Chapter 3
Hydrologic Effects of Residential Development Patterns

3.1 Introduction

Researchers have long recognized the adverse impacts of development on the environment. However, increases in population and a public desire to continue expanding residential and commercial sites into previously undisturbed areas necessitate continued development. The change in land surfaces caused by such development dramatically alters the hydrology of the watershed. The addition of impervious surfaces such as roads, rooftops, driveways, and sidewalks and the addition of lawns (typically less pervious than forested or other undisturbed lands) act to reduce infiltration into the ground and increase surface runoff. The reduction in groundwater recharge also reduces the baseflow of streams. The reduction in rainfall infiltration capacity decreases the natural ability of a watershed to attenuate the impact of a storm event via infiltration, subsurface flow, and surface storage. Greater runoff quantities and the increased conveyance of the new land cover generate increased hydrograph peaks and shorter response periods. The combination of the reduced baseflow and increased storm runoff leads to an increase in the range of flows experienced by a receiving stream. The increased stream flow variability can accelerate in-channel processes that are detrimental to stream health and stability. It is essential for careful land use planning to analyze this flow variability by simulating long-term streamflows, which in turn can yield better assessment of land development impacts.

3.2 Site and Model Selection

This study is undertaken in the Back Creek sub-watershed (145 km^2 /56 mi^2) of the Upper Roanoke River watershed in southwest Virginia because of its proximity to the city of Roanoke and its potential for future development. The study incorporates land development data, hydrologic software HSPF (Bicknell et al., 1997), and pre and post processing programs to evaluate the impacts of development. The sub-watershed is divided into ten sub-areas to model the hydrologic processes, as per HSPF application procedure given in Bicknell et al., 1997 (Figure 3.1).

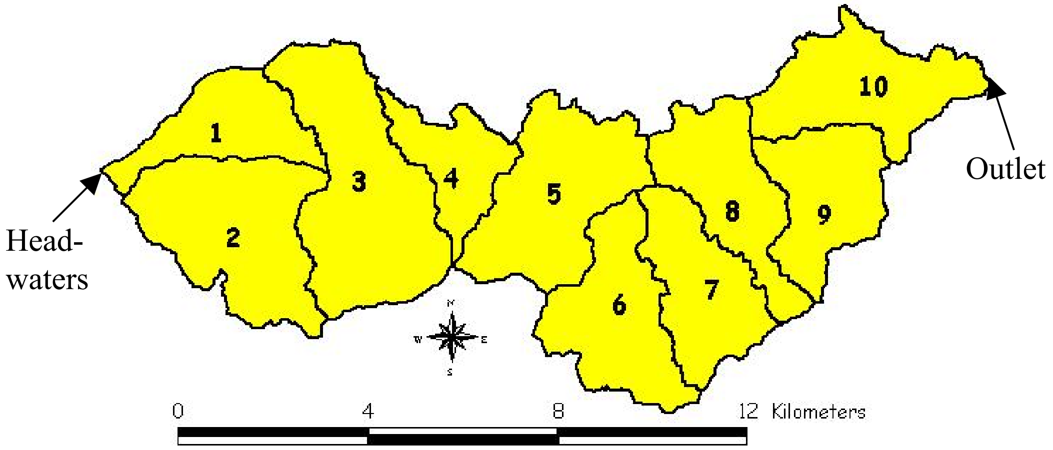


Figure 3.1. Back Creek watershed, Roanoke County,

3.3 Model Data Calibration and Validation

A four year HSPF model of the watershed was first developed by Jeff Chanat (Lohani et al., 2002). Four years (Water Years 1995-1998) of hourly precipitation data from four rain gages close to the watershed were available for input to the HSPF model (Figure 3.2). Monthly temperature data from the nearby Roanoke Airport was used along with the Thornthwaite equation to attain approximations for the potential evapotranspiration (PET) for the watershed. Channel geometry and hydraulic properties of the stream were attained through surveys at representative channel cross sections. Manning's equation calculations were used to complete the routing tables (FTABLES in HSPF). Data from the Virginia GAP project along with analysis by Rob Dietz (2000) were used to create the baseline landuse cover conditions. The first three water years

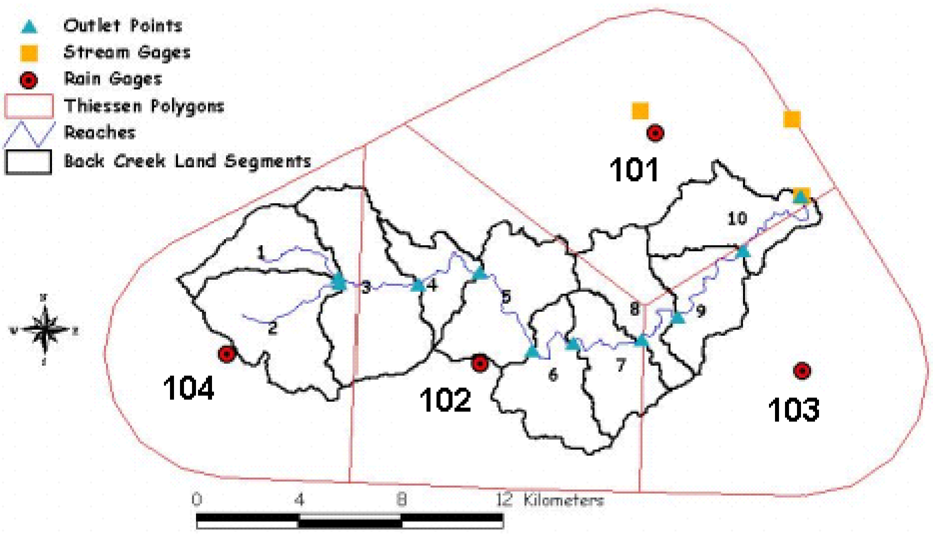


Figure 3.2 Back Creek Watershed with gage, stream, subarea, and Theissen polygon locations

(1995-1997) were used to calibrate the model (Figure 3.3) against the known flows from the Dundee gage (Figure 3.2), a USGS IFLOWS gage located at the bottom of Back Creek Watershed, and the fourth water year was used for model validation (Figure 3.4). Finally, a spatially constant rainfall dataset or mean area precipitation (MAP) was created for the watershed using the Theissen polygons (Figure 3.2) to weight the influence of each rain gage. Model calibration and validation were both successful in matching the recommended guidelines of HSPEXP (the calibration tool in the HSPF suite) and in generating hydrographs that followed the known flow pattern of Back Creek during the appropriate time frame.

