Exploring the Impacts of Urban Development on Fluvial Systems in a Karst Landscape, Burd Run Watershed, South-Central Pennsylvania

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ABSTRACT

Land use is among the most significant variables influencing the various components of the hydrologic budget. Urbanization, in particular, has been shown to result in increased storm runoff, flood frequencies, and peak discharges, resulting in changes to stream channel geomorphology and degradation of aquatic ecosystems. Because of the unique hydrology associated with karst geology, the impacts of urbanization on stream geomorphology in karst landscapes may be different than in non-karst watersheds. In order to explore the hydrologic impacts of urbanization, TR-55 was used to model the amount of runoff generated from a 100-acre area under different intensities of urban development. Results were qualitatively discussed in the context of a karst environment. In order to explore the impacts of urbanization on stream geomorphology in a karst landscape, four study reaches were chosen within the northern portion of Burd Run Watershed, South-Central Pennsylvania. Reaches were chosen upstream of development and downstream of development in losing and gaining reaches of the stream, and cross-sectional locations were identified in riffle, pool, and run sections of each reach. Cross-sectional bankfull geometry measurements were recorded in the riffle section of each reach, and measurements were compared to regional bankfull geometry curves. Results from this study indicate that the karst geology has a substantial influence on the surface water patterns in Burd Run Watershed, which complicates the study of urban impacts on stream geomorphology.
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1.0 INTRODUCTION

Although urban development comprises just 2% of the earth’s surface, its ecological impacts are disproportionately substantial because of the major landscape transformations that occur due to urbanization (Paul and Meyer, 2001). Major transformations from one dominant land use to another severely disrupt the natural flux of a landscape, leading to pollution, habitat destruction, fragmentation, and ecological degradation (Leitao et al., 2006). Because land use is among the most significant variables influencing the various components of the hydrologic budget, fluvial systems are sensitive to land use changes (Ozturk et al., 2013), in particular, urbanization, which has been suggested to impact stream processes more than any other land use (Kang and Marston, 2006; Nelson et al., 2009).

Hydrologically, increases in storm runoff, flood frequencies, and peak discharge commonly occur alongside development because of increases in impervious surface area associated with urbanization (Booth, 1991). Stream channel geomorphology adjusts to accommodate increased storm flows and durations, resulting in increased bed and bank erosion, channel width and cross-sectional area enlargement, decreased sinuosity and large woody debris, and changes in sediment texture and stream flow composition (i.e. pool-riffle sequences) (Paul and Meyer, 2001; Allan, 2004; Cianfrani et al., 2007; Hawley et al., 2013). These changes can have profound impacts on the ecological integrity of a stream system by disrupting aquatic habitat, life cycles, and food webs (Booth et al., 2004; Hawley et al., 2013; Vietz et al., 2014).

Much research has been done attempting to understand the impacts of urbanization on fluvial geomorphology so that mitigation strategies can be more successfully implemented. However, karst landscapes present challenges in understanding the impacts of urbanization on stream channel geomorphology because of the unique hydrology in karst watersheds (White, 1988). Characterized by sinkholes, caves, crevices, and cavities, karst landscapes alter surface runoff patterns, typically resulting in increased infiltration and decreased surface runoff [VADCR, 2014], implying that perhaps the impacts of urbanization on stream channel geomorphology may vary in karst landscapes.

2.0 PURPOSE AND SCOPE

The purpose of this project was to explore the potential impacts of urbanization on surface water hydrology and stream channel geomorphology and explain how the results may be
influenced by a karst landscape. Because the period of investigation included only one week, the scope of the study was limited due to time constraints. Therefore, methods were developed for a full study, but carried out at a limited number of the field monitoring sites. Results include those limited data. The full study was developed to address the following research questions:

- How does urbanization impact storm flows based on hydrological models, and how might the results vary in a karst environment?
- How do channel dimensions differ between urban and non-urban land use conditions?
- How does measured channel geomorphology relate to hydraulic geometry curves of previous literature?
- What are potential ways in which a karst landscape influences the observed impacts of urbanization on stream channel geomorphology?

2.0 LITERATURE REVIEW

3.1 Urban Impacts on Fluvial Systems

In the United States, the highest rate of population growth has been occurring within and around urban areas (Gupta, 1984). The addition of new urban land to accommodate growing populations has replaced forested and agricultural land, thereby compounding the impacts of urbanization (Jantz et al., 2005). In particular, landscapes are being extensively altered by vegetation removal, land grading, and the construction of impervious surfaces, all of which can impact the hydrologic, geomorphic, and ecologic characteristics of fluvial systems (Hogan et al., 2014).

