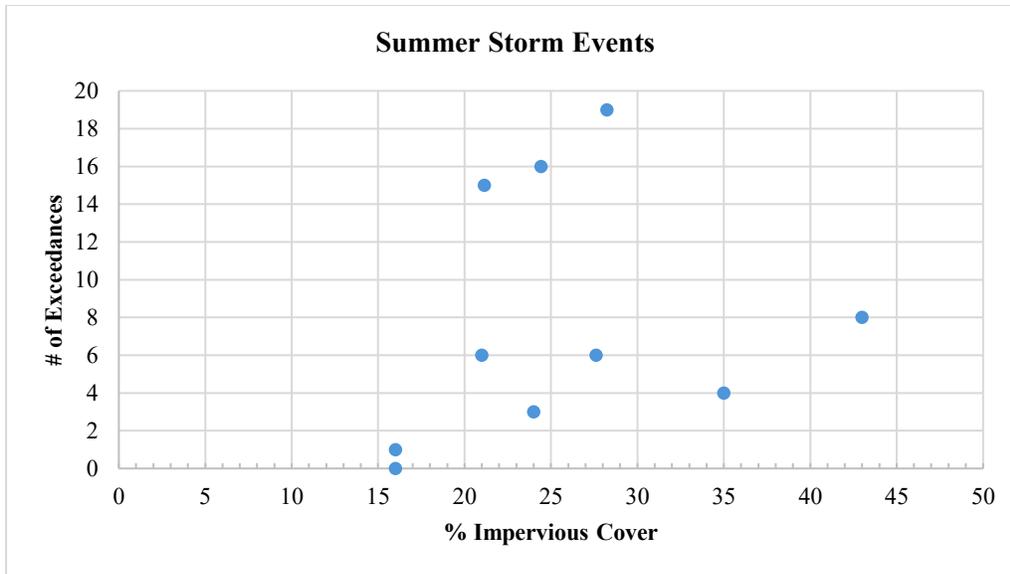


Figure 16 Number of exceedances above critical depth compared to impervious cover. These data indicate two trends, the three sites on the upper portion of the graph are for streams in very small catchments.

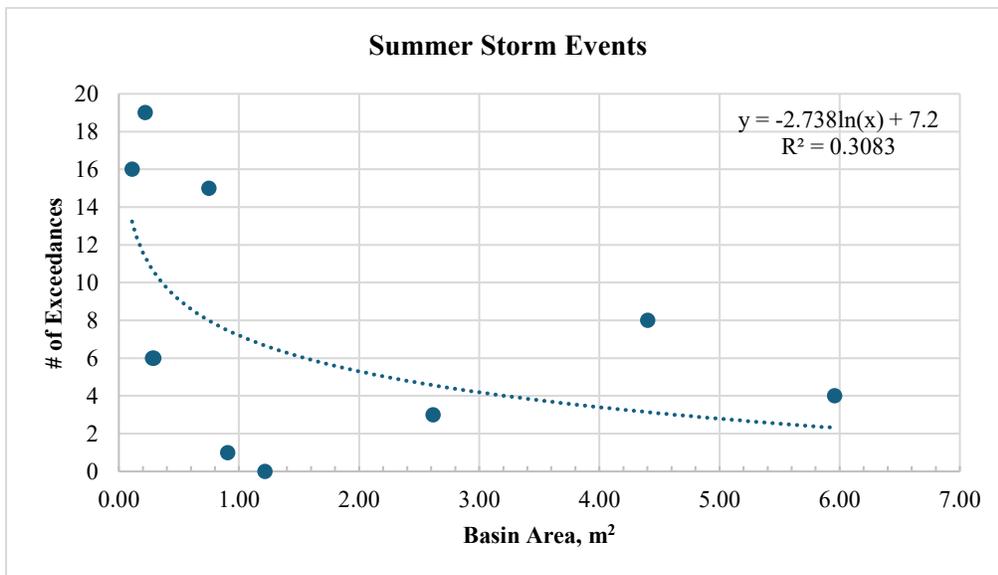


Figure 17 Number of exceedances above critical depth compared to basin area. This graph illustrates that the three sites with high exceedances are three of the smallest catchments.

Comparing the number of exceedances of critical depth to the depth/ $D_{84}$  ratio is a way to determine whether bed characteristics affect frequency of movement. The ratio,  $d/D_{84}$ , is relative roughness, which more generates resistance to flow, but also higher protrusion of particles into the flow, which might facilitate entrainment (Fig. 18). Sites with lower  $d/D_{84}$  ratios tended to have more exceedances, but these were also streams with some of the smallest basin areas. Small catchments respond to shorter duration storm events, which tend to be more intense in this region (NOAA Atlas 14).