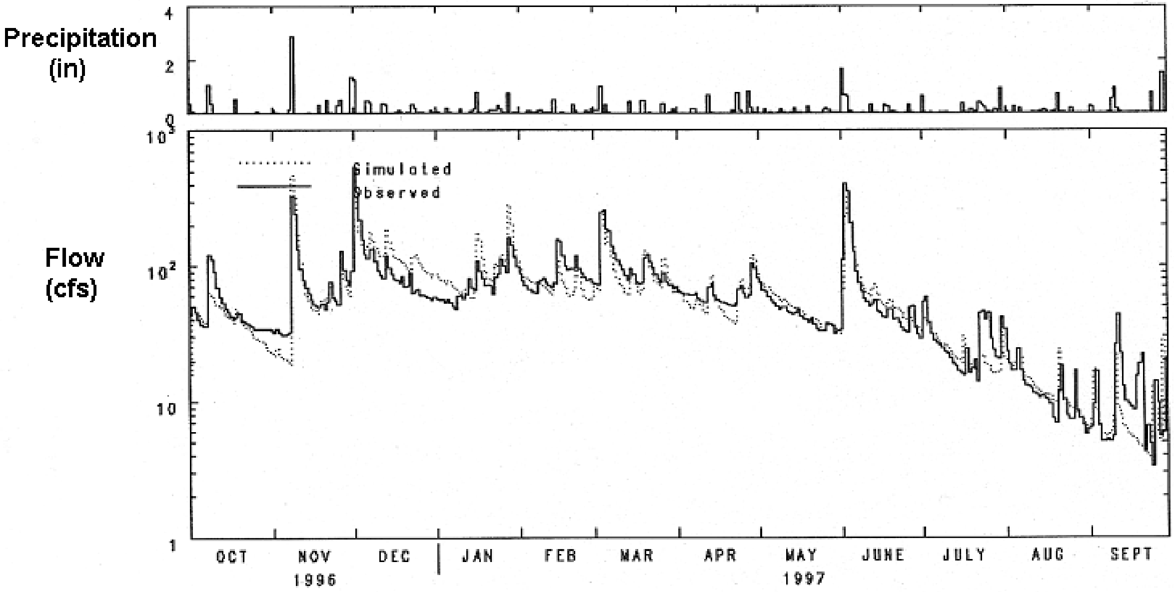


Figure 3.3 Example of calibration results for Water Year 1997 from Lohani et al., 2002

