Severe erosion has been observed in Bull Run, a small suburban stream in Butler County, Ohio. Erosion has led to extremely steep banks with extensive bare sediment exposed throughout large portions of the stream. Fallen trees, exposed roots, and failed banks are common along the length of Bull Run. The channel was investigated to understand the degree of current channel instability and estimate future instability. This study assessed the state of instability within Bull Run, identified which characteristics of Bull Run are most indicative of channel instability, and developed a protocol for assessing stream channel instability. While other rapid channel stability assessments exist, this protocol emphasizes functionality within time and budget constraints and is suitable for use by a novice.
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DEDICATION

This report is dedicated to my mom and dad.

You, above all, have always been the greatest teachers in my life. The wisdom, work ethic, and values you have bestowed upon me are the reasons for my success.

“Setting an example is not the main means of influencing another, it is the only means.”

- Albert Einstein
Streams, and small streams in particular, are of great importance because of their ability to recharge groundwater, decrease flooding downstream, and provide habitat for aquatic life (Meyer et al., 2005). Unfortunately, the services provided by streams are often undervalued and overlooked. Streams in urban areas are especially threatened by ever-encroaching development.

The management of urban streams is complex. In many urban areas, due to increased impervious surfaces, drainage systems are no longer adequate to accommodate stormwater following a storm event. It is difficult to prevent hydrologic regime changes that occur following increased urbanization (Roy et al. 2008). Furthermore, allotment of riparian areas by urban planners and developers is often too small to allow streams the space needed for natural migration. These problems can lead to bank erosion, channel instability, damage to neighboring infrastructure, and habitat degradation (Doll et al. 2002). Solutions to these problems are often not possible within the spatial and budgetary constraints faced by state and local governments. In addition, landowners adjacent the stream, stormwater managers, city municipalities, and local citizens all hold different and sometimes conflicting opinions about urban stream best-management-practices.

Severe erosion has been observed in Bull Run, a small suburban stream in Butler County, Ohio (Figure 1). Erosion has led to extremely steep banks with extensive bare sediment exposed throughout large portions of the stream. Fallen trees, exposed roots, and failed banks are common along the length of Bull Run. Many homeowners along Bull Run are concerned with the integrity of their houses’ foundations and/or the rate at which their property is being removed. Channel instability needs to be assessed to understand the degree of current channel instability and estimate future instability.

This study assesses the state of instability within Bull Run, identifies which characteristics of Bull Run are most indicative of channel instability, and develops a protocol for assessing stream channel instability. While other rapid channel stability assessments exist, this protocol emphasizes functionality within time and budget constraints and is suitable for use by a novice.
Figure 1. The watershed of Bull Run, 1.8 square miles. The yellow arrowed line indicates the study section.
The movement of river channels has been studied for decades to understand why and how stream channels reposition and what causes them to do so (Chin and Gregory, 2005). Urbanization is a primary cause for alterations in the dimension, pattern, and profile of streams, ultimately leading to problems with channel stability (Doll et al., 2002). Urbanization occurs in three basic stages and rivers and streams respond to the various impacts of each stage. The first phase is pre-development. During this time the landscape is stable and streams and rivers are in a state of dynamic equilibrium (Wolman, 1967). Streams have enough space for natural lateral movement and upstream land use remains consistent. The sediment input and stream power within the channel are balanced so that the stream is neither aggrading nor degrading. The pre-development stream is well-vegetated and often interacts with its floodplain (Doll et al., 2002).

Next, development begins and large areas of bare soil are exposed. During development the land is bare and susceptible to erosion. Erosion rates can increase by as much as 40,000 times pre-construction rates (Harbor, 1999). Increasing sediment inputs into streams during the construction phase of urbanization cause aggradation. As much as 80% of this sediment yield can be a product of construction activities (Fusillo et al., 1977). The period of development is usually relatively short compared with the time the stream will take to respond and recover from this disturbance.