3.1.1 Urban Impacts on Hydrology

Increases in impervious surfaces associated with the construction of parking lots, buildings, and road networks are primarily responsible for changes in hydrologic dynamics occurring in watersheds undergoing urbanization (Chin, 2006). Impervious surface increases, in addition to soil compaction and loss of vegetation, lead to decreased evapotranspiration and infiltration, thereby resulting in increased surface runoff (Bonta, 2013; Ozturk et al., 2013). In streams and rivers, these hydrologic changes manifest as increases in peak discharge, and increased frequency and duration of bankfull flows, or those flows that occur just before overtopping the banks. Bankfull flows account for the majority of sediment transport and geomorphic change in a stream channel (Konrad and Booth, 2005). In addition to changes in
overland flow dynamics caused by increases in impervious surface, subsurface stormwater routing typically delivers excess stormwater directly into surface water systems during high flow events, further increasing peak discharge in streams and rivers during storm events (Walsh et al., 2005).

3.1.2 Urban Impacts on Stream Geomorphology

When the hydrologic characteristics and sediment supply of a fluvial system are disrupted by urbanization, the channel geomorphology of the system adjusts to accommodate these changes (Leopold, 1964). The mechanism for geomorphic change is driven by a balance of driving and resisting forces, with stream power representing the primary driving forces responsible for geomorphic alterations. Described as the ability of a stream to transport sediment or perform geomorphic work (Bizzi and Lerner, 2013), stream power ($\Omega$, kg m/s$^3$) has been observed to be a significant predictor of stream erosional capacity (Doyle et al., 2000; Larsen et al., 2006), and can be calculated as the product of discharge ($Q$, m$^3$/s), slope ($S$, m/m) and the specific weight of water ($\gamma$, kg/m$^2$/s$^2$) (Eq. 1) (Larsen et al., 2006).

$$\Omega = \gamma Q S \quad \text{Eq. 1}$$

Therefore, it can be inferred that with increases in peak discharge and frequency of bankfull flow events resulting from urbanization, stream power is increased, leading to a greater propensity for sediment transport and erosional capacity to occur within a channel.

Increased stream power due to urbanization is mainly responsible for the geomorphic changes that are most often observed within urban stream channels. The results of this erosive mechanism are most often cited in the literature, with the majority of studies illustrating that urbanization leads to stream channel enlargement, greater channel incision, enlarged sediment texture, homogenization of stream flow composition, and decreased sinuosity (Hammer, 1972; Mosley, 1975; Trimble, 1997; Pizzuto et al., 2000; Hession et al., 2003; Chin, 2006; Gregory, 2006; Kang and Marston, 2006; Cianfrani et al., 2007; Brown et al., 2009; Hawley et al., 2013).

Because urbanization typically causes unnaturally large, and often rapid, landscape disturbances, imbalances in stream geomorphology can occur, leading to channel instability that may persist for decades or longer if stream channel adjustment is restricted, or disturbances continue (Henshaw and Booth, 2000; Chin, 2006; O’Driscoll et al., 2010; Hawley et al., 2013). Characterized by bank failure and mass wasting events, channel instability, caused by the disequilibrium between the drivers and resisters of geomorphic change, leads to degradation of
the stream channel and increased sedimentation in downstream receiving waters (Paul and Meyer, 2001). Channel instability may also lead to challenges in protecting urban infrastructure such as bridges, sewers, and culverts from large mass wasting events (Hawley et al., 2013). In addition to these physical impacts occurring within fluvial systems due to urbanization, changes in the hydrologic and geomorphic characteristics of a watershed can have profound impacts on aquatic ecosystems.

3.2 Karst

Karst landforms refer to distinctive formations created by the dissolution of carbonate rocks and minerals when contacted by acidic water. Characterized by sinkholes, caves, crevices, and surface depressions, karst landscapes have a unique surface water hydrology with close interactions with groundwater (White, 1988). Because karst landscapes contain conduit like subsurface structures, increased infiltration occurs in watersheds underlain by carbonate bedrock, resulting in a redistribution of the rainfall-runoff patterns that would be typical of a non-karst watershed. With an increased proportion of the rainfall in a karst watershed infiltrating into groundwater, a decrease in runoff occurs at the surface, leading to decreased peak flows in streams and rivers (VADCR [accessed 2014]).

Reduced storm flows in a karst landscape imply that the degree of urban impact on stream geomorphology may be more variable as compared with a non-karst watershed. If a greater proportion of increased runoff generated by a developed area enters swallets (surface depressions exposed to the subsurface), cracks, or crevices, instead of flowing overland into rivers and streams, the surface impacts of urbanization may be diminished. However, in areas of intense development with a high percentage of impervious surface, it is likely that the karst landscape would have little effect on the increases of overland runoff due to urbanization. Additionally, stream geomorphology would be impacted by directly connected impervious areas in urban areas regardless of karst landforms.

