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Evaluation of the Impact of Land Use Change on Stream Flow of Monocacy Creek, Northampton County, PA

Junxing Lan
Dickinson College

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EVALUATION OF THE IMPACT OF LAND USE CHANGE ON STREAM FLOW OF MONOCACY CREEK, NORTHAMPTON COUNTY, PA

By Junxing “Angelo” Lan

Department of Environmental Studies

Prof. Candie Wilderman, Supervisor

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May, 9th, 2012
ABSTRACT

The objectives of this research were to understand and use HEC-HMS, a hydrological model developed by US Army Corps of Engineers, to develop a method to document land use changes over time in a small watershed, and to evaluate the impact of land use changes on the stream flow of Monocacy Creek, Northampton County, PA. Geospatial and land use data of the Monocacy Creek Watershed in 1958, 1986, and 2008 were collected and processed in ArcGIS. The input variables for model building in HEC-HMS were then calculated based on those GIS data. Three simulation models of the surface runoff and stream flow based on information from the three different years were then established and calibrated with the actual rainfall and discharge records. The calibrated models were then used to run the model for each land use scenario on the same rainfall event and the volume of generated runoff and the resulting stream flows are compared with one another. The results showed that as the urban development in terms of residential areas increased more than four times from 1958 to 2008, the runoff generated from the watershed area increased by almost six times from 1958 to 2008. In addition, an exponential relationship could possibly exist between the size of residential areas and stream flow discharge. Since the increase was consistent from 1958 to 1986 and from 1986 to 2008, we conclude that urban development has a significant impact on the stream flow of Monocacy Creek. Future study on the change of channel shapes and flooding patterns of Monocacy Creek can help fully assess the impact of the land use changes in the watershed.
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INTRODUCTION

The water in a stream comes mainly from channel flow and overland flow (Manning, 1996). For limestone streams, base flow from numerous springs along the stream supplied by groundwater makes up the majority of its channel flow (MCWA, 2003). The natural overland flow is primarily determined by the infiltration rate of the ground (Horton, 1933). With the construction of impervious surfaces such as roads and parking lots, the infiltration rates are altered. As a result, during precipitation events, most rainfall ends up as runoff to the streams nearby. It has also been demonstrated that runoff values are directly related to sub-watershed impervious surfaces (Schueler, 1987). Besides impervious surfaces, urban grasslands such as parks and lawns also have lower permeability than natural woodlands. Urban soils are more compacted during the construction process and the removal of topsoil can decrease the infiltration capacity and permeability, causing increased runoff (Pawlows & Pawlowski, 2007). In addition to urban development, agricultural land could also generate runoff from its irrigation. Compared to woodlands, croplands have lower permeability and generate more runoff (Pawlows & Pawlowski, 2007). Quite often crops are grown too close to the stream, which allows runoff to enter the stream more rapidly and without being filtered by streamside vegetation (Wildlands Conservancy, 1999).

Besides the volume of runoff, the runoff velocities and efficiency with which water is delivered to streams is also increased by urban development. In particular, the lag time between the onset of precipitation events and the peak of runoff is shortened as impervious surfaces increase (Shuster, 2005). Furthermore, increased urban development also contributes to decreased base flow of the local streams. Since less rainfall infiltrates through the soil to replenish the
groundwater due to urbanization, the base flow that depend on groundwater supply decreases (Spinello & Simmons, 1992).

In order to evaluate impact from urban development on runoff, many hydrologic models have been developed and used in various studies. The USGS Geo Stream Flow model was employed for modeling land use change effects on river flow in Mara River Basin, Kenya. The model operates in ArcView 3.2 and requires data in GIS format including remote sensing data, ground observation data and digital elevation data. It can produce a precipitation-runoff simulation that estimates the impact of land use (Mutie, et al., 2006). The HEC-HMS hydrological model developed by US Army Corps of Engineers is also widely used. For example, Dr Kawasaki et al. (2010) studied the precipitation and land use impact on stream flow in Srepok River basin, Vietnam, using the HEC-HMS model together with its GIS data model GeoHEC-HMS as the major tool for hydrological modeling.