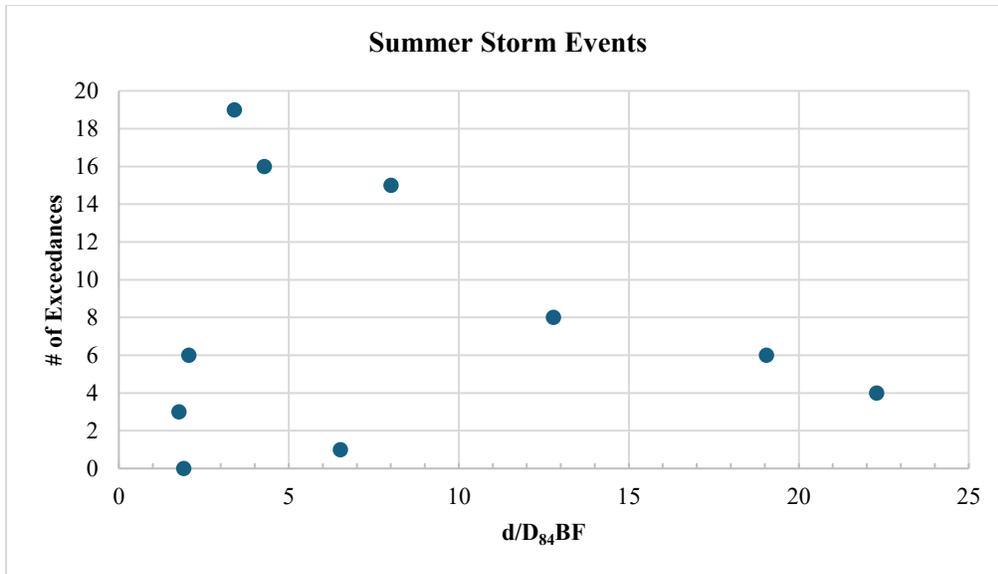


Figure 18 Number of exceedances above critical depth compared to depth to D84 bankfull ratio.

The final parameter to compare against number of exceedances above critical depth is the dimensionless shear stress ratio (Fig. 19). Streams with a  $\tau_{BF}^*/\tau_{crit}^*$  ratio above one are not threshold channels.

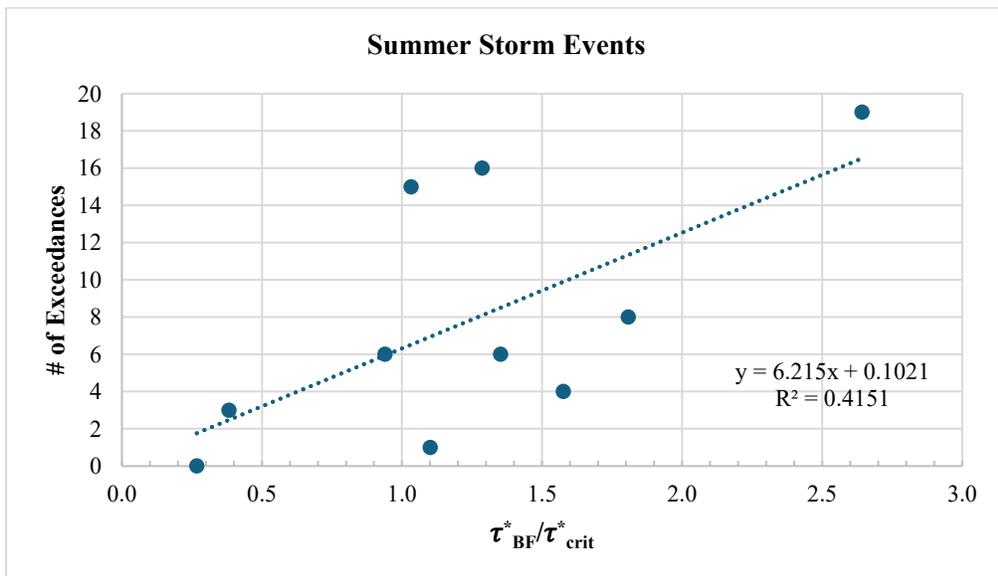


Figure 19 Number of exceedances above critical depth compared to  $\tau_{BF}^*/\tau_{crit}^*$ . The number of exceedances increases with the bankfull to critical shear stress ratio. Three of the smallest basins, all with shear stress ratios greater than 1, fall above the trend of the other streams.

**Summary and Implications**

The goal of this project is to evaluate catchment, geomorphic, and sediment characteristics that affect the mobility of streams after urban development. To do this, I measured channel cross-sections, surface and subsurface grain size distributions, and longitudinal profiles in small

catchments with a range of urban cover. These data were used to evaluate bankfull channel stability using shear stress ratios. has been collected from which flow conditions can be determined. The data was used to calculate shear stresses to determine threshold channel conditions, as well as the effects of higher urbanization of a stream on its equilibrium state. Additionally, I used 9 months of gauge height data from each of the streams to determine the frequency at which threshold conditions were reached or exceeded.

Stream channels adjust to changes in discharge, sediment supply, and grain size (Leopold et al., 1964). Sand bed material can significantly reduce the shear stresses required to mobilize gravel in streams, and coarse gravel surface layers maintain channel stability. This study was designed to evaluate sites in urban streams with varying amounts of both urbanization and sand in the bed.

The geomorphic relationships found in this study suggest that many of the channels are nearly threshold channels. Systematic increases in bankfull discharge and channel width with basin area suggest that many of these urban stream channels are in a dynamic equilibrium (Leopold et al., 1964). The width to depth ratio of most sites is between 10 and 15, which are typically indicators of a stream in dynamic equilibrium (Homan, 2024). The data indicates that half of the channels have  $\tau_{BF}^*/\tau_{crit}^*$  ratios greater than 1.5 or less than 0.5, suggesting that these channels are not threshold channels. Therefore, the first null is not supported by the data, as not all sites are threshold channels. The alternative hypothesis states that streams with low percentages of sand in the stream bed will be threshold channels. Most sites with less than 15% sand in the bed have  $\tau_{BF}^*/\tau_{crit}^*$  ratios in threshold range (0.75 – 1.25). Batchellors Run has 13% sand in the bed but has a  $\tau_{BF}^*/\tau_{crit}^*$  ratio below one. Batchellors Run, however, transitions from a narrow, sand bed stream to a wide gravel bed stream at the study site, suggesting that the sand content in the bed at the study site might be variable and not indicative of the larger reach. In general, streams with low percentages of sand in the stream bed are threshold channels.