After construction the third stage, the urban landscape, emerges. This new landscape includes houses, rooftops, gutters, sewers, roads, and parking lots (Chin, 2006). Soil and vegetation have been removed and replaced with impervious surfaces. Increased runoff is a product of the spread of impervious surfaces and decreases in infiltration rates (Wolman 1967, Doyle et al. 2000, Chin and Gregory 2001). Stormwater drainage systems force small channels to accommodate increased amounts of water. Lag time between peak precipitation and peak discharge decreases. Stream flows that increase in magnitude but decrease in duration, compared to before urbanization, are referred to as “flashy”. These alterations in hydrology occur in drainage areas that contain as little as 10 to 15% impervious surfaces (Moscrip and Montgomery 1997). Moreover, an increase of 5,500 persons/square mile in an originally rural setting can cause the magnitude of the average annual flood to double (Hammer 1973). To put this population density in perspective, as of the last census, Manhattan had a population density
of 70,595 person/square mile (U.S. Census Bureau). Stream power within the channel is escalated by the increased runoff and begins to move the previous aggradation. The now-developed urban land produces a low sediment yield (Allemendinger et al. 2007). Eventually, channel incision and enlargement of channel width begin as the input/output of sediment balance no longer exists. At the same time, increased flows and a smaller riparian buffer cause bank erosion. Bank erosion leads to taller and less stable banks. Channel incision and bank erosion combined often lead to the channel becoming disconnected from its floodplain. Stream channels experiencing this disconnection can no longer reach bankfull and flood the neighboring riparian area, except during infrequent large floods (Doyle and Shield 1998). This forces the stream channel itself to accommodate the increased volume of water through widening, bank cutting, and channel incision (Galster et al. 2008). The riparian corridor is then unavailable for water storage during flooding and to decrease the amount and power of water heading downstream (Chin 2006, Bledsoe 2002, Doyle et al. 2000, Simon and Downs 1995, Wolman 1967).

The ability for a stream to recover from the effects of urbanization and ultimately achieve a new, stable equilibrium depends upon two main variables. First, construction within the stream's watershed must substantially decrease or proper basins must be installed to catch sediment. This will stop the continuing input of sediment into the stream. In addition, stormwater drainage systems and the final amount of impervious pavement must be completed. These two variables are necessary for equilibrium to potentially exist again within a stream system that has undergone a disturbance such as urbanization. The new equilibrium may be much different than the original. Equilibrium in the context of a disturbed stream may refer more to its stability than its original dynamic equilibrium. The ability of the stream to once again reach this equilibrium is also affected by bank soil cohesiveness, size of riparian area/riparian vegetation, confinement of stream location, climate change, and management practices (Chin 2006). The time required for streams to undergo these stages varies, but the majority of streams fall into a twenty to forty year timeline (Chin, 2006).

In general, stream channels are thought of as unstable if they vary significantly from other streams within the same relative area, in rates of erosion or aggradation (Doyle et al. 2000). Channel instability may be lateral, as channel migration or bank failure, or vertical, as aggradation or degradation. Stream channel instability can damage land and human infrastructure, deteriorate water quality through increased sedimentation, diminish the condition
of riparian vegetation, and decrease aquatic biodiversity. It is important to be able to identify stream channel instability in order to properly address the concerns associated with it.

Various indicators and methods of identifying stream channel stability have been developed for a variety of reasons including engineering management, stream restoration, and prediction of stream erosion. Pfankuch (1978) and Simon and Downs (1995) both developed qualitative rating methods. These studies identified characteristics such as landform slope, mass wasting, debris-jam potential, vegetative bank protection, channel capacity, bank rock content, obstructions (flow deflectors, sediment traps), cutting, deposition, bar development, bank soil texture and coherence to be potential indicators of channel instability. In these rating methods each indicator has a rating system associated with it and depending upon how a feature is scored determines if it is rated as excellent, good, fair, or poor, with excellent meaning that a particular characteristic does not indicate channel instability and poor meaning a feature is very indicative of stream channel instability. Site evaluation forms are available for this type of qualitative assessment to be conducted as a rapid geomorphic assessment. A rapid assessment is appropriate for a study assessing channel stability on a local scale (e.g. at a road crossing or bridge) to focus on how channel instability affects a particular site or structure. These forms can be completed quickly, which is important when many assessments must be completed within a short time period. Qualitative assessments are attractive because they require less time in the field, but they are difficult to compare to other stream assessments due to differences in stream type (Doyle et al., 2000). The “degree of instability” within a stream may be easily identifiable for an experienced observer, but is still a subjective measure of channel stability. However, when completed correctly, qualitative assessments can gather important information that would otherwise be nonexistent.