The objective of this research is to understand the hydrologic modeling process and apply the model to evaluate changing land use impact over five decades on the stream flow of the Monocacy Creek in Northampton County, PA (Figure 1). The Monocacy Creek (Figure 2), a 4th order tributary of Delaware River, is one of only 56 limestone streams in the state of Pennsylvania (Wildlands Conservancy, 1999). Its watershed encompasses 48.8 square miles in eastern Lehigh and western Northampton counties, just south of Blue Mountain in southeastern PA. Its headwaters lie in the slate belt near the borough of Chapman (elevation 900ft.). From Chapman, the Monocacy follows a meandering 20.3-mile course through the limestone Lehigh Valley, to its confluence with the Lehigh River in the city of Bethlehem (elevation 212 ft.). In addition the Monocacy Creek is renowned for its natural stock of wild brown trout (MCWA, 2003). As a result,
Monocacy Creek is classified in Chapter 93 of the PA Water Quality Standards as a “High Quality-Cold Water Fishery” (HQ-CWF). The creek provides many services to the residents and visitors of Lehigh and Northampton Counties. Recreational uses and water withdrawal of the Monocacy are especially important to the region (Wildlands Conservancy, 1999).

![Map of Pennsylvania divided by county. The location of Monocacy Creek Watershed within Pennsylvania is indicated by the cyan patch on the map.](image)

**Figure 1:** Map of Pennsylvania divided by county. The location of Monocacy Creek Watershed within Pennsylvania is indicated by the cyan patch on the map.

![Map showing the Monocacy Creek Watershed boundaries and the streams.](image)

**Figure 2:** The Monocacy Creek Watershed boundaries and the streams.
Census data showed that from 1950 to 2010, the population of Bethlehem and Moore Townships increased by 48.2% from 73,005 to 108,210 (LVPC, 2012). Consequently the amount of land used for residential purposes increased with the population (Wildlands Conservancy, 1999). To a low order stream like the Monocacy Creek, the runoff resulting from such land use conversion could significantly impact the water quantity of the stream, and therefore change the habitat for trout and the recreational services provided by the stream (Horton, 1933). Moreover there are 15 private and public well supplies within the Monocacy Creek watershed. Water withdrawal from those wells will also be impacted due to lack of aquifer replenishment as impervious surfaces increase from urban development. Therefore how the land use has impacted the water quantity is crucial to the local community. A hydrological model of the Monocacy Creek Watershed can help assess impact of future land use scenarios and predict water availability of the stream. It can also provide valuable information on management of the ecosystem that depends on the stream. In addition, since land use impacts stream flow differently from one watershed to another due to differences in the watershed’s landscape and hydrogeological characteristics, model results based on other watersheds might not be applicable to Monocacy Creek (Cheng et al., 2007). Therefore, the purpose of this project was to develop a customized model for Monocacy Creek that would reflect relationships between land use and stream flow, and therefore help project the impact of future changes.

**METHODOLOGY**

The integration of two software programs forms the main structure of the research: HEC-HMS as the hydrological simulation model and ArcGIS as the data management and processing tool. HEC-GeoHMS is the ArcGIS-based system application that is extensively used in
this research to generate and process geospatial data of the watershed such as the stream flow path, watershed boundary, sub-basins, elevations, soil type and rock type (Kawasaki et al., 2010). As one of the major challenges, data searching is a critical part of this research. Information on the topographic and geologic characteristics of the Monocacy Creek watershed, together with the land use and rainfall are three main sets of data that are needed. Data obtained are then processed in ArcGIS to generate the required parameters for model input.

**Data collection**

Land use data of the watershed were obtained for 1958, 1986 and 2008 for comparison. The chosen periods are approximately 25 years apart in order to capture significant changes of land use. The Lehigh Valley Planning Commission (LVPC) kindly provided the GIS layer of land use in the years 1986 and 2008 (Romig, 2011). Since no digitized land use data before 1986 were available, historical aerial photographs of the watershed in the year 1958 were obtained from Penn Pilot Photo Center, an online aerial photographic resource (Pennsylvania Geologic Survey, 2011). The aerial photographs were then digitized in ArcGIS to capture geometry and attribute data for land use categorization. Geospatial data of landmarks in the watershed such as highways were the major references for the digitization of the aerial photographs.