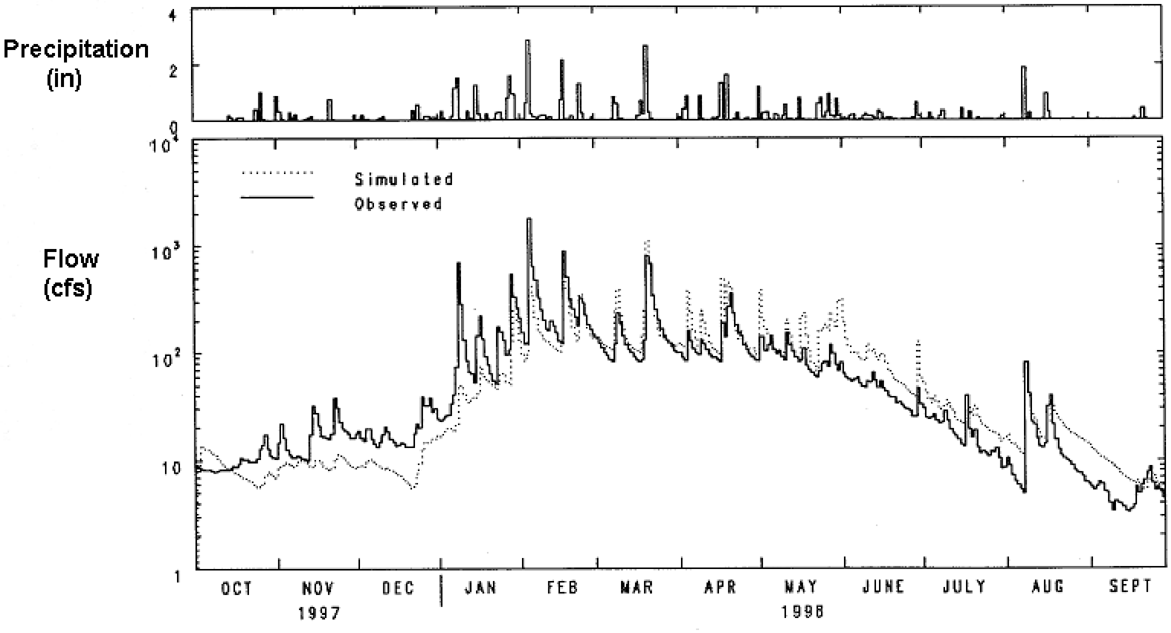


Figure 3.4 Validation results for Water Year 1998 from Lohani et al., 2002

3.4 Scenario Development

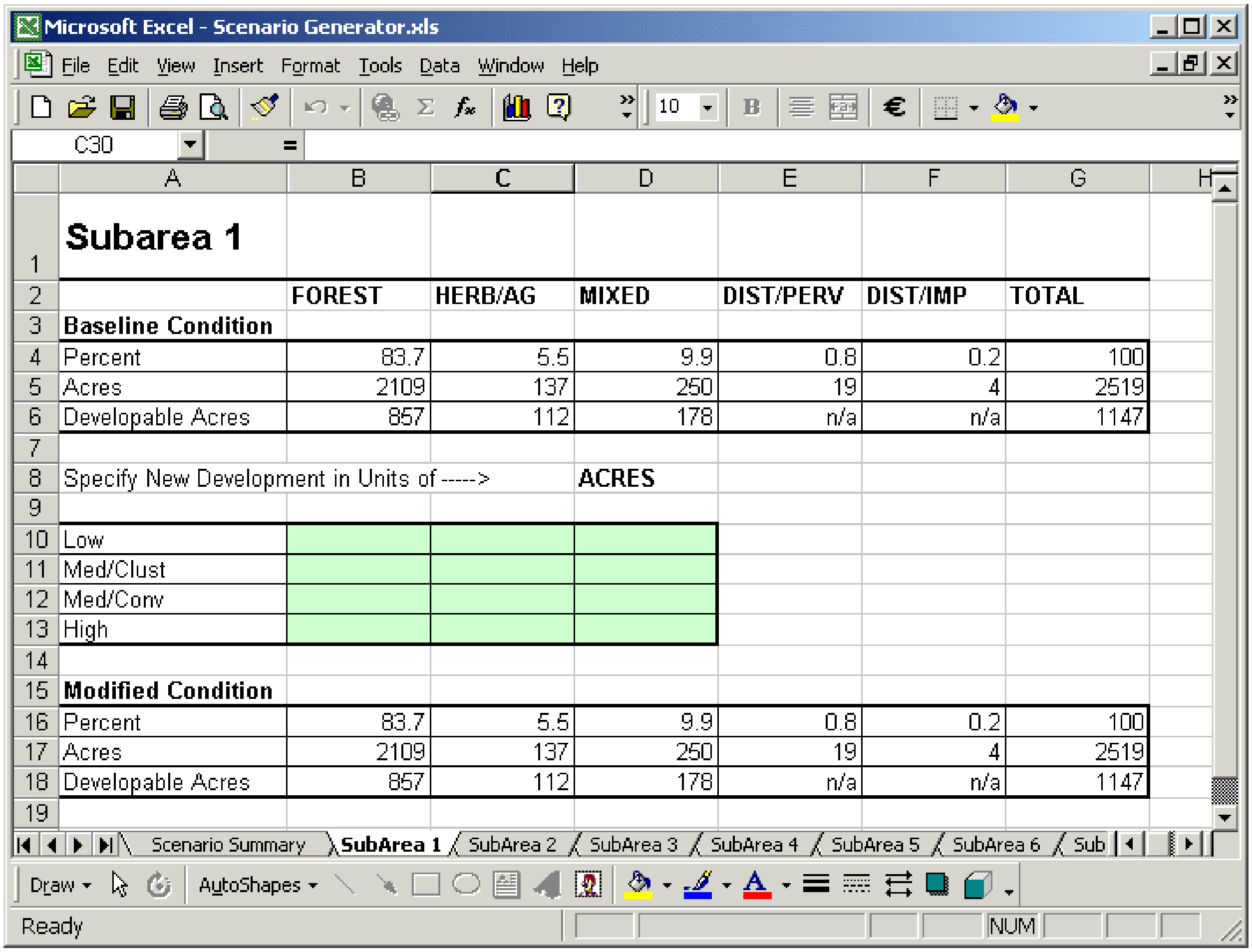
Residential development patterns were developed in consultation with GIS (Dietz, 2000) and landuse experts (Stephenson and Bosch, personal communications), along with relevant literature (Arendt, 1994; Schueler, 1998). These included low density development typical of rural areas, medium density conventional and cluster development typical of suburbs, and high density development typical of urban areas. Land use was grouped into five general categories: forested land, herbaceous/agricultural land, mixed land, disturbed pervious land, and disturbed impervious land. Restrictions on development were implemented to exclude land with high slopes (greater than 20%), disturbed land, water bodies, and reserved land held in national forests, parks, and flood plains. These restrictions left approximately 51.4 % of the total area for development (Bosley et al., 2001). Four scenarios of development that consider these restrictions are summarized in Table 3.1. For example, the scenario "low density full build out with restrictions" means developing all land not labeled as undevelopable at a low density distribution. It can be seen that the proportion of impervious fraction increases up to 19% from a baseline value of 1%. In order to further increase the impervious land fraction, four additional scenarios are created with the restrictions on land development lifted. In other words, development is allowed to occur everywhere in the watershed except in places already developed (see Table 3.2). These eight scenarios are translated into the user control interface (UCI) file (the input file for the HSPF model) with the help of a program called Scenario Generator (Figure 3.5) that is developed using Visual Basic for Applications macros in Microsoft Excel and Microsoft Word (see Lohani et al., 2002 for more details).

Table 3.1. Descriptions and distributions of scenarios with restricted development.

Full Build Out Scenarios with Restrictions	**% Impervious**	**Additional People**
Baseline	1%	0
Low Density	6%	15301
Medium Density (Cluster)	11%	109292
Medium Density (Conventional)	15%	109292
High Density	19%	191260

Table 3.2. Descriptions and distributions of scenarios with no restrictions on development.

Full Build Out Scenarios without Restrictions	**% Impervious**	**Additional People**
Low Density	10%	28115
Medium Density (Cluster)	20%	200822
Medium Density (Conventional)	26%	200822
High Density	34%	351438



Subarea 1

	FOREST	HERB/AG	MIXED	DIST/PERV	DIST/IMP	TOTAL
Baseline Condition						
Percent	83.7	5.5	9.9	0.8	0.2	100
Acres	2109	137	250	19	4	2519
Developable Acres	857	112	178	n/a	n/a	1147
Specify New Development in Units of ----->			**ACRES**			
Low						
Med/Clust						
Med/Conv						
High						
Modified Condition						
Percent	83.7	5.5	9.9	0.8	0.2	100
Acres	2109	137	250	19	4	2519
Developable Acres	857	112	178	n/a	n/a	1147

Figure 3.5 Scenario Generator input screen for SubArea 1

3.5 Extension of the Calibrated Model to 43 Years

Following the calibration and validation, the simulation period was then extended to 43 years (water years 1957-1999) using hourly rainfall records available from the Roanoke Airport rain gage, located just outside the Back Creek watershed. Due to the extremely low current development of the watershed (1% imperviousness), the current landuse patterns were assumed to be unchanged over the past 43 years enabling usage of a temporally constant landuse pattern. In addition to the validation, further confidence in the extension of the model time frame from the initial 4 years to 43 years was gained because three different types of precipitation years (wet, dry and normal) were used in the calibration of the 4 year model. Because the airport gage was located just outside the watershed, the precipitation recorded at the airport was compared to the precipitation of the MAP using a double mass curve (Figure 3.6). The double mass curve showed that although the two rainfall datasets did not have the same amount of rainfall, the datasets were correlated. The airport gage data was then adjusted by a factor of 1.2094 to make the airport rainfall dataset more representative of rainfall typical for the Back Creek watershed. Potential evapotranspiration (PET) data was extended from 4 years to 43 years using a simple extrapolation procedure based on the relative precipitation classification of each water year. Each water year was classified as wet, dry, or normal based on annual precipitation totals (Figure 3.7) and the PET data from the calibration years with the corresponding precipitation class was used. The thresholds for wet, dry, and normal years were determined from discussion of the known precipitation of the watershed area. This process is thought to produce accurate model results considering the relative insensitivity of HSPF to PET. All other model data in the binary watershed data management (WDM) file were left unchanged from the 4-year model.