Stream channel stability analysis has also been conducted using qualitative methods coupled with quantitative data consisting of hydraulic geometry analysis and sediment transport calculations (Thorne et al., 1996; Johnson et al., 1999). Hydraulic geometry analyses can be conducted by comparing measurements of the current stream channel to calculations obtained using equations empirically derived for stable stream channels (Hey and Thorne, 1986). Differences between the two may indicate channel instability. However, the empirically derived equations may not always be applicable and therefore must be used with caution (Johnson et al., 1999). Sediment transport calculations including stream power, excess shear stress, and a ratio
of average boundary shear stress to critical shear stress are important measures of movement within the channel bed and can be used to quantitatively assess channel stability (Olsen et al., 1998, Doyle et al., 2000; Johnson et al., 1999).

Cross-sectional stream power is the rate at which work is done per unit width; it is often used to describe the erosive capacity of a stream (Gordon et al., 1992). Brookes (1987) used stream power per unit area as an indication of stream channel stability; his study conducted in the United Kingdom determined that natural stream channels (i.e. not engineered) never exceeded a stream power of 35 W/m².

Boundary shear stress is a friction that causes flow resistance along the channel boundary or bed (Gordon et al., 1992). Critical shear stress is the amount of friction necessary to induce movement of bed material (Olsen et al., 1998). Calculating the ratio of boundary shear stress to critical shear stress ($\tau_c$) at bankfull elevation can serve as an indication of channel stability. When $\tau_c > 1$, the sediment begins to move and depending upon the sediment input to the stream, this movement may cause degradation. When $\tau_c < 1$, the stream is not moving bed material and aggradation may occur. At a $\tau_c > 3$, the entire bed may become mobile (Pitlick, 1992; Simon, 1996).

Calculating the threshold of motion provides another means of assessing channel stability. The particle size at the threshold of motion is expected to be approximately the D₅₀ in a stable channel (Mecklenburg and Ward, 2007). However, a large discrepancy between the particle size at the threshold of motion and mean grain size of bed material indicates channel instability. The threshold of motion equation uses Shield’s parameter, which also known as dimensionless critical shear stress. It relates particle shape, fluid properties, and surface particle arrangement (Gordon et al., 1992). A Sediment Equations version 4.0 workbook was developed in which inputs of depth (at bankfull elevation), slope, and Shield’s parameter calculate the grain size at the threshold of motion (Mecklenburg and Ward, 2007).

Calculating stream power and the threshold of motion require knowing bankfull discharge and bankfull depth, respectively. Bankfull elevation is the elevation at which water fills a channel and just begins to overflow its banks (Wolman and Leopold, 1957). In general, bankfull elevation occurs every 1.5 to 2 years (Sherwood and Huitger, 2005). Bankfull discharge is the volume of water flowing past a point over a period of time when bankfull elevation has been reached. It was difficult to establish a bankfull elevation within Bull Run due
to the channel being incised. Incision has made it impossible for Bull Run to overflow its banks, baring a flood of unusual magnitude. However, in many places a small incipient floodplain, (a floodplain with a width that is usually shorter than the width of the channel) has formed. This incipient floodplain, which is sometimes referred to as an in-channel bench, occurs at an elevation higher than the channel bed, but lower than the highest banks (Erskine and Livingstone, 1999). Another indication of bankfull elevation is change in bank slope, that is, where a vertical bank becomes horizontal. In addition to bankfull elevation, knowing longitudinal slope is another necessary factor in determining bed load movement (Olsen et al., 1997).

The Bank Stability and Toe Erosion Model, Static Version 4.1 (Simon and Curini, 1998), can be used predict the stability of banks through input geometry. Geometry inputs include: bank height (m), bank angle (°), bank toe length (m), bank toe angle (°), shear surface angle (°), mean soil friction angle (°), mean bank angle (°), elevation of flow (m), slope of channel, and duration of flow (hrs). The model calculates a factor of safety, where a value > 1 indicates stability, and a value < 1 indicates instability.

Many methods with which to assess channel stability are available, and while many rapid channel stability assessments have been previously developed there is a lack of assessment protocols that emphasize producing accurate results without requiring expert knowledge. The goal of this study was to develop a protocol for assessing stream channel instability that is accurate, time-efficient, and does not require previous experience in identifying stream channel characteristics. This goal was achieved by first accomplishing the following objectives:

1) Quantitatively assess lateral migration of the Bull Run stream channel using aerial photographs from 1938 to 2006. This allows identification of sites that are undergoing the greatest amount of movement and therefore the most unstable portions of the stream.