The land use categorization for the three land use years follows the Perkiomen Creek Plan developed by LVPC to classify land use in the Delaware River Basin (LVPC, 2009). As shown in Table 1 there are 13 land use categories. The residential area (categories 4, 5, 6) and agriculture land (category 3) are the two major land use types in the area.

<table>
<thead>
<tr>
<th>Land use categories</th>
<th>Land use type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Woodland</td>
</tr>
<tr>
<td>2</td>
<td>open/vacant space</td>
</tr>
</tbody>
</table>
Other than the land use data, LVPC also provided the hydrologic soil group layers of the watershed. Since the infiltration rate of soil depends on subsurface permeability and surface intake rate, soils are classified into four hydrologic soil groups, namely A, B, C, and D according to their minimum infiltration rate (SCS, 1986). The GIS layer contains the distribution of the hydrologic soil groups in the watershed area.

Furthermore, in order to create the basin model to generate runoff simulation in HEC-HMS, parameters reflecting the physical characteristics of the watershed have to be computed in ArcGIS. A Digital Elevation Model, or DEM, in the resolution of 30 feet by 30 feet of the Monocacy Creek watershed area was obtained from the USGS National Elevation Dataset. The DEM describes the terrain of the watershed and is essential for the basin model (US Army Corps of Engineers, 2010b). The DEM was then processed using HEC-GeoHMS to find the stream path, the watershed boundary and basin slope. The watershed was then further divided into 53 sub-basins based on the terrain and flow path. The length of the stream segment and the area of the sub-basins were calculated through HEC-GeoHMS.

The breakdown between the three residential densities is as follows: Low Density = less than or equal to 2 dwelling units per acre; Medium Density = between 2 and 5 units per acre and High Density = greater than or equal to 5 units per acre. (Romig, 2011)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>agriculture</td>
</tr>
<tr>
<td>4</td>
<td>low residential</td>
</tr>
<tr>
<td>5</td>
<td>medium residential</td>
</tr>
<tr>
<td>6</td>
<td>high residential</td>
</tr>
<tr>
<td>7</td>
<td>industrial</td>
</tr>
<tr>
<td>8</td>
<td>commercial</td>
</tr>
<tr>
<td>9</td>
<td>institutional</td>
</tr>
<tr>
<td>10</td>
<td>big impervious</td>
</tr>
<tr>
<td>11</td>
<td>water body</td>
</tr>
<tr>
<td>12</td>
<td>transportation</td>
</tr>
<tr>
<td>13</td>
<td>quarry/mine</td>
</tr>
</tbody>
</table>

Table 1: Land use categorization for Monocacy Creek Watershed (Romig, 2011).
The stream flow discharge record was also obtained from USGS Monocacy Creek gauging station (US Geological Survey, 2012). The gauging station has kept a record of daily discharge from 1948 until the present. In addition, the rainfall record was obtained from National Oceanic and Atmospheric Administration's gauging station in Allentown (NCDC, 2012). The gauging station is about 10 miles away from the watershed area, but since it is the only gauging station with a complete daily rainfall record of the region throughout the years studied, we have to assume that the rainfall recorded by the gauging station reflects the rainfall events in the watershed area.

**Data assembly**

The Soil Conservation Service (SCS) curve number (CN) was used to measure land use. The SCS CN is an indicator of the land’s potential to generate surface runoff. It is determined based on land cover types, percentage of impervious surface (Table 2), the hydrological soil groups of the land, the treatment and the hydrologic conditions of the land. CN has a range from 0 to 100. A higher CN value indicates a lower the infiltration capacity. Thus it can be used to estimate runoff (SCS, 1986). For each type of land use and hydrologic soil group there is a corresponding CN value (Table 3). The total CN for each sub-basin is calculated by taking the average of area-weighted CN. The CN value and the impervious surface percentage for each sub-basin will also be the parameters characterizing land use in the HEC-HMS model.