Because of the hydrologic variability caused by karst landforms, uncertainty exists surrounding the impacts of land use change in karst watersheds. Although there has been a substantial amount of research done about karst and about the impacts of urbanization on fluvial systems, respectively, there has been very little attention given to the impacts of urbanization on fluvial systems in karst landscapes. Therefore, it was the purpose of this study to explore the impacts of urban development on stream geomorphology in the context of a karst environment.
4.0 STUDY AREA

Located in South-Central Pennsylvania, Burd Run Watershed drains an area of nearly twenty square miles. The headwaters of Burd Run begin on South Mountain where the watershed is heavily forested. After flowing through Michaux State Forest, Burd Run flows through a dominantly agricultural portion of the watershed and eventually enters the Borough of Shippensburg where it crosses the campus of Shippensburg University before flowing into Middle Spring Creek (Figure 1).

![Burd Run Watershed map](image)

**Figure 1** – Burd Run Watershed, the study area located in South-Central Pennsylvania (map produced by Molly Moore).

Because nearly half of the watershed is on state forest land, significant urban development within the southern portion of the watershed has not occurred, and will likely be limited in the future. However, commercial and residential land uses have been increasing rapidly in the northern portion of the watershed, mimicking urbanization trends that are currently occurring across the United States (Figure 2). New urban land increased by over five percent
within Burd Run Watershed in only five years between 2003 and 2008, and is projected to continue to increase if current growth trends in the region continue (Jantz et al., 2010).

The bedrock underlying Burd Run Watershed varies from quartzite dominated units in the southern portion, to carbonate dominated units in the northern portion, including limestone and dolostone (Figure 2). Due to the carbonate bedrock located in the valley of Burd Run Watershed, a significant number of karst landforms have formed within the limestone (Figure 2). However, the hydrologic effects of the karst landscape in Burd Run are difficult to isolate because of the additional influence of a thick layer of colluvium covering the carbonate bedrock at the base of South Mountain, typically resulting in longer subsurface residence time than is usually characteristic of groundwater in karst environments (Feeney, 2013).
At the surface, the hydrologic effects of the karst landscape can be observed by the limited streamflow in the downstream main channel of Burd Run, which in some reaches is ephemeral, despite the relatively large drainage area. This is true for the reach between Airport Road, and Route 11, where streamflow only occurs during the wet spring season (Figure 3) (based on personal observation and lecture notes from Feeney, 2013). In reaches where discharge decreases in the downstream direction, Burd Run is classified as a losing stream, or a stream whose surface water is lost to groundwater (Lindsey, 2005). Shortly after passing under Route 11, Burd Run becomes a gaining stream once again, or a stream that increases in discharge in the downstream direction. These gaining and losing distinctions in the Burd Run stream channel provide an interesting opportunity to investigate the impacts of urban development on stream geomorphology in the context of a unique karst environment.

5.0 METHODS
5.1 Hydrologic Modeling

The hydrologic modeling program TR-55 was used to investigate the impacts of land use on the rainfall-runoff relationship of a 100-acre area. A pre-development agricultural scenario and several different urban land use scenarios with varying intensities of development were modeled in order to replicate various zoning laws within Shippensburg, Pennsylvania (Table 1). The variables needed for the TR-55 model included the watershed area, weighted curve number, time of concentration, type of rainfall distribution, and frequency and duration parameters based on the design storms.

Table 1 – land use scenarios used to investigate the rainfall-runoff relationship from a 100-acre area.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Zoning Code</th>
<th>% Impervious</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>Row Crops</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>1-ac lots</td>
<td>R1</td>
<td>30</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1-ac lots</td>
<td>R1</td>
<td>45</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1/4-ac lots</td>
<td>R3</td>
<td>50</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>1/4-ac lots</td>
<td>R3</td>
<td>65</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>100 ac commercial</td>
<td>C1</td>
<td>70</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>100 ac commercial</td>
<td>C1</td>
<td>85</td>
</tr>
</tbody>
</table>
For this investigation, 24-hour design storms were used with frequencies of 2, 10, and 100 years. Localized rainfall intensity data from Shippensburg, PA, and based on the frequency and duration of the design storms, were gathered from the National Weather Service, operated by NOAA. Precipitation magnitudes that were used for the design storms included 2.85 inches, 4.13 inches, and 6.92 inches for the 2, 10, and 100 year storms, respectively.

The intensity of rainfall varies during a storm, and is represented by synthetic rainfall distributions developed by the Natural Resources Conservation Service. Each synthetic rainfall distribution is intended to represent, most closely, the pattern of rainfall intensity that occurs specific to a geographic region. The Type II rainfall distribution is the most intense, short duration rainfall, and is characteristic in the majority of the United States (USDA, 1986). Type II distribution was used in the initial investigation. However, Type I rainfall distribution, which is less intense and more characteristic of maritime regions, was also used as a strategy to better represent the rainfall-runoff relationship in a karst landscape (VADCR [accessed 2014]). By using the less intense rainfall distribution in a region that is characterized by more intense rain storms, a greater proportion of the modeled rainfall is expected to infiltrate, thereby better capturing the rainfall-runoff dynamics typical in a karst environment.