2) Quantitatively assess channel instability through hydraulic geometry measurements, sediment transport calculations, and erosion rates.
Site Description

The city of Oxford and the surrounding area was primarily agricultural prior to development. The population density of Oxford in 2007 was 3,810 persons per square mile (U.S. Census Bureau). According to a population density shapefile of Butler County, the population density of Bull Run’s watershed in 2000 was 1,198 persons per square mile. From 1960 to 1970, during which time the majority of development immediately adjacent to Bull Run occurred, the population of Oxford more than doubled. Between 2000 and 2009, Oxford’s population increased by about 20% (U.S. Census Bureau).

Bull Run has undeveloped and agricultural land in its headwaters. Land use immediately adjacent to the study section of the stream is mainly residential and commercial (Figure 2). The drainage area is 1.8 mi². Average annual precipitation in Oxford is about 33 inches. The watershed is comprised of approximately 10% impervious surfaces (2001 National Land Cover Dataset). The length of the study section is approximately 4000 feet (Figure 1). In this area the channel ranges from 30 to 55 feet wide and flows through a residential area with very little riparian corridor and houses as close as 43 feet from the bank. The banks are composed primarily of glacial till. There are multiple stormwater inputs along Bull Run, as well as a few small tributaries. In many places stream bank stabilization techniques (block walls, poured concrete, and rip-rap) have been deployed to help stabilize the banks. Recent attempts to stabilize banks may have also accelerated or intensified the erosion of portions of the bank downstream. As a result of bank erosion, one bordering house has been condemned. Other properties may be vulnerable in the future. Chunks of soil as large as one by three feet have sloughed off the top of banks. In January, 2009 a telephone pole had to be repositioned when the stream bank reached less than one foot from the pole.
Figure 2. Land use within the watershed of Bull Run as of 2006.
METHODS

Quantifying Historical Channel Migration

Channel migration was determined using aerial photographs from 1938, 1951, 1968, 1979, 1995, and 2006 (USGS). The photographs were georectified and the center of the stream channel was digitized using ArcGIS. GPS points were obtained at the thalweg of each measured cross-section (Figure 3). The digitized stream channels were layered, allowing the distance of lateral movement between various years to be measured at the GPS points of the cross-sections. Lateral migration rates (feet/year) were calculated so as to be compared to one another.

Each aerial photograph used to assess channel migration was also used to delineate three types of land use within Bull Run’s watershed: forest, agriculture and developed. The landuse was digitized using ArcGIS and area of each of the three newly created polygons was determined and calculated as a percentage of the total area of the watershed.
Figure 3. Black line is outlining the watershed of Bull Run. Numbers refer to locations of measured cross-sections.
Quantifying Channel Stability

Eight cross-sections were surveyed to determine the shape of the channel in various places along the study section (Figure 3). Bankfull elevation, depth, and discharge were also determined using the surveyed cross-sections to be used in sediment transport calculations. Bankfull elevation was estimated from the surveyed cross-sections. Incipient floodplains were used to determine bankfull elevation in some locations (Figures 4 and 7). Change in bank slope was used to estimate bankfull elevation in other locations (Figures 5 and 6). Pebble counts (n = 100) were taken at four of the eight cross-sections to determine median grain size (Wolman, 1954). The longitudinal profile was also surveyed, which was used to determine the overall slope of the section, as well as the slope between smaller sections of the study section (Figure 8).

Figure 4. Profile of cross-section 4 and estimated bankfull elevation.
Figure 5. Profile of cross-section 5 and estimated bankfull elevation.

Figure 6. Profile of cross-section 6 and estimated bankfull elevation.
Figure 7. Profile of cross-section 8 and estimated bankfull elevation.

Figure 8. Longitudinal profile of the study section of Bull Run. Distance zero is the beginning of the study section, immediately upstream of Bull Run’s confluence with Collins Run.
At sites where pebble counts were conducted, cross-sectional stream power ($\omega_l$) was calculated using the following formula:

$$\omega_l = \rho_w \times g \times Q_{bf} \times S$$  \hspace{1cm} (1)

where, $\rho_w$ is density of water (kg/m$^3$), $g$ is gravitational acceleration (m$^2$/s), $Q_{bf}$ is bankfull discharge (m$^3$/s) (estimated using cross-section profiles), and $S$ (m) is slope (Rhoads, 1987).