---

2 Treatment describes the management of agricultural land such as what mechanical practices or management practices are used (SCS, 1986).
3 Hydrologic condition describes the effect of land cover and treatment on infiltration of the land (SCS, 1986).
4 See Appendix I.
<table>
<thead>
<tr>
<th>Land use type</th>
<th>Impervious surface percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>woodland</td>
<td>0</td>
</tr>
<tr>
<td>open/vacant space</td>
<td>0</td>
</tr>
<tr>
<td>agriculture</td>
<td>0</td>
</tr>
<tr>
<td>low residential</td>
<td>20%</td>
</tr>
<tr>
<td>medium residential</td>
<td>38%</td>
</tr>
<tr>
<td>high residential</td>
<td>65%</td>
</tr>
<tr>
<td>industrial</td>
<td>72%</td>
</tr>
<tr>
<td>commercial</td>
<td>85%</td>
</tr>
<tr>
<td>institutional</td>
<td>40%</td>
</tr>
<tr>
<td>big impervious</td>
<td>100%</td>
</tr>
<tr>
<td>water body</td>
<td>100%</td>
</tr>
<tr>
<td>transportation</td>
<td>30%</td>
</tr>
<tr>
<td>quarry/mine</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 2: Average impervious surface percentage of various land use types (Bartholomew, 2011).

<table>
<thead>
<tr>
<th>Land use type/Hydrologic soil group</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>woodland</td>
<td>55</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>open/vacant space</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>agriculture</td>
<td>76</td>
<td>83</td>
<td>86</td>
</tr>
<tr>
<td>low residential</td>
<td>68</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>medium residential</td>
<td>75</td>
<td>83</td>
<td>87</td>
</tr>
<tr>
<td>high residential</td>
<td>85</td>
<td>90</td>
<td>92</td>
</tr>
<tr>
<td>industrial</td>
<td>88</td>
<td>91</td>
<td>93</td>
</tr>
<tr>
<td>commercial</td>
<td>92</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td>institutional</td>
<td>76</td>
<td>84</td>
<td>87</td>
</tr>
<tr>
<td>big impervious</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>water body</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>transportation</td>
<td>72</td>
<td>81</td>
<td>85</td>
</tr>
<tr>
<td>quarry/mine</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Curve Number table with different land use types and hydrologic soil groups (Bartholomew, 2011).

In addition, discharge and rainfall data were converted into HEC-DSS data format for model input⁵. Each discharge entry measures the average flow rate during that particular day while each rainfall entry measures the incremental rainfall during that particular day (US Army Corps of Engineers, 2010a). Moreover, since the base flow is part of the stream flow that is not directly

⁵See Appendix II.
impacted by surface runoff, we subtracted base flow from the observed stream flow in order to have a more accurate comparison with the runoff volume. The base flow rate was estimated for each discharge record using the Web-based Hydrograph Analysis Tool (Lim, 2005). However, since the analysis model tends to overestimate base flow during storm events, the modified observed stream flow after subtracting the base flow tends to be underestimated (Lim, 2005).

Moreover, the stream channel slope, Manning’s coefficient n and channel width were estimated from the measurement of the stream in 1985 by LVPC (Bartholomew, 2012). The stream was divided into 100 segments and all the parameters were measured for each segment. Since the segmentation is different in the HEC-HMS model, we applied the average parameter value from measurement in 1985 to all stream segments in the HEC-HMS model. Those average values were then used in establishing the basin model.

Modeling

Three basin models were created in total for Monocacy Creek watershed. Each model uses parameters from either 1958, 1986 or 2008. Parameters measured or estimated were used as model input. Besides the parameter value, a specific method was selected to estimate total runoff and thus stream flow (Figure 3).
Since SCS CN is used as the variable to compare land use differences in 1958, 1986 and 2008, the SCS Curve Number method is used as the loss method for each basin model. The loss method calculates the actual infiltration (US Army Corps of Engineers, 2010a). For each sub-basin, the CN, impervious surface percentage and initial abstraction are required for modeling. CN and impervious surface percentage are provided by the HEC-GeoHMS as illustrated in the previous section. The initial abstraction is estimated from the CN (SCS, 1986). In addition, the SCS Unit Hydrograph method is used as the transform method to calculate the surface runoff (US Army Corps of Engineers, 2010a). Lag time is the only parameter for this transform method and it can be calculated in HEC-GeoHMS (US Army Corps of Engineers, 2010b).