The second null is not supported by the data, as the sites reach bankfull discharge more frequently than 1-2 times per year. All site data supports the second alternative apart from Batchellors Run and Nursery Run, which had exceedances of critical depth in the past year of 0 and 1, respectively. Every other site supports the second alternative, having over 3 exceedances in the summer months. The streams in the smallest drainage basins had the highest number of events above critical depth. In the larger drainage basins, sites with the most impervious cover as well as bed sand percentages experienced the most numbers of exceedances above critical depth. These data indicate that the amount of urbanization influences the frequency of movement in small streams during storm events.

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**Appendix**

**Time Series Data**

*Batchellor Run*

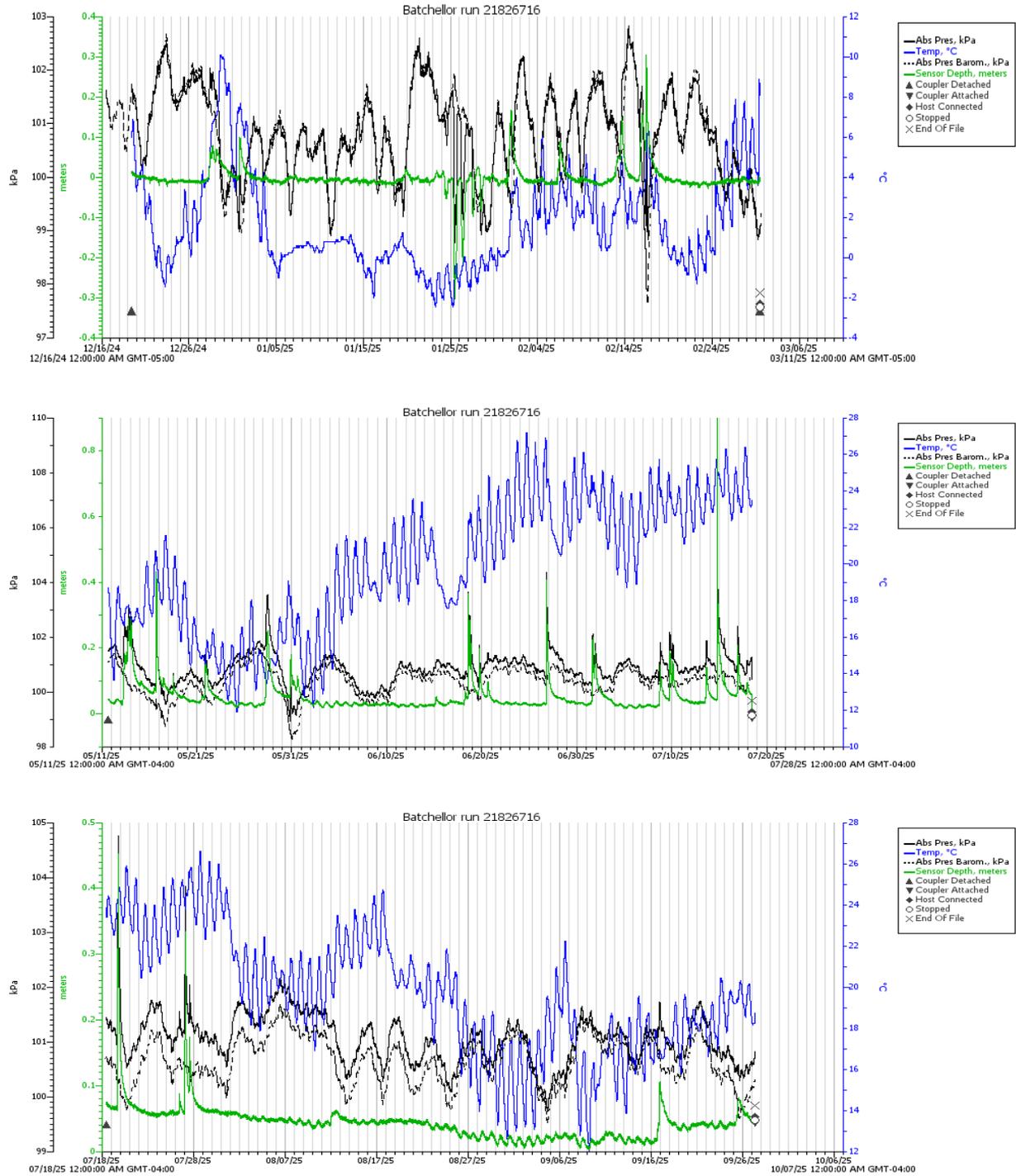


Figure 20 Time series of January through September flow data for Batchellors Run.