Time of concentration was estimated using the Kirpich equation (Equation 2) (Kirpich, 1940), where \( t_c \) is equal to the time of concentration (min), \( L \) is equal to the length of flow from the most remote point in the watershed to the outlet (ft.), and \( H \) is equal to the difference in elevation between the most remote point and the outlet (ft.).

\[
t_c = 0.0078 \left( \frac{L^3}{H} \right)^{0.385}
\]

Eq. 2

In order to estimate using Kirpich’s equation, the 100-acre area was assumed to be more or less square, with the longest flow path possible to be 2,952 feet. Several points were identified within Burd Run Watershed that could represent this flow path and the differences in elevation were recorded and averaged from a 10-meter digital elevation model.

Because much of the agricultural land in the Cumberland Valley is devoted to row crops, a curve number reflecting row crop agriculture in good condition was chosen for the pre-development scenario. Curve numbers for the urban scenarios were developed based on data from the National Engineering Handbook (NEH). Because the curve numbers listed in the NEH were developed assuming an average percent of impervious area, curve numbers needed to be recalculated based on the percent impervious area specific to each scenario. To do this, the
composite runoff curve number equation was solved backwards to obtain the pervious runoff curve number for each land use (Equation 3). After the pervious curve number was obtained, the equation was solved for composite runoff curve number using the percent impervious area given in each scenario.

\[
CN_C = CN_P + \left( \frac{P_{imp}}{100} \right) (98 - CN_P)
\]

Eq. 3

where:

- \(CN_C\) = composite runoff curve number
- \(CN_P\) = pervious runoff curve number
- \(P_{imp}\) = percent imperviousness

In order to contextualize the 100-acre runoff models, the National Streamflow Statistics program (NSS), issued by the United States Geological Survey (USGS), was used to model the total expected flood discharges for the entirety of Burd Run Watershed. NSS is the program used by USGS StreamStats to model runoff after basin characteristics are developed by the ArcGIS server. NSS contains all of the USGS-developed regression equations for estimating flood-frequency statistics (USGS, 2014). Although StreamStats gathers basin characteristics and runs the NSS program to develop storm discharges, basin characteristics were manually calculated using ArcGIS and entered into NSS directly because the StreamStats server was down during the period of study.

### 5.2 Site Selection for Data Collection

Four reaches were chosen in the northern portion of Burd Run Watershed in order to investigate the impacts of urbanization on the geomorphology of the main stem of Burd Run. Two study reaches were chosen in a losing stretch of Burd Run (labeled BR01 and BR02), while two study reaches were chosen in a gaining stretch of Burd Run (labeled BR03 and BR04) (Figure 3). Within the gaining and losing stretches of the stream, one study reach was chosen upstream of major development, while the other study reach was chosen downstream of major development. The study reaches chosen downstream of development contained at least one identified stormwater input, while the reaches upstream of development were absent of stormwater inputs within the reach length (Table 2). The longitudinal length of all reaches spanned at least twenty bankfull widths and included at least two riffle-pool sequences.
**Figure 3** – locations of reaches and cross-sections chosen for study in Burd Run Watershed, South-Central Pennsylvania (map produced by Molly Moore).

**Table 2** – characteristics of the study reaches in Burd Run Watershed. Drainage area and percent urban were calculated using ArcGIS, while the remaining characteristics were determined during field measurements.

<table>
<thead>
<tr>
<th>Reach</th>
<th>DA (mi²)</th>
<th>% Urban</th>
<th>Status</th>
<th>Stormwater Inputs</th>
<th>Dominant Riparian Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR01</td>
<td>14.6</td>
<td>7.1</td>
<td>Losing</td>
<td>N</td>
<td>Forested Forested</td>
</tr>
<tr>
<td>BR02</td>
<td>17.3</td>
<td>10.7</td>
<td>Losing</td>
<td>Y</td>
<td>Urban Forested</td>
</tr>
<tr>
<td>BR03</td>
<td>18.9</td>
<td>14.5</td>
<td>Gaining</td>
<td>N</td>
<td>Grass/wetland Grass/wetland</td>
</tr>
<tr>
<td>BR04</td>
<td>19.1</td>
<td>14.7</td>
<td>Gaining</td>
<td>Y</td>
<td>Grass Forest</td>
</tr>
</tbody>
</table>
Because the impacts of urbanization on fluvial geomorphology can be difficult to quantify without comparison or long term data, four study reaches in two nearby watersheds, Bulls Head Branch and Letort Spring Run, were chosen to contextualize the results obtained from Burd Run. Geologically, both Bulls Head Branch and Letort Spring Run Watersheds are characterized by carbonate bedrock and are underlain by several of the same bedrock formations that underlie that northern portion of Burd Run Watershed where the study reaches are located. In addition to their likeness in carbonate geology, Bulls Head Branch and Letort Spring Run were primarily chosen for comparison purposes because of their similarities to Burd Run in drainage area and shape, but varying levels of urbanization (Figure 4) (Table 3).