In addition, the shear stress ratio, $\tau_e$, was calculated as another indicator of stream channel stability (Olsen et al., 1998). The shear stress ratio is defined as:

$$\tau_e = \frac{\tau_o}{\tau_c}$$  \hspace{1cm} (2)

where $\tau_o$ = average boundary shear stress, and $\tau_c$ = critical shear stress.

$$\tau_o = \gamma \times R \times S$$  \hspace{1cm} (3)

where, $\gamma$ is specific weight of water (kg/m$^3$), $R$ is hydraulic radius, and $S$ is slope and

$$\tau_c = \theta \times (\gamma_s - \gamma) \times D$$  \hspace{1cm} (4)

where, $\theta$ is Shield’s parameter, $\gamma_s$ is specific weight of sediment (kg/m$^3$), and D (mm) is median grain size.

The grain size at the threshold of motion was determined using the Sediment Equations version 4.0 workbook (Mecklenburg and Ward, 2007). This worksheet uses Shield’s threshold of motion equation,

$$D_s = \frac{\tau}{((\rho_s - \rho) \times g \times S_p)}$$  \hspace{1cm} (5)

where $D_s$ is the diameter of sediment particle (mm), $\tau$ is shear stress (N/m$^2$) ($\rho \times g \times \text{depth} \times \text{slope}$), $\rho_s$ is density of sediment (2560 kg/m$^3$), $\rho$ is density of water (1000 kg/m$^3$), $g$ is gravitation acceleration (9.8 m/s$^2$), and $S_p$ is Shield’s parameter (typically in the range of 0.04 to 0.07).

At cross-sections 3, 5, and 6, bank height (m), bank angle (°), bank toe angle (°), and bank toe length (m) were measured to calculate factor of safety. In addition to the model, bank erosion was monitored through the installation of erosion pins in grid formation into the side of exposed banks, at four erosion “hotspots” (Figure 9). Pins were inserted horizontally into the stream bank flush with the soil surface. Depending upon the area of bank exposed, pins were
spaced between 1.5 to 3.5 feet apart in grids consisting of 9 to 14 pins. Pins inserted into banks possessing non-homogenous material were noted in order to account for differences in erosion rates produced by differences in soil cohesion. Pin exposure was measured at various time intervals to indicate amount of soil loss over time. Pins were repositioned flush with the bank after measurements were recorded. The pins were installed in June, 2008 and monitored approximately every 4-6 weeks from June, 2008 to February, 2009.

Figure 9. Erosion monitoring pin grid, indicated by arrows. Orange flagging indicates location of erosion pin.
RESULTS

Channel Migration

Over the sixty-eight years of available aerial photographs (1938-2006) the channel of Bull Run has undergone substantial lateral migration (Figure 10). Rates of lateral migration varied among aerial photograph intervals and individual cross-sections within each time period. For most cross-sections, time periods of 1951 to 1968 and 1968 to 1979 experienced the greatest rates of average yearly lateral migration (Figure 11). Averaging the yearly rates of lateral migration of all cross-sections for each time interval revealed that the 1979 to 1995 time period had the lowest rate of yearly lateral migration (Figure 11). Almost all cross-sections also individually experienced the lowest rates of lateral migration during this time period (Figure 10). Since 1979, cross-sections 3 and 8 have experienced the greatest average yearly migration rates (Figure 12).

The photograph intervals that experienced the greatest movement (1951-68 and 1968-79) coincided with the time period of greatest initial urban development within the watershed (Figure 13). The photographic interval from 1938 to 1951 also had substantial migration, 2.35 ft/yr, as agriculture was the original disruption to the natural landscape. The progression of land use within the watershed of Bull Run can also be viewed visually (Figures 14-19) as well as the corresponding lateral channel migration (Figures 20).
Figure 10. Lateral migration rates (ft/yr) for each cross-section at each photographic interval.
Figure 11. Average lateral migration rates of all cross-sections per time period.
Figure 12. Average migration rates at all cross-sections between 1979 and 2006.
Figure 13. Percentage of Bull Run’s watershed allocated to each land use for each aerial photograph.
Figure 14. Land use of the Bull Run watershed in 1938 over a 1938 aerial photograph.
Figure 15. Land use of the Bull Run watershed in 1951 over a 1951 aerial photograph.
Figure 16. Land use of the Bull Run watershed in 1968 over a 1968 aerial photograph.
Figure 17. Land use of the Bull Run watershed in 1976 over a 1976 aerial photograph.
Figure 18. Land use of the Bull Run watershed in 1994 over a 1994 aerial photograph.
Figure 19. Land use of the Bull Run watershed in 2006 over a 2006 aerial photograph.
Figure 20. 2006 aerial photograph showing the study section of Bull Run and digitized overlays of channels from 1938, 1951, 1968, 1979, 1995, and 2006.
Channel Stability