Bel Pre

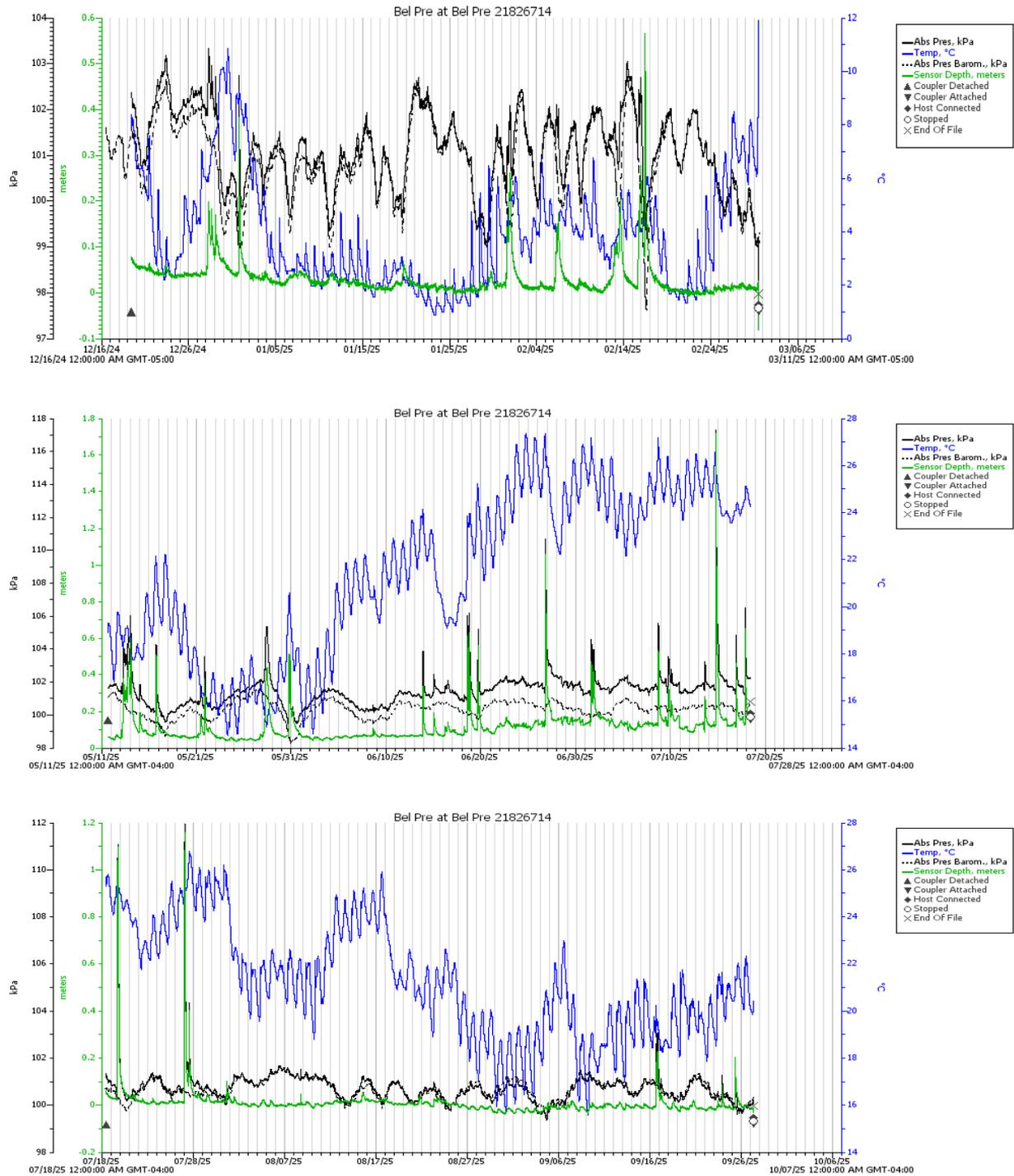


Figure 21 Time series of January through September flow data for Bel Pre.