Figure 4 – land use for Burd Run, Bulls Head Branch, and Letort Spring Run Watersheds in Cumberland County, South-Central Pennsylvania (map produced by Molly Moore, land cover data acquired from the National Land Cover Dataset from 2011).
Table 3 – urban land use characteristics compared among Burd Run, Bulls Head Branch, and Letort Spring Run Watersheds in Cumberland County, South-Central Pennsylvania.

<table>
<thead>
<tr>
<th></th>
<th>Drainage Area (km²)</th>
<th>% Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burd Run Watershed</td>
<td>51.7</td>
<td>15.4</td>
</tr>
<tr>
<td>Bulls Head Branch</td>
<td>62.3</td>
<td>8.8</td>
</tr>
<tr>
<td>Letort Spring Run</td>
<td>56.5</td>
<td>42.3</td>
</tr>
</tbody>
</table>

Dominated by agricultural land, Bulls Head Branch provided a comparison watershed whose area is less influenced by urban development. Alternatively, Letort Spring Run provided a comparison watershed whose area is heavily influenced by urbanization, much more so than Burd Run (Table 3). By comparing the results from Burd Run to reaches influenced by a spectrum of development levels, the specific impacts of urbanization on stream geomorphology in Burd Run can be more accurately discussed in the context of nearby carbonate watersheds.

Study reaches were chosen in Bulls Head Branch and Letort Spring Run Watersheds at locations representing similar drainage areas to the study reaches in Burd Run Watershed (Figure 5). The criteria for choosing reaches in the reference watersheds focused primarily on drainage area so that stream channel geometry could be most effectively compared across sites. However, the limited scope of this project did not permit the time necessary to field verify the study reaches in the reference watersheds. Therefore, many characteristics that would be valuable for site selection if a full study were to take place, such as the gaining or losing status of the reaches, are unknown.
5.3 Field Methods

Within each of the four reaches in Burd Run, cross-sections were identified within a riffle, pool, and run section of the stream. Because of the limited time for the project, measurements were taken at the riffle sections only. Locating a riffle to measure within the losing reaches was difficult because there was no streamflow within this portion of Burd Run during the time of study. Therefore, riffle locations were visually estimated based on relatively shallow and narrow stream channel area. The following measurements were taken at each riffle cross-section:

**Figure 5** – locations of study reaches in reference watersheds, Bulls Head Branch and Letort Spring Run, chosen to represent similar drainage areas to the study reaches in Burd Run Watershed.
- **Depth cross-section** – a standard measuring tape was stretched from floodplain to floodplain across the channel to mark horizontal distance, while a stadia rod was used to measure the height from the tape measure to the bottom of the channel. These heights were subtracted from an arbitrary number to develop a representation of the cross-sectional shape and depth (Appendix 1).

- **Bankfull width** – bankfull height was identified using field indicators as described by Vermont Agency of Natural Resources (2009). These indicators included, in order of their weight given in the field, flat depositional benches or lateral bars, erosion or scour features, lower extent of persistent woody vegetation, and change on the bank from steep to more gentle slope (Vermont Agency of Natural Resources, 2009). The associated width was measured using a standard measuring tape and marked on the depth cross-section.

- **Wetted perimeter** – the wetted perimeter of the channel was measured using a standard measuring tape. Rocks were used to hold down the measuring tape under water.

- **Pebble count** – pebble counts were completed at the cross-sections using methods modified from Wolman (1954). Transects were established along the channel cross-section and a particle was chosen at random with every step taken. Particles were measured using calipers. If the particle chosen was too small to measure, it was classified as sand if it was grainy to the touch, or silt if it was smooth to the touch.

- **Manning’s roughness value** (**n**) – **n** was estimated based on channel bed and bank substrate texture and condition using the published table provided by Chow, 1959.

### 5.3 Derived Geomorphic Data

The following characteristics of cross-sectional channel geomorphology were calculated:

- **Width/depth ratio** – width to depth ratio was determined by dividing bankfull width by the mean bankfull depth as measured by the depth profile.

- **D<sub>16</sub>, D<sub>50</sub>, D<sub>84</sub>** – the **D<sub>50</sub>** refers to the median particle size, the **D<sub>16</sub>** refers to the diameter for which **16%** of particles are finer, and the **D<sub>84</sub>** to the diameter for which **84%** of particles are finer. The **D<sub>16</sub>, D<sub>50</sub>, and D<sub>84</sub>** were determined by plotting the size of sediment particles recorded from the pebble count data against cumulative percent of sediment particles.
- **Slope** – the average of several channel bed elevations were used to estimate the water surface slope using a 1-meter resolution digital elevation model.