*Sediment Transport*

In addition to determining channel migration rates, it is also useful to understand the current conditions of a stream channel. Sediment transport calculations reveal the amount of available force within the channel able to do work, that is, mobilize bed materials. Currently, the amount of boundary shear stress available within the channel of Bull Run at bankfull conditions is much greater than the critical shear stress. Typically, Shield’s parameter lies within the range of 0.04 to 0.07. Using the Sediment Equations worksheet, Shield’s parameter at cross-sections within Bull Run ranged between 4 to 36 times greater than the typical values (Table 1). In addition, using a typical Shield’s parameter value of 0.04, the particle size at the threshold of motion ranged from 6 to 25 times larger than the current D_{50} particle size.

Shear stress ratios (boundary shear stress/critical shear stress) were all found to be well above 3, indicating that at bankfull conditions the entire channel bed may be mobilized and moved downstream at all cross-sections (Table 2).

Table 1. Parameters included in Sediment Equations Spreadsheet.

<table>
<thead>
<tr>
<th>Cross-section #</th>
<th>D_{50} (mm)</th>
<th>Slope</th>
<th>Avg. depth at bankfull (m)</th>
<th>Shield's parameter, θ</th>
<th>Particle size at threshold of motion using theta of .04 (mm)</th>
<th>Shear stress ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.7</td>
<td>0.01</td>
<td>0.80</td>
<td>1.03</td>
<td>121</td>
<td>14.14</td>
</tr>
<tr>
<td>5</td>
<td>6.4</td>
<td>0.02</td>
<td>0.75</td>
<td>1.43</td>
<td>227</td>
<td>39.08</td>
</tr>
<tr>
<td>6</td>
<td>6.4</td>
<td>0.01</td>
<td>0.33</td>
<td>0.31</td>
<td>50</td>
<td>7.73</td>
</tr>
<tr>
<td>8</td>
<td>6.7</td>
<td>0.01</td>
<td>0.28</td>
<td>0.25</td>
<td>42</td>
<td>7.23</td>
</tr>
</tbody>
</table>
Erosion Monitoring

Using the Bank Stability and Toe Erosion Model (Simon and Curini, 1998), the calculated factor of safety values for the three banks measured were determined to be well within the stable range (Table 3). That is, the banks were not in danger of mass failure. The bank erosion pins showed no movement until the winter months. During December, 2008 and January, 2009, pins were found up to 6 inches out from the bank as well as buried under soil fallen from the top of banks. After the winter months there was no more movement.

Table 2. Factor of safety values determined using the Bank Stability and Toe Erosion Model (Simon and Curini, 1998)

<table>
<thead>
<tr>
<th>Cross-section #</th>
<th>Bank angle</th>
<th>Toe angle</th>
<th>Factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>53.22</td>
<td>24.44</td>
<td>5.28</td>
</tr>
<tr>
<td>5</td>
<td>61.99</td>
<td>38.97</td>
<td>14.09</td>
</tr>
<tr>
<td>6</td>
<td>59.76</td>
<td>66.66</td>
<td>4.63</td>
</tr>
</tbody>
</table>
DISCUSSION

A channel in a healthy state of dynamic equilibrium naturally moves laterally; however it should retain its cross-sectional shape and not display symptoms of channel instability (e.g. widespread mass wasting, severe undercutting of banks) as have been observed in Bull Run. While there are no baseline data (i.e. prior to agriculture) for lateral migration rates this study is able to characterize lateral channel migration comparatively, within the 1938 to 2006 time frame, as land use becomes increasingly urbanized.

Analysis of lateral migration rates over the past sixty-eight years in conjunction with an analysis of land use change within the watershed of Bull Run illustrate the effect of land use and increased urbanization on channel stability. Rates of lateral migration were consistently as high as 3.5 to 4.5 ft/yr from 1938 to 1979 (Figure 10). Land use analysis shows that the years following the initial spike in urban development coincide with the greatest rates of lateral migration. During the 1979 to 1995 photographic interval, there is a dramatic decrease in yearly lateral migration rates (Figures 10 and 11). This decrease in lateral movement likely indicates the period of time in which the channel began incising. During this period of time, immediately following the most intensive period of urbanization within the watershed, stream power stopped eroding banks and depositing sediment (which previously caused lateral migration) and began eroding the stream bed. The incision may be related to downcutting in Four Mile Creek, into which Bull Run flows. The increased rate and amount of runoff caused by increased urbanization and impervious surfaces caused increased stream power and shear stress. This increase in stream power, coupled with a dramatic decrease in sediment input after construction ceased, forced the bed to begin incising.