Guilford Run

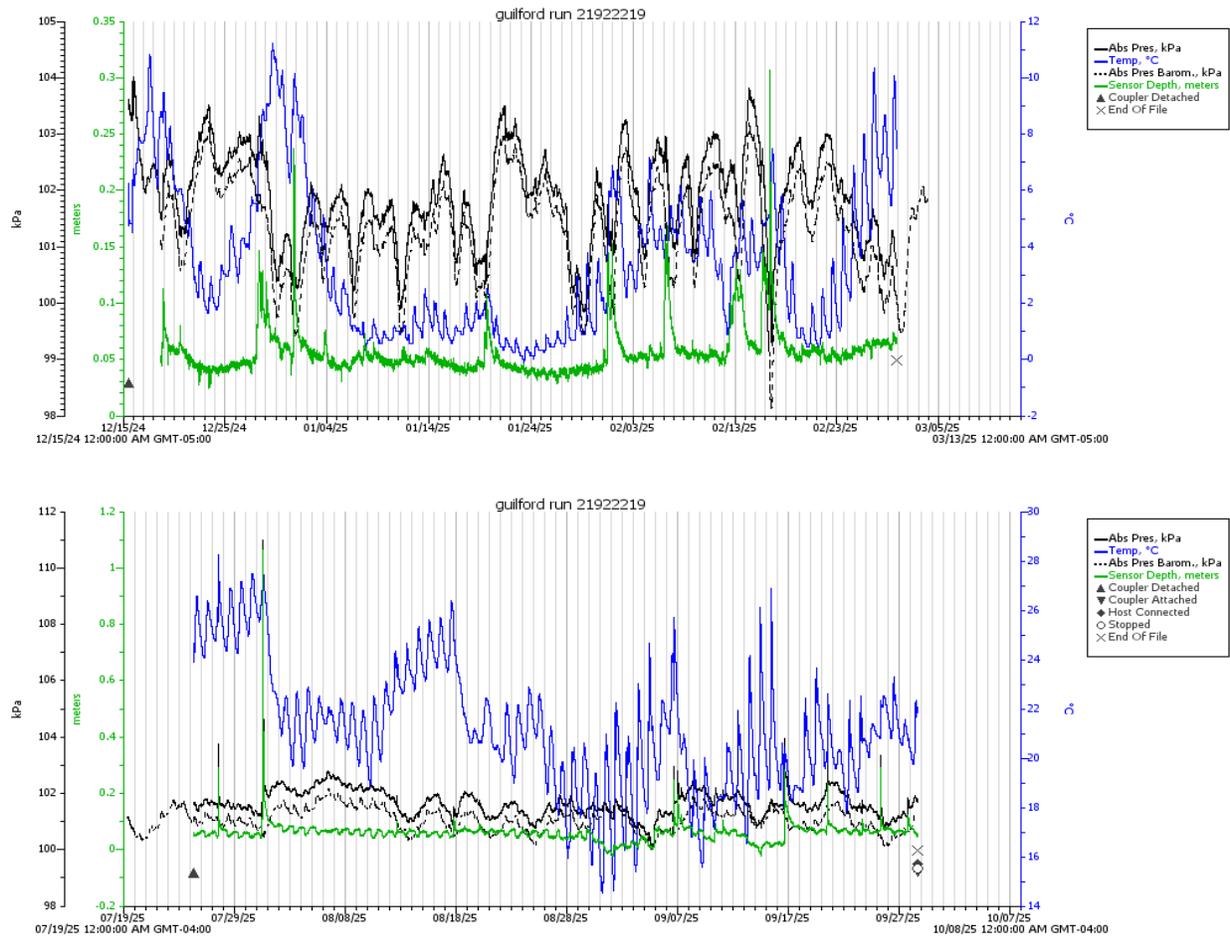


Figure 22 Time series of January through September flow data for Guilford Run.

Manor Run

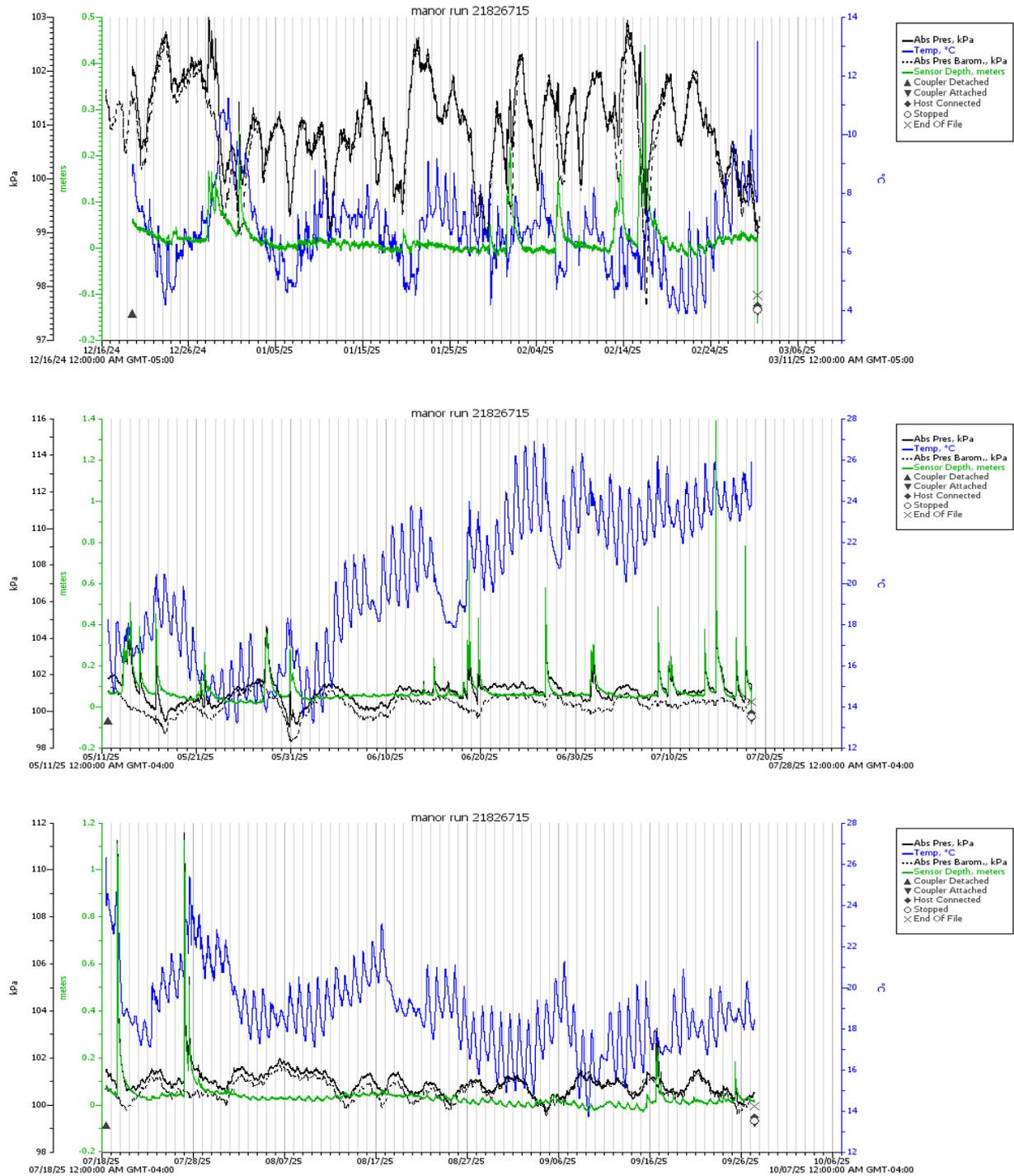


Figure 23 Time series of January through September flow data for Manor Run.