Three different rainfall periods were selected from the rainfall record for each basin model. For model calibration purposes, the year of each rainfall period corresponds with each land use year. Each rainfall period is shorter than 14 days since the current model cannot perform continuous simulation with long intervals. Moreover, due to a lack of rainfall records from other stations, we assume that the rainfall record from the Allentown station can be applied to the entire watershed area equally.
We then created a simulation run for each basin model using the designated rainfall period. The simulation run contains the simulated runoff during the rainfall period and the simulated stream flow. The actual stream flow observed at the USGS gauging station was then used to calibrate the basin model. The calibration was achieved by model optimization which automatically adjusts parameter values to obtain a minimum objective function value\(^6\) (US Army Corps of Engineers, 2010a). In this case we chose the peak-weighted RMS error function as the objective function since it gives more weight to above average flow which is our primary concern. We also set the adjusted parameter to be the CN. Since there is only one gauging station with observed flow for the entire watershed, we applied one scale factor to adjust the CN of all sub-basins.

After each basin model was calibrated, we chose three more rainfall periods and used all three basin models for each rainfall period. So for each rainfall period we ended up with three different simulation runs for comparison. In order to avoid thunderstorm events, which generates high surface flow in a short period of time and saturates the soil, all three rainfall periods were from winter events. For each simulation run an estimated runoff volume for each sub-basin in each land use year was computed. We then compared the runoff volume and hydrograph from each land use year using statistical tests.

**RESULTS**

The land use changes in 1958, 1986 and 2008 are fairly dramatic as shown in Figure 4, 5 and 6. In addition, Table 4 shows the area of each land use category in the three study periods. From 1958 to 1986, residential development increased by 183% and farmland decreased by 70%. Most

\(^6\)Objective function measures the degree of variation between computed hydrograph and observed hydrograph (US Army Corps of Engineers, 2010a).
of the agricultural land was converted to open space, thus increasing open space or vacant land from 1958 to 1986. From 1986 to 2008, residential development increased by another 36%.

Although farmland did not decrease significantly, 63% of the open space was utilized for urban development. Figures 7, 8, and 9 show the changing patterns of agricultural, residential and open space land use over the 3 study periods.

<table>
<thead>
<tr>
<th>Land use</th>
<th>1958</th>
<th>1986</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.7606</td>
<td>3.277</td>
<td>2.753</td>
</tr>
<tr>
<td>2</td>
<td>2.0091</td>
<td>22.532</td>
<td>8.112</td>
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<tr>
<td>3</td>
<td>35.489</td>
<td>10.512</td>
<td>13.945</td>
</tr>
<tr>
<td>4</td>
<td>1.2702</td>
<td>1.484</td>
<td>8.047</td>
</tr>
<tr>
<td>5</td>
<td>0.5348</td>
<td>4.864</td>
<td>3.586</td>
</tr>
<tr>
<td>6</td>
<td>1.6368</td>
<td>3.407</td>
<td>0.635</td>
</tr>
<tr>
<td>7</td>
<td>0.2912</td>
<td>0.539</td>
<td>2.628</td>
</tr>
<tr>
<td>8</td>
<td>0.1275</td>
<td>1.035</td>
<td>1.918</td>
</tr>
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<td>9</td>
<td>0</td>
<td>0</td>
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<tr>
<td>10</td>
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<td>11</td>
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<td>0</td>
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<tr>
<td>12</td>
<td>0.4177</td>
<td>0.221</td>
<td>4.602</td>
</tr>
<tr>
<td>13</td>
<td>1.0186</td>
<td>1.051</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: The area of each land use in square miles.
Figure 4: Land use map of the Monocacy Creek Watershed in 1958.

Figure 5: Land use map of the Monocacy Creek Watershed in 1986.

Figure 6: Land use map of the Monocacy Creek Watershed in 2008.
Figure 7: Agricultural land changes in the three land use years.

Figure 8: Residential land changes in the three land use years.