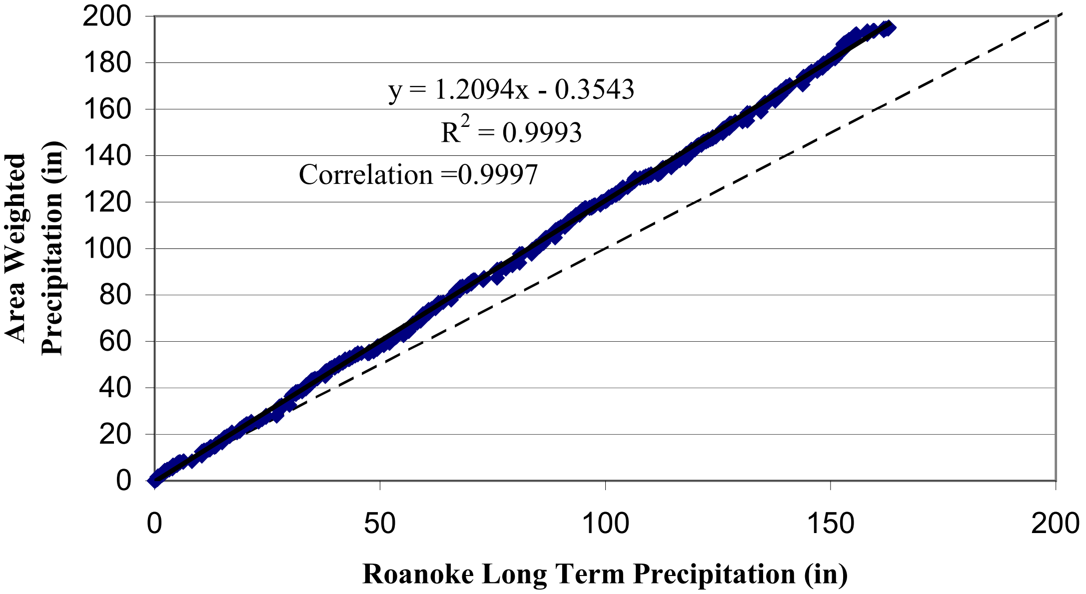


Figure 3.6 Double mass curve of Roanoke long term precipitation (43 years) and MAP (4 years)

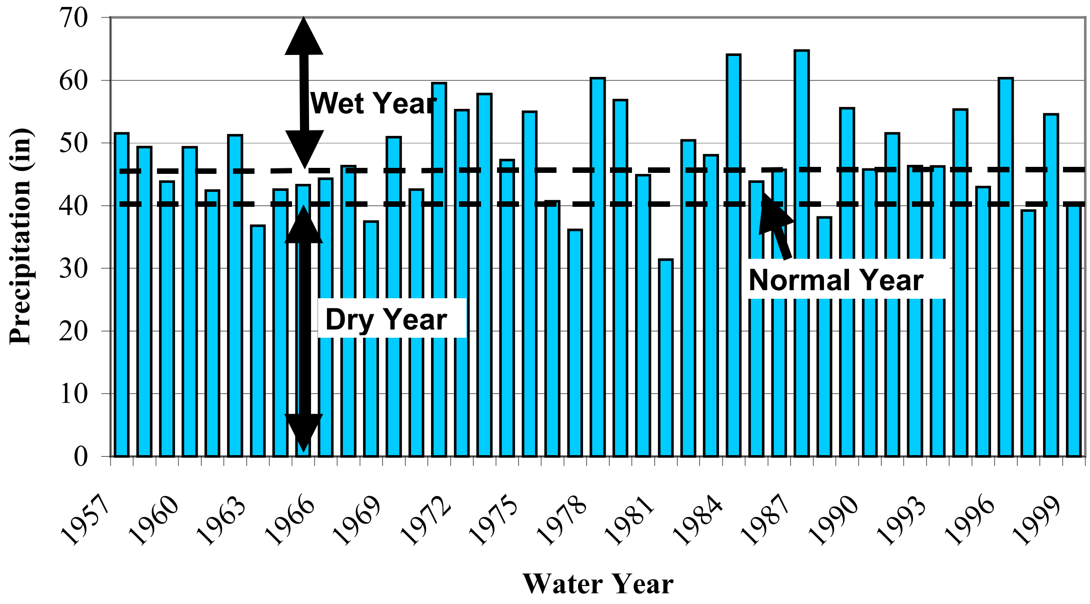


Figure 3.7 Annual precipitation of the adjusted Roanoke Airport data

The HSPF model simulates hourly groundwater recharge and overland flow in each subarea, plus reach flow in the main channel of Back Creek for the 43 year period. This study is based upon results simulated at the outlet from the Back Creek watershed, thereby significantly reducing the HSPF output. However, even with the data reduction, almost 377,000 data points per scenario remained for analysis. Due to restrictions on the number of cells in Microsoft Excel and other spreadsheet programs, importing the dataset into a spreadsheet proved impossible. A stand-alone Visual Basic program, HSPF Post Processor was developed to handle the large dataset and perform the following analyses:

- Flood frequency curves
- Flood event classification
- Low flow statistics
- Log Pearson Type 3 density for flood flows

The flood frequency analysis calculates the discharge for 2, 5, 10, 25, 50, and 100 year return period floods using an annual series Log Pearson distribution. Storm runoff events are then separated from baseflow by allowing the user to identify a time frame during which a change in flow magnitude by a set relative percentage would indicate a storm event (See figure 3.8). The "time" and "percentage" parameters were optimized so that the minimal amount of difference in total storm number was produced, thus minimizing artificial storm mixing and identification of false peaks. The storms are then divided into classes delineated by the above return periods (based on the baseline file), and tallied. This shows how the return period for historical storms has changed due to development. Representative storm hydrographs for each return period discharge (if a representative hydrograph exists in the dataset) are also selected from the dataset and listed. Low flow calculations also are based on a Log Pearson 3 analysis to calculate the 1, 7, 15, 30, 60, and 90 day low flows for the 2, 10, and 50 year return periods. Log Pearson 3 probability density calculations were performed to detect shifts in the flow regime.