Nursery Run

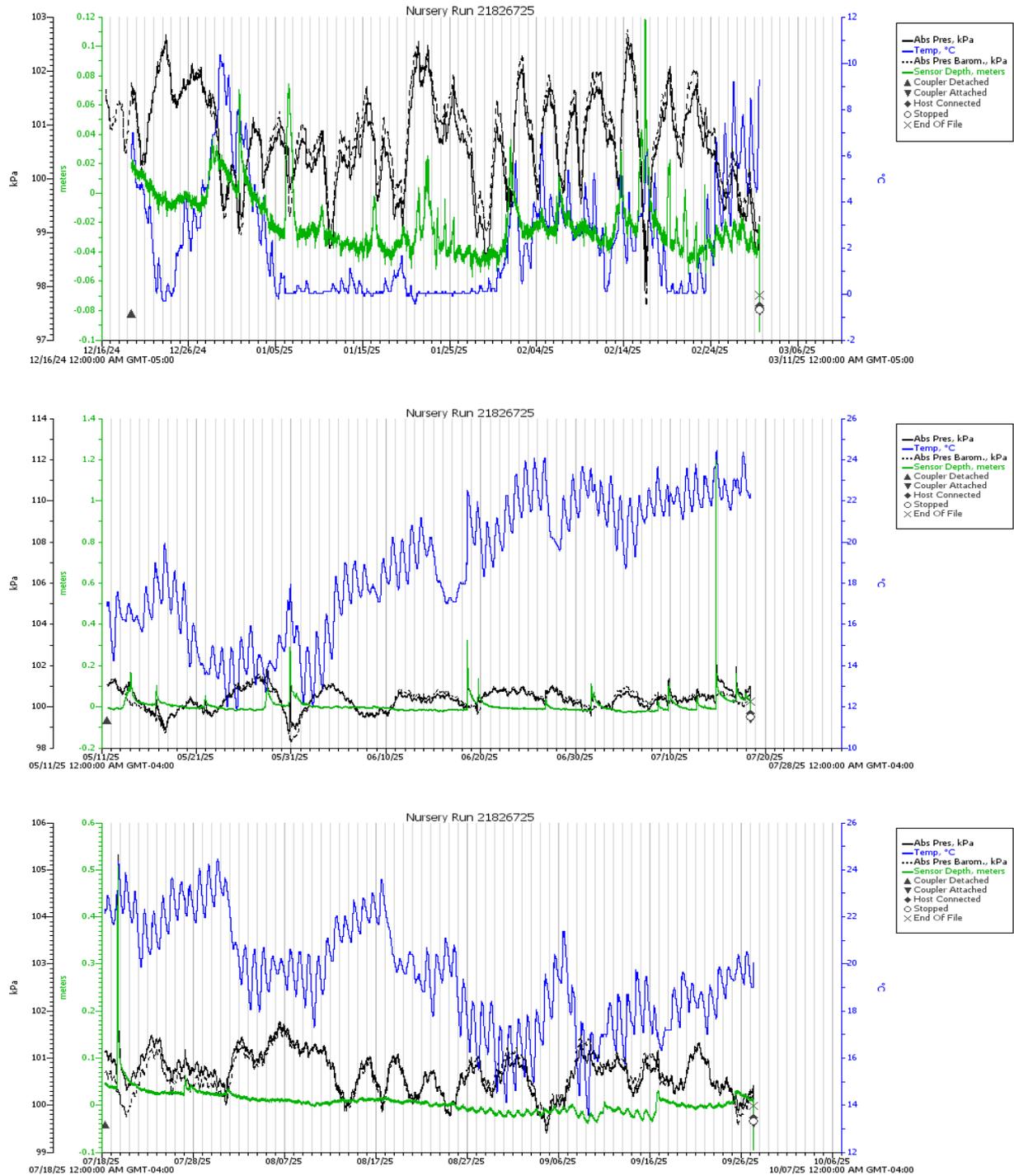


Figure 24 Time series of January through September flow data for Nursery Run.