- **Cross-sectional area** – bankfull cross-sectional area was calculated by adding the product of width and mean depth for each cross-sectional interval.

- **Bankfull velocity** – bankfull velocity was determined using Manning’s equation:
  \[
  V_{bf} = \frac{R^{2/3}S^{1/2}}{n}
  \]
  where \(V_{bf}\) is the bankfull velocity, \(R\) is the hydraulic radius, or the cross-sectional area divided by the wetted perimeter, \(S\) is the water surface slope, and \(n\) is Manning’s roughness coefficient.

**Bankfull discharge** – bankfull discharge was determined by the product of bankfull velocity and bankfull cross-sectional area.

### 5.4 Watershed Delineation

The drainage area at each cross section was an important characteristic needed in order to compare the relationship between geomorphic variables and drainage area to previous literature. Therefore, the watershed area for each cross-section was derived using the ArcHydro tools within ArcGIS 10.2. A digital elevation model with a resolution of 10 meters, available from the United States Department of Agriculture, Natural Resources Conservation Service, was used as the input in order to derive a flow direction surface, which was used, along with points representing the cross-section location, to establish a watershed boundary for each cross-section.

### 5.5 Land Use / Land Cover

Land use and land cover data from 2011 were used to estimate the amount of urban development within each of the cross-sectional watersheds. Although the spatial resolution of the National Land Cover Dataset (NLCD) has been found to underestimate low-density urban development (Irwin and Bockstael, 2007), the NLCD was used in this project because of its widespread availability. Temporally, the dataset is relatively up to date, however, would not be representative of new development added since 2011. Given more time, this dataset would be used as a base and updated using aerial imagery to resolve the resolution and temporal limitations.

### 5.6 Analysis

Hydrologic modeling results were entered into a database and visually compared. Qualitative descriptions were provided in order to justify possible discrepancies between
modeled results. Relationships between geomorphic variables measured at the cross-sections were compared using scatterplots. Relationships were qualitatively described. Geomorphic relationships were then compared to previous literature done in karst dominated watersheds (Agouridis et al., 2011).

6.0 RESULTS AND DISCUSSION
6.1 Hydrologic Modeling Results and Discussion

With the exception of Scenario 1, the curve numbers for all urban scenarios were higher than the curve number for the pre-development agricultural scenario. Surprisingly, the curve number calculated for Scenario 1, which included the least intense urban development, was lower than the curve number for the pre-development scenario. This may be due to the soil compaction taken into account in areas of agricultural land use. As expected, increases in urban intensity and percentage of impervious surface area among the six development scenarios resulted in increased curve numbers (Table 4). Because the curve number was the primary independent variable in the TR-55 model, changes in the curve number led to substantial differences in the volume of runoff and the peak discharge for all storm events (Table 4). To be expected, the higher the curve number, the larger the volume of runoff generated from the 100-acre surface area, leading to higher predicted peak discharges at the outlet of the watershed (Figure 6).

Table 4 – Results from TR-55 hydrologic modeling of six urban land use scenarios and one pre-development agricultural scenario for a 100-acre area.
As expected, the higher frequency storms produced less runoff and a lower peak discharge relative to the lower frequency storms (Figure 6). However, the percent increase in peak discharge was significantly greater in the 2-year storm than the lower frequency storms (Figure 7), indicating that bankfull flows, or those that occur every one to two years, experience the most significant percent increase in peak discharge as an effect of urbanization. Because bankfull flows are those flow events whose frequency and magnitude combine to account for the majority of sediment transport and geomorphic change in a stream channel (Konrad and Booth, 2005), it can be inferred that the large increases in the magnitude of 2-year storm events demonstrated by the TR-55 results would lead to a higher frequency of bankfull flow events, thereby increasing the propensity for geomorphic change within the stream channel.

Figure 6 – peak discharge generated from a 100-acre area with differing land use scenarios during a 24-hour 2-, 10-, and 100-year storm, as modeled by TR-55.
Figure 7 – percent increase in discharge generated from a 100-acre area with increasing levels of urban intensity during a 24-hour 2-, 10-, and 100-year storm as modeled by TR-55. Percent increase is based on the predevelopment agricultural scenario.

The modeling program TR-55 does not account for underlying geology. Therefore, the runoff generated from the 100-acre area likely overestimates the runoff that would be generated from a 100-acre developed area within Burd Run Watershed. This speculation is consistent with the results of the NSS model for Burd Run Watershed, which do take into account the carbonate geology and creates a discrepancy between the results of the two models. Peak discharge amounts for Burd Run Watershed as modeled by the NSS program are much lower than would be expected based on the runoff generated from the 100-acre area modeled with TR-55. For example, the peak discharge generated by TR-55 from only 100-acres of quarter-acre development with 65% impervious surface accounts for nearly half the peak discharge in the entire 12,736 acre Burd Run Watershed as modeled by NSS during a 24-hour 2-year storm (Figure 8). Although this discrepancy is believed to be due, in part, to the consideration of carbonate geology, it is likely that the spatial scale of the modeled watersheds also influenced the runoff generated from the modeled rainfall events. Just as antecedent moisture conditions and
rainfall distribution characteristics influence the volume and timing of stream discharge, so too do the size and shape of the watershed. Therefore, the consideration of carbonate geology cannot be solely attributed to the discrepancies in the modeled results obtained from watersheds of varying spatial scales.