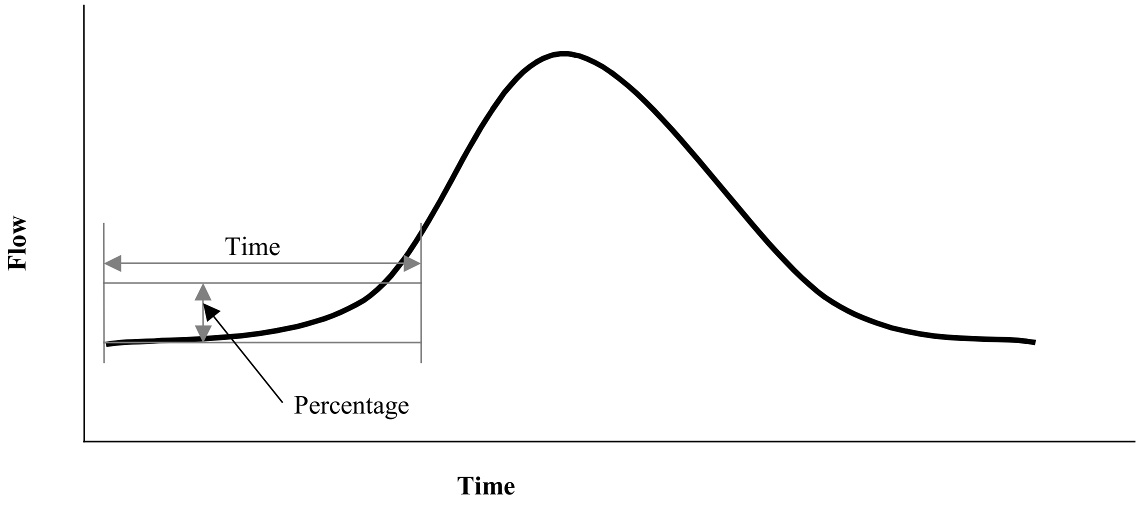
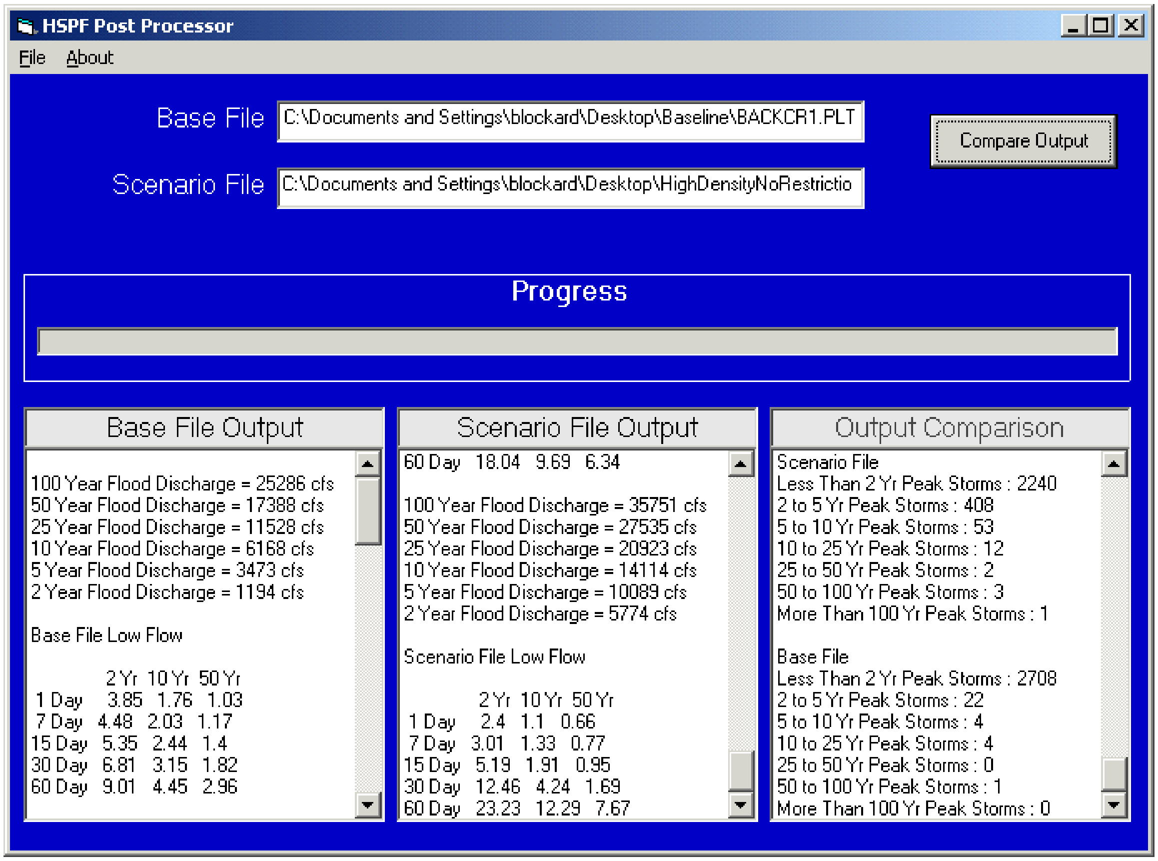


Figure 3.8 Method to separate storm events from baseflow

The HSPF Post Processor allows the user to select the baseline file and scenario file for comparison and performs the complete set of analyses on both files. The output comparison between the scenario and baseline data is displayed on screen (see Figure 3.9 and Figure 3.10) and results are also saved to a comma separated value (CSV) file for easy import into Microsoft Excel and other spreadsheet programs. This process greatly eases analysis of large datasets and eliminates repetitive data preparation. Since all scenarios for the 43-year model produce the same volume and type of output, the only adjustment necessary is the selection of the appropriate scenario output file from HSPF.