Williamsburg Run

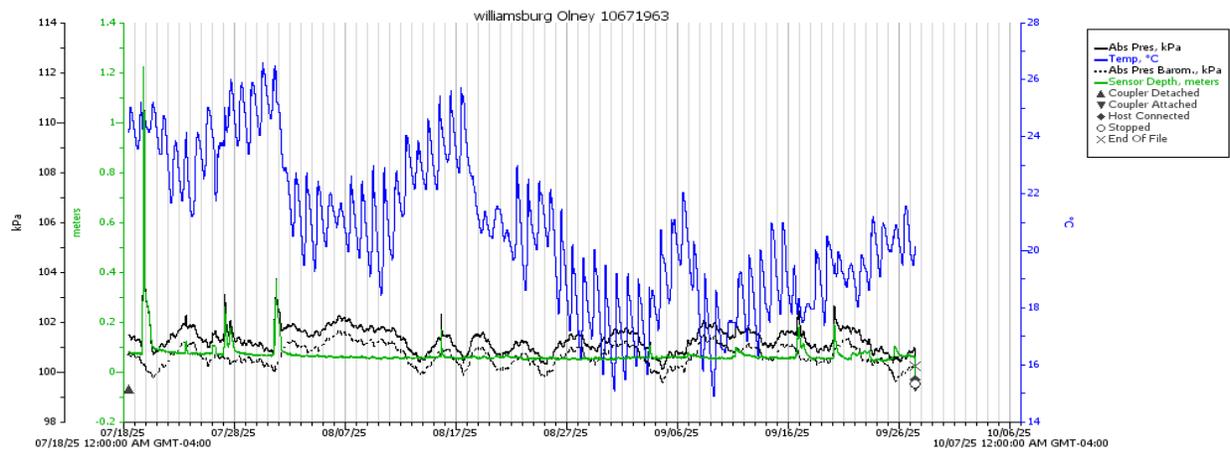
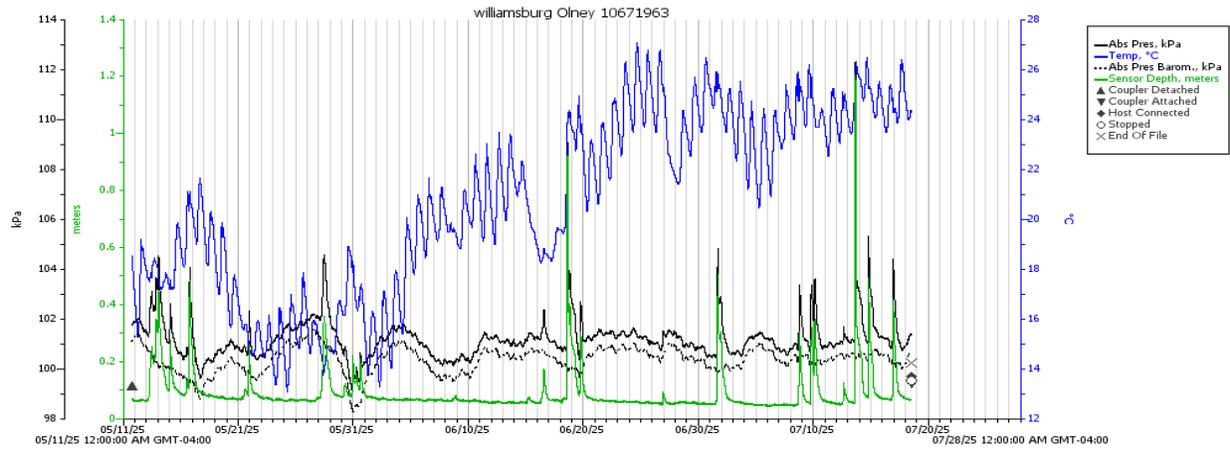


Figure 25 Time series of January through September flow data for Williamsburg Run.

N1

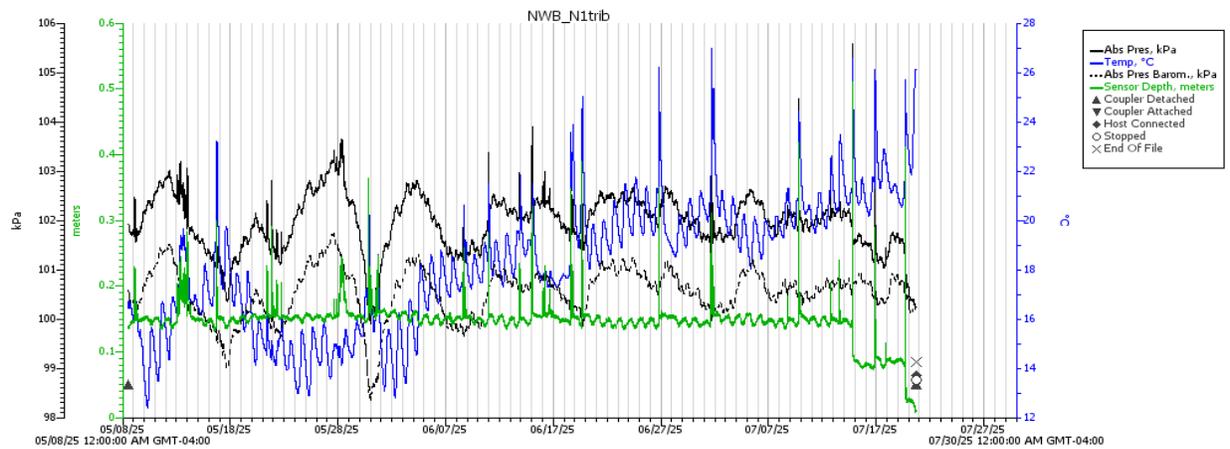


Figure 26 Time series of May through July flow data for N1.