Because a Type I rainfall distribution is characterized by a less intense rainfall pattern than a Type II rainfall distribution, using Type I reduced the amount of modeled runoff generated from the design storms. By using a Type I rainfall distribution in a Type II area, the reduced peak discharge may be more realistic relative to a karst environment (Figure 8), but likely not very accurate as this method does not take into account the underlying geology in any meaningful way other than reducing the volume of runoff. Additionally, in the areas of intense development, the runoff generated would likely not be influenced by the karst geology because of the higher percentage of impervious area. Therefore, this method would not be suitable for correcting for karst landforms in a heavily urbanized area.

![Graph showing peak discharge comparison](image)

**Figure 8** – peak discharge generated for current conditions in Burd Run Watershed as modeled by the National Streamflow Statistics program compared to peak discharge generated from a 100-acre area with quarter-acre development and 65% impervious surface as modeled by TR-55 with and without corrections for the karst geology.
Overall, the hydrologic modeling has illustrated that as the intensity of urban development increases, the volume of runoff increases, thereby resulting in a greater peak discharge in streams and rivers. Larger peak discharges increase stream power which results in greater sediment transport and erosive capabilities, the mechanism by which urban channels experience width and cross-sectional enlargement, larger grain sizes, and decreased sinuosity. Unfortunately, the modeling used for this project did not allow for an analysis of the impacts of urbanization on the hydrology of a karst watershed other than to indicate that peak discharge may be lower for all scenarios. Although this suggests that urbanization may not have as large an impact in karst landscapes, this may not be the case if the percent increase in peak discharge is similar to that of a non-karst watershed.

6.2 Channel Geomorphology Results and Discussion

The cross-sectional channel geometry measurements were compared to hydraulic geometry curves developed in a Kentucky region with extensive karst geology in an attempt to account for the karst landforms in Burd Run. However, bankfull discharge, as well as channel dimensions, measured in Burd Run were significantly lower than expected based on the hydraulic curves published by Agouridis et al., 2011 (Figure 9). This may be explained by the unique hydrologic conditions across karst terrains, as well as regional differences between the Kentucky and Pennsylvania study areas. Agouridis et al. (2011) found that in their study area, the bankfull channel dimension curves in the karst watersheds had no statistical difference from those of non-karst watersheds, implying that the karst landforms in that region had little influence over the surface hydrology. Alternatively, the results from this study indicate that the karst terrain has a substantial influence on the surface water hydrology of Burd Run Watershed.

The unique and variable geology and land use across Burd Run may be potential causes for the significant differences observed between these results and those reported by Agouridis et al., 2011. The northern and southern portions of Burd Run Watershed are drastically different from one another in land use and geology, contributing to unique hydrologic conditions. The deep layer of colluvium atop the carbonate bedrock in Burd Run also contributes to the unique local conditions. Therefore, it is implied that the influence of a karst landscape on surface water hydrology is unique to local geologic and land use conditions and characteristics that may be further impacted by regional differences.
The evidence of karst influence on the hydrology of Burd Run Watershed is further strengthened by the inconsistencies in downstream channel enlargement observed in Burd Run. Regional hydraulic geometry curves have demonstrated that increased channel dimensions typically occur in the downstream direction to accommodate increases in discharge from a larger drainage area. Although channel dimensions increased in the downstream direction in the losing and gaining cross-sections, respectively, channel dimensions were unexpectedly less at the two downstream most cross-sections, than the two upstream most cross-sections. This indicates that although the downstream most cross-sections were predicted to have the largest drainage area according to surface topography, interactions between the surface water and groundwater typical of karst environments increased the uncertainty of the drainage area because of the subsurface conduit-like flow patterns that were not accounted for when deriving drainage area from a digital elevation model.

The relationships between bankfull discharge and various bankfull dimensions observed in this study were more consistent with results from Aguiridis et al., 2011 (Figures 10 and 11). The downstream urban cross-sections located in reaches BR04 and BR02 had a greater width, depth, and cross-sectional area than their upstream urban counterparts. BR02 was 23.5%, 33.0%, and 83.3% larger than BR01 in width, depth, and cross-sectional area, respectively.