Base File: C:\Documents and Settings\blockard\Desktop\Baseline\BACKCR1.PLT

Scenario File: C:\Documents and Settings\blockard\Desktop\HighDensityNoRestrictio

```
100 Year Flood Discharge = 25286 cfs
50 Year Flood Discharge = 17388 cfs
25 Year Flood Discharge = 11528 cfs
10 Year Flood Discharge = 6168 cfs
5 Year Flood Discharge = 3473 cfs
2 Year Flood Discharge = 1194 cfs

Base File Low Flow

         2 Yr  10 Yr  50 Yr
 1 Day   3.85  1.76  1.03
 7 Day  4.48  2.03  1.17
15 Day  5.35  2.44  1.4
30 Day  6.81  3.15  1.82
60 Day  9.01  4.45  2.96
```

```
60 Day  18.04  9.69  6.34

100 Year Flood Discharge = 35751 cfs
50 Year Flood Discharge = 27535 cfs
25 Year Flood Discharge = 20923 cfs
10 Year Flood Discharge = 14114 cfs
5 Year Flood Discharge = 10089 cfs
2 Year Flood Discharge = 5774 cfs

Scenario File Low Flow

         2 Yr  10 Yr  50 Yr
 1 Day    2.4   1.1   0.66
 7 Day   3.01   1.33  0.77
15 Day   5.19   1.91  0.95
30 Day  12.46   4.24  1.69
60 Day  23.23  12.29  7.67
```

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Scenario File
Less Than 2 Yr Peak Storms : 2240
2 to 5 Yr Peak Storms : 408
5 to 10 Yr Peak Storms : 53
10 to 25 Yr Peak Storms : 12
25 to 50 Yr Peak Storms : 2
50 to 100 Yr Peak Storms : 3
More Than 100 Yr Peak Storms : 1

Base File
Less Than 2 Yr Peak Storms : 2708
2 to 5 Yr Peak Storms : 22
5 to 10 Yr Peak Storms : 4
10 to 25 Yr Peak Storms : 4
25 to 50 Yr Peak Storms : 0
50 to 100 Yr Peak Storms : 1
More Than 100 Yr Peak Storms : 0
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Figure 3.9 Sample numerical output from HSPF Post Processor for the high density full build out without restrictions scenario.

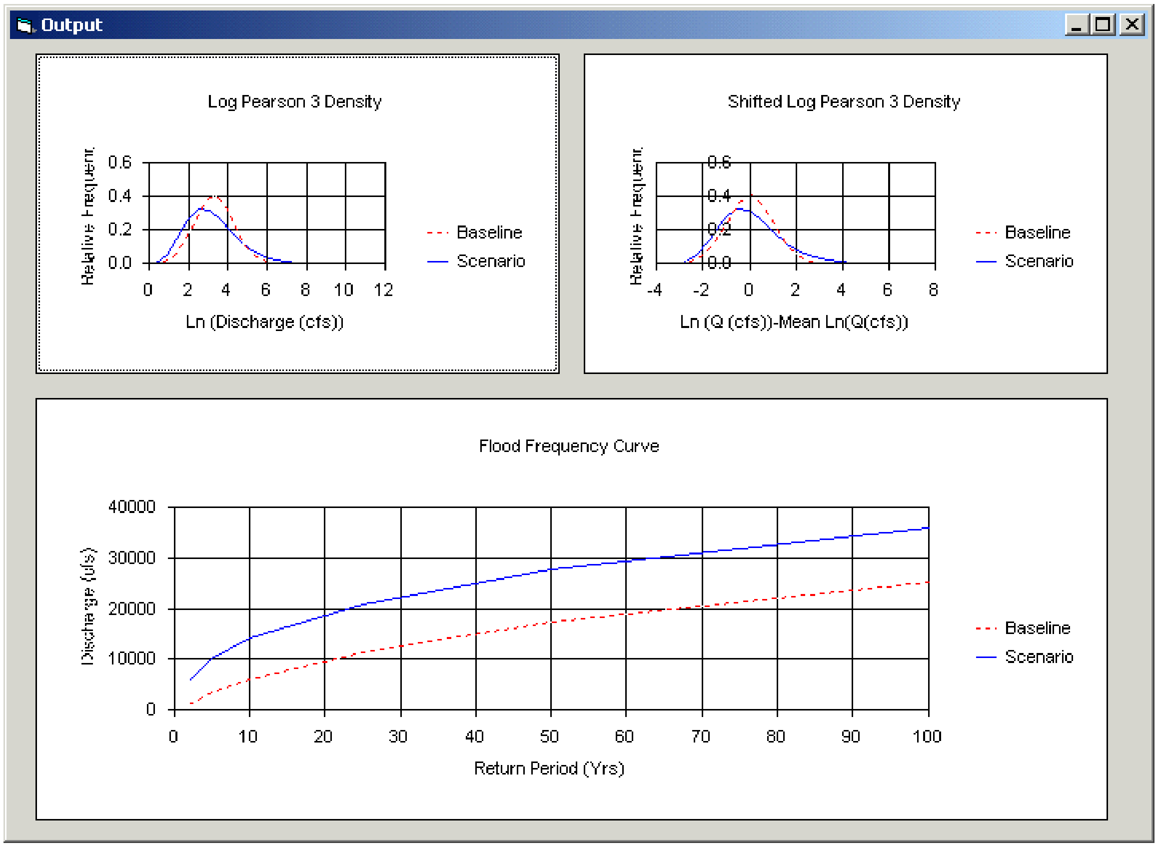

Figure 3.10 Sample graphical output from HSPF Post Processor corresponding to Figure 3.9**.**

3.6 Results and Discussion

As expected, the flood frequency curves (see Figure 3.11) show an upward/leftward shift as the watershed is developed from the baseline condition. This shift indicates that floods of a given magnitude will occur, on average, more often in a developed watershed than in the baseline condition. For example, the 100 yr flood for the baseline condition (25,286 cfs) can be expected to occur, on average, once every 40 years in the high density full build out without restrictions scenario (see Figure 3.9). While the changes in major floods are worth considering, the more significant change in flow regime may occur in the high frequency/lower return period floods. While the changes in flood peaks at these return periods are less dramatic at the flood frequency curve scale, these flowrate changes may affect the channel the most, since they occur with much greater frequency (Roesner et al. 2001). This idea is especially pertinent in the case of relatively small channels, like Back Creek, where changes in flow regime can dramatically alter the physical and ecological aspects of the water body. Figure 3.11 shows the shifts in flood frequency curve as a function of different development scenarios. The importance of impervious fraction is clearly indicated in the magnitude of the shift away from the baseline curve as the amount of imperviousness increases.