Figure 9: Open space changes in the three land use years.

Figures 10, 11, and 12 show the corresponding simulated hydrograph of the rainfall periods.

The peak discharge from 2008 land use is the highest while the peak discharge in 1958 is the lowest. Due to the fact that only daily data are available, the hydrograph does not show time lag.
difference of the peak flow as timing for peak flow cannot be determined from the rainfall record, since the resolution on daily records is too coarse.

Figure 10: Combined hydrograph of each land use year for the rainfall event from Jan 3rd to Jan 15th, 2002.

Figure 11: Combined hydrograph of each land use year for the rainfall event from Jan 1st to Jan 12th, 1993.
Figures 13, 14, and 15 show the statistical test results for the simulations on the three rainfall periods. For this statistical test we assumed that the variance was constant throughout the simulation results. As the results show, p-values from the ANOVA are very small, suggesting that at least one runoff result is significantly different from the other two. Further analysis using the Tukey method shows that all three runoff results are different from one another.


<table>
<thead>
<tr>
<th>Source</th>
<th>30</th>
<th>29</th>
<th>31</th>
<th>30</th>
<th>31</th>
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<tr>
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<td>156</td>
<td>156</td>
<td>156</td>
<td>156</td>
<td>156</td>
<td>156</td>
</tr>
</tbody>
</table>

$S = 3.05T \quad K = 29.79 \quad \text{K-Sq(adj)} = 29.098$

**Individual 95% CIs for Mean Based on Pooled Sdev**

<table>
<thead>
<tr>
<th>Level</th>
<th>2000</th>
<th>2006</th>
<th>1986</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>6.009</td>
<td>6.494</td>
<td>2.994</td>
</tr>
<tr>
<td>Sdev</td>
<td>2.037</td>
<td>2.022</td>
<td>0.994</td>
</tr>
</tbody>
</table>

**Pooled Sdev = 3.05T**

**Grouping Information Using Tukey Method**

<table>
<thead>
<tr>
<th>X</th>
<th>From Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
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</tr>
<tr>
<td>2006</td>
<td>6.494 A</td>
</tr>
<tr>
<td>1986</td>
<td>2.994 C</td>
</tr>
</tbody>
</table>

Means that do not share a letter are significantly different.

**Figure 13: ANOVA analysis result summary for one of the three precipitation events from Jan 3rd to Jan 15th, 2002.**
**DISCUSSION**

Based on the modeling results, we are confident that the increase of runoff is highly associated with the land use changes from 1958 to 2008. Under the same precipitation event, the runoff generated in 2008 is about 6 times more than the runoff generated in 1958 and twice the runoff generated in 1986. Since in the model simulation, the only different variables among the three models are those affected by land use change, and residential area increased by a factor of 4 from 1958 to 2008, it can be inferred that the difference in the runoff volume is caused by the
change in land use. The high runoff volume in 2008 can be attributed to the high percentage of residential development in that year. Thus we expect any further urban development in the watershed will result in more runoff, assuming there is no dramatic change in rainfall patterns.

As Figure 16 suggests, there is very likely a relationship between the area of residential development and the stream flow discharge which is related to the runoff volume. All three rainfall events showed a potential exponential growth of discharge as the area of residential development increases. Future study should be conducted on how the channel depth and width have changed throughout the 50 years period and how increase of surface runoff can have any impact on the channel shape and thus on risk of flooding.

![Figure 16: The relationship plot between stream flow discharge and residential development area for the three rainfall events and three land use development.](image)

**Sources of error**

Although our modeling results showed that the change of land use through urban development has a significant impact on the stream flow of the Monocacy Creek, certain
limitations of the modeling process should be carefully considered before interpreting the data.

First of all, the methods used to construct the land use maps are different from one another. The 1958 land use map was sketched based on historical aerial photographs. During the process it was especially difficult to tell the difference between open space and agriculture land from the historical photographs. Since the agricultural land use has higher CN than the open space has and more lands were categorized as agricultural land, the model for 1958 might generate more runoff than the actual runoff. Also there exist some inconsistencies in terms of land use categorization criteria between the 1986 and the 2008 maps. According to LVPC, the 1986 data was digitized off of mylar prints that were colored by hand and manually entered into the computer using a grid system. The 2008 data is based on much more accurate data (parcels) that account for more details of the street and buildings on the ground (Romig, 2011). Therefore 2008 map is more accurate than 1986 map in terms of representing the actual land use on the ground.