**Figure 9** – drainage area versus bankfull discharge in the context of the geometry curve developed by Agouridis et al., 2011.
BR04 was 76.3%, 38.0%, and 132.0% larger than BR03 in width, depth, and cross-sectional area, respectively. However, this enlargement cannot be solely attributed to the urban development because it is expected for channel dimensions to increase in the downstream direction. Additional data are needed to be able to conclude whether the stream channel enlargement downstream of urban areas is increased due to development.

**Figure 10** – bankfull discharge versus bankfull width in the context of the geometry curve developed by Aguiridis et al., 2011.

**Figure 11** – bankfull discharge versus bankfull area in the context of the geometry curve developed by Aguiridis et al., 2011.
The sediment size distribution revealed a greater proportion of small sediments at cross-sections in BR01 and BR02, the losing stream reaches that were dry during the study. At these cross-sections, the $D_{16}$ was the size of sand. This may be explained by the ephemerality experienced by this section of the stream. As streamflow lessens during dry periods, it is likely that fine sediments are deposited on the stream channel bed because of the decreased stream power, or ability of the stream to transport sediments. It is expected that the sediment distribution at these cross-sections would tend toward larger grain sizes during periods of higher streamflow. With the exception of the cross-section in reach BR02, the relationship between bankfull discharge and $D_{50}$ was expected, with the $D_{50}$ increasing with increases in bankfull discharge (Figure 12). This indicates that the cross-section in BR02 may be more heavily influenced by increased sedimentation and erosion due to upstream development, resulting in a greater amount of fine particles being deposited during no-flow periods relative to cross-section BR01, which was also located in a dry portion of the stream.

![Figure 12 - bankfull discharge versus $D_{50}$ for study cross-sections within Burd Run Watershed.](image)

7.0 LIMITATIONS

Because the period of study included only one week, the scope of this research was limited to very few study sites. Additional data may have provided a better understanding of
the geomorphic characteristics within Burd Run Watershed. However, the overall conclusion of the study, that the karst landscape has a heavy influence on surface water hydrology in Burd Run and complicates the study of urban impacts on stream geomorphology, likely would not have changed.

The drainage areas for the cross-sections were calculated using a 10-meter DEM. Although time did not permit the use of a finer resolution, a 10-meter resolution was likely too coarse a resolution to make fine distinctions in watershed boundaries with cross-sections so near one another. Additionally, subsurface drainage patterns due to the karst landscape and urban stormwater routing were not taken into account, resulting in decreased accuracy in the cross-sectional drainage areas. Similarly, the use of a DEM to remotely estimate water surface slope was not as accurate as if it was measured in the field. Although field measurements of channel slope to estimate water surface slope would have been more accurate, the lack of available assistance made it impossible to measure this in the field.

8.0 CONCLUSION

Because of the inconsistencies in the results due to the unique influence of the karst landscape in Burd Run Watershed, the impacts of urbanization on stream channel geomorphology were relatively inconclusive. Though it seems there may be channel enlargement downstream of urban development, this is inconclusive because of typical increases in the downstream direction due to increased drainage area. The sediment size distribution also provided evidence of geomorphological changes with increased urbanization. Larger particle sizes were inclined toward downstream urban areas, except in the downstream urban dry reach which included the smallest sediments, indicating increased deposition from fine sediments downstream of development. Additional data collected from Bulls Head Branch and Letort Spring Run Watersheds could provide contextual evidence of the degree of impact that urban development has on stream geomorphology in Burd Run.

Though the TR-55 modeling suggested that greater intensities of urban development result in a greater volume of surface runoff and larger peak discharge in streams, the modeling did not account for the carbonate geology. Perhaps the best strategy for further investigating the impacts of urbanization in a karst watershed is to have a better understanding of the surface water hydrology in the local karst environment. With a better understanding of the movement of
water through Burd Run Watershed, more accurate information about drainage areas and channel characteristics can be used to more successfully explore the impacts of urbanization on stream channel geomorphology in a karst environment.
9.0 REFERENCES


APPENDIX 1
CROSS-SECTIONAL CHANNEL PROFILES

Location: Study Reach BR01, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle

[Graph showing cross-sectional channel profile with arbitrary elevation and horizontal distance.]
Location: Study Reach BR02, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle

Graph showing arbitrary elevation and horizontal distance. The Bankfull level is marked on the graph.

Images of upstream and downstream views of the channel cross-section.
Location: Study Reach BR03, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle
Location: Study Reach BR04, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle

![Upstream View of Channel Cross-Section](image1.png)

![Downstream View of Channel Cross-Section](image2.png)
APPENDIX 2
CHANNEL CROSS-SECTION SEDIMENT DISTRIBUTIONS

Location: Study Reach BR01, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle
Location: Study Reach BR02, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle

![Graph showing percent finer than various particle sizes.](image-url)
Location: Study Reach BR03, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle
Location: Study Reach BR04, Burd Run Watershed, South-Central Pennsylvania
Flow Composition: Riffle

![Graph showing percent finer than particle size (mm)]