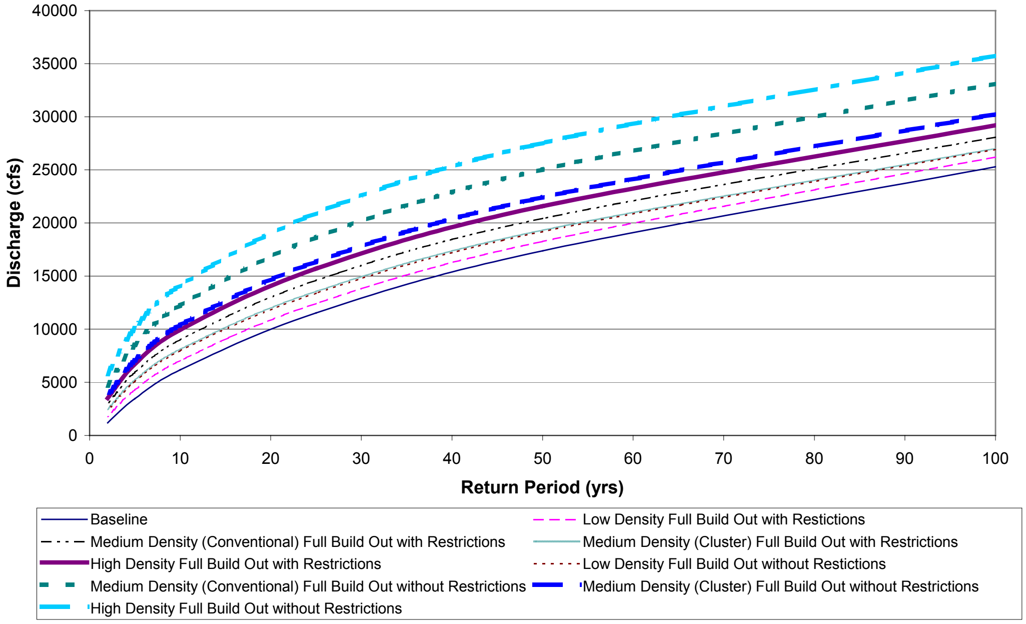

Figure 3.11 Flood frequency curves for the scenarios

Table 3.3 Number of flood events in each baseline flood class for the various scenarios

Storm Class	Baseline	Full Build Out Scenarios with Restrictions				Full Build Out Scenarios without Restrictions			
		Low Density	Medium Density (Conventional)	Medium Density (Cluster)	High Density	Low Density	Medium Density (Conventional)	Medium Density (Cluster)	High Density
< 2 Yr Storms	2708	2782	2723	2802	2617	2782	2421	2563	2240
2 to 5 Yr Storms	22	66	115	75	181	66	301	199	408
5 to 10 Yr Storms	4	7	9	6	12	7	28	16	53
10 to 25 Yr Storms	4	6	5	7	7	6	8	6	12
25 to 50 Yr Storms	0	0	3	0	3	0	4	4	2
50 to 100 Yr Storms	1	0	0	0	0	0	1	0	3
> 100 Yr Storms	0	1	1	1	1	1	1	1	1

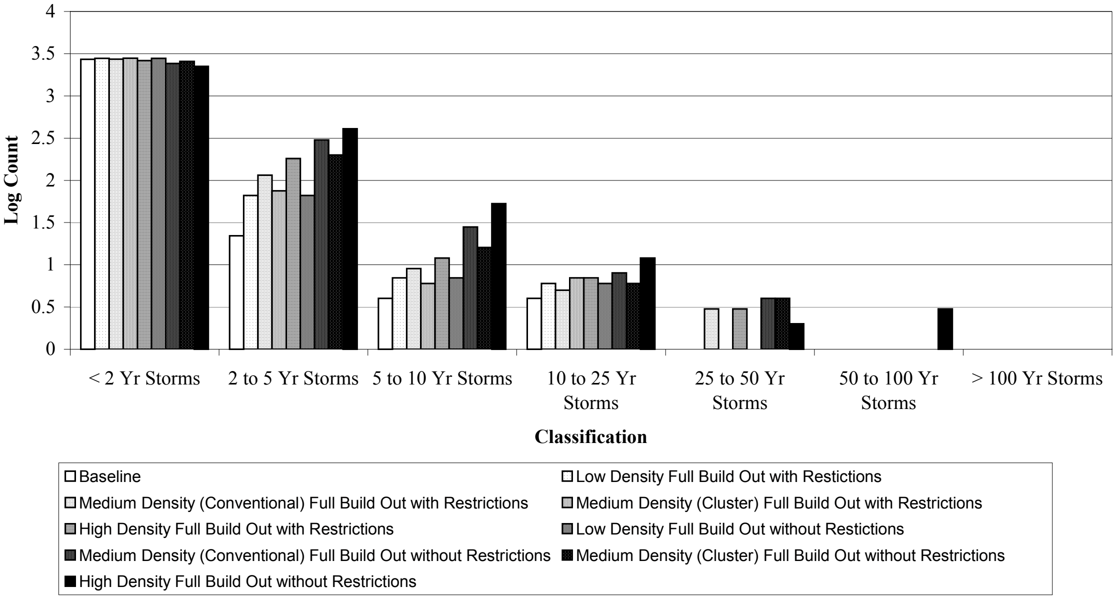

Figure 3.12 Log base10 of the number of flood events in each baseline flood class for the various scenarios

In order to determine the effect of development scenarios on number of flood events representing varying return periods, the author examined different class limits for the flood events identified from analysis of baseline data (Table 3.3). The logarithm of the number of floods corresponding to different return periods are plotted for each scenario in Figure 3.12. This bar graph shows that the number of flood events in each flood class tends to increase as the level of development increases. For example, the number of storms producing flood events classified as 5 to 10-year events increases from 4 in the baseline condition to 53 in the high density full build out without restrictions scenario. This indicates that the same historical rainfall events are triggering greater runoff events, thus reinforcing the concept of the flood frequency curve shift.