After incision had occurred for perhaps a couple decades, banks became unstable as they were undercut eventually causing mass wasting, which again contributed to lateral movement. This is suggested by the increase of yearly lateral migration rates following the photographic interval of 1979 to 1995. Mass wasting provides additional sediment inputs to the stream thereby pausing incision rates. Banks that are in the process of massive erosion are currently still present along much of the study length of Bull Run.

In addition to channel migration, sediment transport calculations also indicate channel instability. The shear stress ratio calculated for bankfull conditions was well above 1 at all cross-
sections, indicating a degrading stream. In addition, all shear stress ratios were above 3 as well, which suggests that at bankfull conditions, all bed material may be mobilized. In addition, particle sizes at the threshold of motion were found to be as much as 25 times larger than the current median grain size at each cross-section (Table 1, Figure 22). Thus sediment transport calculations reveal that Bull Run is currently an unstable stream channel.

Erosion pin grids were originally included in this study to quantify the erosion rates of the banks. However, monitoring of erosion rates was a time-consuming and rather uninformative method. Pins needed to be checked at least twice a month in order to obtain detailed information on erosion rates, but movement was not detected until the winter months (December 2008 and January 2009). This winter movement may have been due to freezing and thawing of the banks which could push the pins out from the bank. Therefore, it is uncertain whether pins found 6 inches out from the bank had actually lost 6 inches of soil around them because this type of dramatic pin movement was only observed during December and January. The majority of banks were losing soil from the tops of their banks and not from the sides of the banks, which is where the pin grids were located. In addition, the Bank Stability and Toe Erosion Model (Simon and Curini, 1998) was not useful in this study. Because banks in Bull Run are not undergoing mass wasting by falls or topples (i.e. large chunks of earth becoming dislodged from the bank due to the presence of vertical cracks) the model used did not identify the banks as unsafe. However, the severe mass wasting observed in many locations in Bull Run indicates a degree of instability.
Managing streams in urban environments is a difficult task because every scenario is

different and complex; urbanization does not affect all streams in the same way. Conducting an
assessment of channel instability within an urban stream channel is both challenging and time-

consuming. However, this evaluation is necessary to protect land and human infrastructure,
rehabilitate a channel, and to preserve future water quality. Stormwater managers, urban
developers, city municipalities, and stream restorers are all faced with similar constraints: lack of
time and appropriate resources to conduct a channel stability analysis.

The purpose of the urban stream channel stability assessment protocol is to make
identification of unstable channels accurate, time-efficient, and without requiring previous
experience in identifying stream channel characteristics. If staff is available, these assessments
may be made by local agencies without needing the assistance of an outside consulting firm.
Locating unstable channels in an area can then allow rehabilitation/management techniques to be
prioritized to those channels most in need. In addition, land adjacent an unstable channel should
not be further developed. Knowing a channel is already unstable may also be useful in future
stormwater management practices.

While this protocol was developed within Bull Run, it can be applied in other urban
streams and may be used in riparian land-use planning, application of stormwater best
management practices on both a local and watershed scale, as well as in identifying appropriate
stream rehabilitation or bank stabilization efforts. The protocol is described below.
Urban Stream Channel Stability Assessment Protocol

I. Channel Migration

Aerial photographs can be obtained at no or low cost and the lateral movement of a channel can be assessed without leaving the office. This preliminary assessment will reveal how long the watershed of a stream has been urbanizing and if the lateral migration of the stream is occurring at an increasing or decreasing rate. This assessment can potentially assess the degree of changes expected in the future. In addition, specific sites that are experiencing the most severe channel instability can be identified.

Steps to Completion:

1. Obtain photographs (can be found at city municipalities, county engineers offices, local universities and libraries, and with the USDA) of study stream during winter months. Photographs taken during winter months when leaves are not present on trees are essential in being able to digitize the stream channel.
2. Assign photographs a coordinate system using GIS software.
3. Digitize stream channel centerline (or both sides of channel if possible).
4. Measure lateral movement at multiple, consistent points throughout the study reach for each photographic interval.

II. Sediment Transport

Sediment transport calculations are possible after completion of a few simple data-collection procedures. Sediment transport calculations are integral in determining channel stability because they reveal what size sediment is mobile and how much power the flowing water possesses.