N5

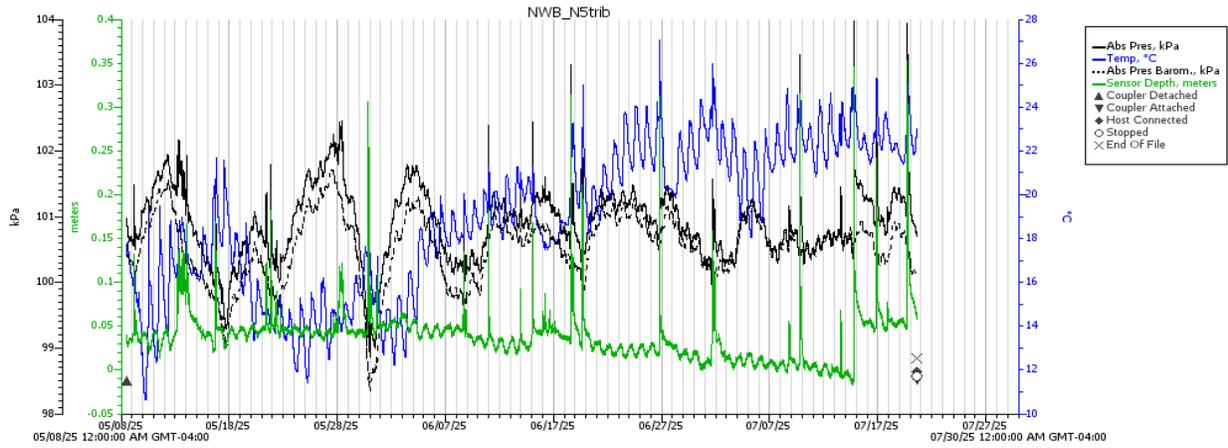


Figure 27 Time series of May through July flow data for N5.

N6

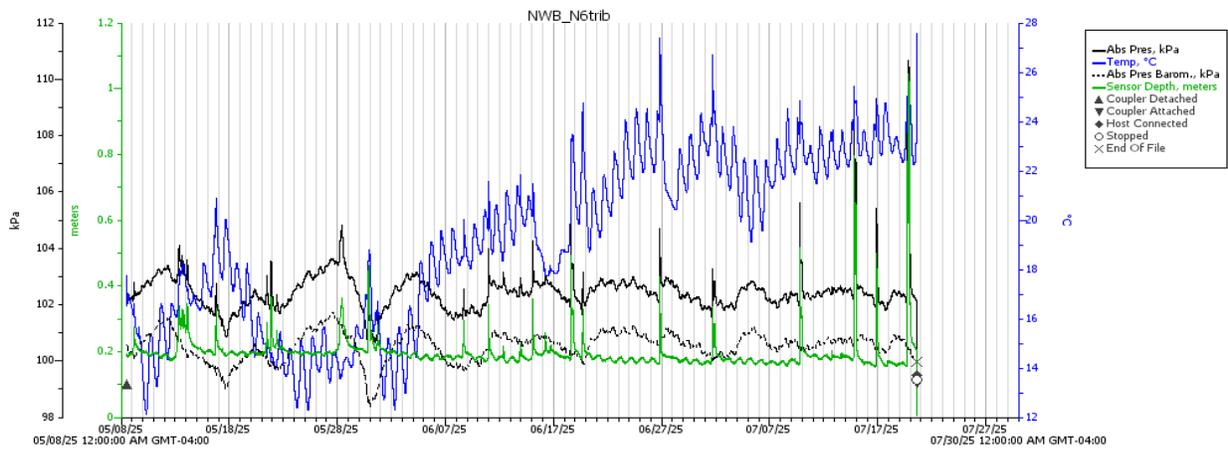


Figure 28 Time series of May through July flow data for N6.

SI

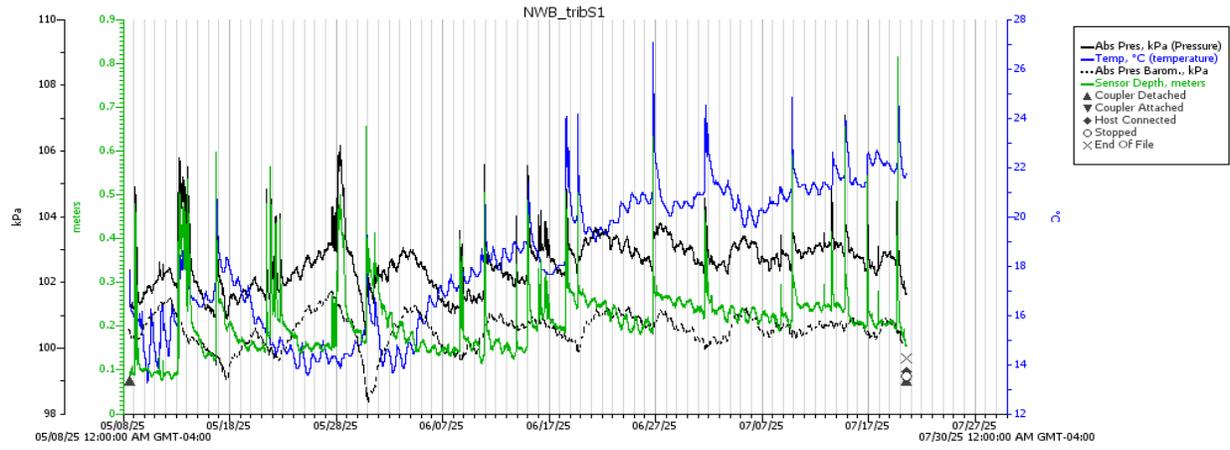


Figure 29 Time series of May through July flow data for SI.

**Honor Code**

“I pledge on my honor that I have not given or received any unauthorized assistance on this assignment/examination.”