Furthermore, for the sake of simplicity, the model uses CN as the only parameter to characterize land use. However, CN describes average conditions that are useful for design purposes rather than predicting runoff based on historical rainfall events. It also applies only to direct surface runoff while in reality large sources of subsurface flow might contribute significantly to the stream flow of the Monocacy Creek (SCS, 1986).

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APPENDIX I: Estimation of runoff using Curve Number

**SCS runoff curve number method**

The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985). The SCS runoff equation is

\[ Q = \frac{(P - I_a)^2}{(P - I_a) + S} \]  \hspace{1cm} [eq. 2-1]

where

- \( Q \) = runoff (in)
- \( P \) = rainfall (in)
- \( S \) = potential maximum retention after runoff begins (in) and
- \( I_a \) = initial abstraction (in)

Initial abstraction (\( I_a \)) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. \( I_a \) is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, \( I_a \) was found to be approximated by the following empirical equation:

\[ I_a = 0.2S \]  \hspace{1cm} [eq. 2-2]

By removing \( I_a \) as an independent parameter, this approximation allows use of a combination of \( S \) and \( P \) to produce a unique runoff amount. Substituting equation 2-2 into equation 2-1 gives:

\[ Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \]  \hspace{1cm} [eq. 2-3]

\( S \) is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and \( S \) is related to CN by:

\[ S = \frac{1000}{CN} - 10 \]  \hspace{1cm} [eq. 2-4]

*Figure A1: Equations for runoff calculation. This is an excerpt from Chapter 2 of Technical Release 55 by Soil Conservancy Service on how to calculate runoff using curve number.*
APPENDIX II: Managing data using HEC-DSS

One challenge for the modeling process is to enter the rainfall and stream flow record into the HEC-HMS program. Direct input from a spreadsheet is not available for HEC-HMS. The only two ways for data input are a manual input or DSS input. With daily rainfall and flow records for 50 years, a manual input is not an efficient technique. The Hydrologic Engineering Center has the free software HEC-DSS that helps compile and manage data in the DSS format. The HEC Data Storage System, or HEC-DSS, is a database system designed to efficiently store and retrieve scientific data that is typically sequential, for example, time-series data. Thus data stored in HEC-DSS can be directly retrieved and used for modeling in HEC-HMS.

Before transferring time-series data into HEC-DSS, all data records must be stacked into one column in the spreadsheet. The best way to do this is to copy all data records into a new spreadsheet with every column containing the records of one month. In this case we have records of every month from 1958 to 2008. Then select all records and press Alt+F11 to open the VBA interface in Excel. Then select the workbook that contains the records and choose Insert-Module to open code pane. Figure A2 shows the code to stack data into one column. After typing the code, press F5 to run the code. All the data should then be stored in one column of the spreadsheet.
When all records are stacked, open up the HEC-DSS program and create a new DSS file.

Then select Data Entry-Manual time series. An interface of Times Series Data Entry (Figure A3) will show up. In the pathname parts, each slot will be filled to identify the path for the dataset. In Part C it should be "Flow" for discharge records and "Precip-Inc" so that in HEC-HMS, it can be identified as discharge and rainfall data respectively. For rainfall record one day is chosen for Part E since we have only daily records. After finishing pathnames, start date and time should be filled in the form of "1 January 1958" and "24:00". The units should be "cfs" for discharge and "inch" for rainfall. In the "type" part, for precipitation, it is "per-cum" since the record is the cumulative rainfall for the time interval. For discharge the type is "per-aver" since it is the record is the average within the time interval. After finishing setting up the dataset, the stacked record can be copy-paste in the "manual entry" table under "value" column.
As you create new time-series manager in HEC-HMS, choose DSS file as input method and type in the path name of your dataset as in Figure A3. You will then have the discharge and rainfall data in the HEC-HMS program.