Steps to Completion:
1. Survey cross-sections within study section. The number and location of cross-sections will depend upon the length of study section, where surveying is physically possible, and where information is most desired (e.g. an eroding portion of the stream near infrastructure may be a priority location to survey a cross-section). The study section should include at least an entire meander (i.e. two bends). For basic information regarding surveying and choosing an appropriate location refer to the USDA technical report: *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson et al., 1994). It is important to note that to properly assess channel stability, the entire channel cross-section from bank to bank must be surveyed. This will be discussed further below.

2. Measure the longitudinal profile (slope) by gathering elevations throughout the study section.

3. Conduct a pebble count at each cross-section. A sample size of 100 has found to be adequate for using these data in sediment transport calculations. A pebble count can be completed using the methods of Wolman (1954).

4. Determine bankfull channel depth. Bankfull depth will allow for calculation of sediment transport at bankfull discharge. If a channel is unstable, it is very likely that it is also incised. Therefore, determining bankfull depth within an incised channel may not be possible as the incised stream rarely overflows its banks. If it is concluded that the stream channel is incised, bankfull may not exist and the “modern” bankfull height must be determined. This can be identified as a bench or step in elevation on either side of the channel bed where the bank angle becomes horizontal or nearly so. Because the channel is incised, much higher banks will exist beyond this bench or incipient floodplain. Other indications of bankfull location include: undercut banks, height of water marks or debris, recently deposited fine sediments, point bar elevations, a change in vegetation or bank material (Sherwood and Huitger, 2005).
III. Degree of Incision

Incision of a channel is an important indicator of channel instability. Water flowing through an incised channel will rarely if ever reach the top of the channel’s highest banks. An incipient floodplain (bench) may be observed, but the length of this floodplain will most likely be shorter than the width of the current channel. In addition, higher bank elevations will exist beyond the insipient floodplain.

Steps to Completion:

1. If it was not possible to survey the entire channel due to obstacles or severe incision, elevations of the entire channel must be estimated. This can be done either by measuring the height of bank beyond what was possible to survey or by obtaining LiDar data or other fairly accurate elevation data set.

2. Calculate the mean depth, width, cross-sectional area, or discharge of this bankfull Bankfull elevation in this case referring to the traditional definition of the discharge that just fills the channel without spilling over the bank.

3. Compare values of the mean depth, width, cross-sectional area, or discharge at bankfull elevation and the contributing drainage area of the stream at the point of the cross-section to regional curves for bankfull characteristics. The regional curves for Ohio are provided in the UGSG publication, *Bankfull Characteristics of Ohio Streams and Their Relation to Peak Streamflows* (Sherwood and Huitger, 2005). Regional curves for bankfull characteristics are available in other states as well.
CONCLUSIONS

Assessments of channel migration and sediment transport calculations were found to be the most indicative characteristics of channel stability within Bull Run. These assessments, combined with an investigation of land use change, yielded overwhelming evidence that Bull Run is an unstable channel and put forward reasons for why Bull Run is currently unstable. Determination of erosion rates using erosion pins was not effective. Furthermore, the time spent in this study employing methods that provided no or very few data, suggests that a simplified, time-efficient protocol is necessary for further studies of channel stability.

The stream stability assessment protocol described in this study can provide stormwater managers, urban developers, city municipalities, stream restorers, etc. with a tool that can be applied in streams both effectively and efficiently. The stability protocol can identify processes occurring within the stream channel to assist in making stream management decisions.

Over the course of this study, desired data were not always available. For example, it was not possible to create a rating curve (a graph relating discharge and stage) which would aid in describing the relationship between frequency of precipitation events and their effect on erosion and sediment transport. In addition, the frequency of the bankfull elevations used in the sediment transport calculations is not known. Because of the difficulty in identifying bankfull elevations in an incised channel, this study might be improved by gathering daily sediment samples to determine the effective discharge. Unfortunately, effective discharge measured through water sampling is time-consuming and costly to conduct.

This study collected sediment information at four locations. If more detailed knowledge is desired, it would be useful to collect additional sediment data to understand how sediment transport differs among sites within the same stream. These data would reveal whether both stable and unstable sites exist within the same stream channel. However, while improvements can be made to this study, the methods employed were able to identify characteristics of Bull Run’s channel that were indicative of instability. In addition to identifying channel instability, this study focused on identifying practical and effective methods in an effort to be applicable for practitioners in the field.
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