The Log Pearson Type 3 probability density analysis (see Figure 3.13 and Appendix B for general calculation steps) performed on all data points shows a change in curve shape from the baseline for the different scenarios. The shape change indicates that the flow regime is becoming more variable as development increases. The reduction in frequency of the mode and the increase in width of the density curve point to a flow regime that no longer fluctuates as closely about its most frequently occurring value. The increase in thickness of the tails for the scenarios is strong evidence that extreme events are occurring with greater frequency. Because the mode is closely aligned with low flowrates, the reduction in numerical *value* of the mode is indicative of the reduction in baseflow and groundwater recharge caused by the increase in impervious surfaces.

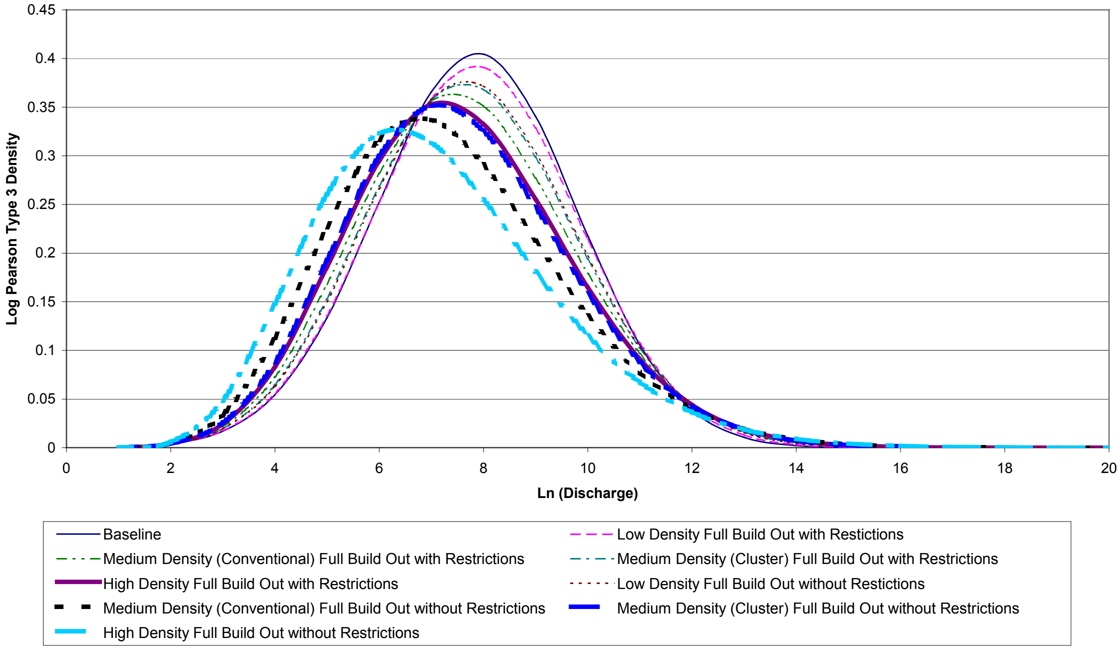

Figure 3.11 Log Pearson Type 3 density curves for the scenarios.

Low flow values (Table 3.4) from the annual series of different time averages for the scenarios revealed trends similar to that of the 50-year return period plot in Figure 3.14 and so only the 50-year plot is shown here. The trends show low flows to be extreme for areas with the highest impervious fraction and the greatest development during the *shortest* average low flow periods. That trend changes and in fact reverses during *longer* low flow averages. This is evident in Table 3.9, where the 1-day, 7-dat, and 15-day low flows show a decline in the high density scenario, while the 30-day and 60-day low flows show an increase relative to the base case. Although the reversal in order during longer low flow averages may be an unexpected result, further evaluation of the watershed yields a logical explanation. During shorter time periods, averages have a

Table 3.4 Summary of low flow values (cfs) for the scenarios

Low Flow	Baseline	Full Build Out Scenarios with Restrictions				Full Build Out Scenarios without Restrictions			
		Low Density	Medium Density (Conventional)	Medium Density (Cluster)	High Density	Low Density	Medium Density (Conventional)	Medium Density (Cluster)	High Density
$1Q_{2}$	3.85	3.67	3.28	3.44	3.11	3.47	2.73	3.04	2.40
$1Q_{10}$	1.76	1.67	1.50	1.57	1.43	1.59	1.25	1.39	1.10
$1Q_{50}$	1.03	0.98	0.89	0.93	0.84	0.93	0.75	0.83	0.66
$7Q_{2}$	4.48	4.48	4.07	4.25	3.87	4.29	3.41	3.78	3.01
$7Q_{10}$	2.03	2.04	1.84	1.93	1.74	1.95	1.52	1.70	1.33
$7Q_{50}$	1.17	1.18	1.06	1.11	1.01	1.13	0.88	0.98	0.77
$15Q_{2}$	5.35	6.06	6.11	6.16	6.02	6.15	5.60	5.94	5.19
$15Q_{10}$	2.44	2.62	2.48	2.56	2.39	2.56	2.14	2.35	1.91
$15Q_{50}$	1.40	1.42	1.30	1.36	1.24	1.37	1.09	1.22	0.95
$30Q_{2}$	6.81	8.82	10.55	9.93	11.11	9.77	11.88	11.18	12.46
$30Q_{10}$	3.15	3.87	4.26	4.15	4.33	4.11	4.31	4.31	4.24
$30Q_{50}$	1.82	2.07	2.03	2.07	1.98	2.07	1.83	1.95	1.69
$60Q_{2}$	9.01	11.89	15.93	14.32	17.69	13.93	20.63	18.04	23.23
$60Q_{10}$	4.45	6.37	8.63	7.77	9.54	7.55	10.96	9.69	12.29
$60Q_{50}$	2.96	4.42	5.80	5.31	6.29	5.18	6.96	6.34	7.67

much greater chance of including time periods with no storm events. However, as the time period for the average increases, the possibility of seeing no storms during the time period decreases. Since Back Creek is a surface runoff driven system, and more development leads to an increased runoff volume with a short response time, the impact of a storm occurring during the longer time frame can be substantial. Therefore, the best indicators of the true extreme low flow events are the shorter time averages. So, for 15 days and below, the most developed and highest impervious percent scenarios have the lowest low flows.

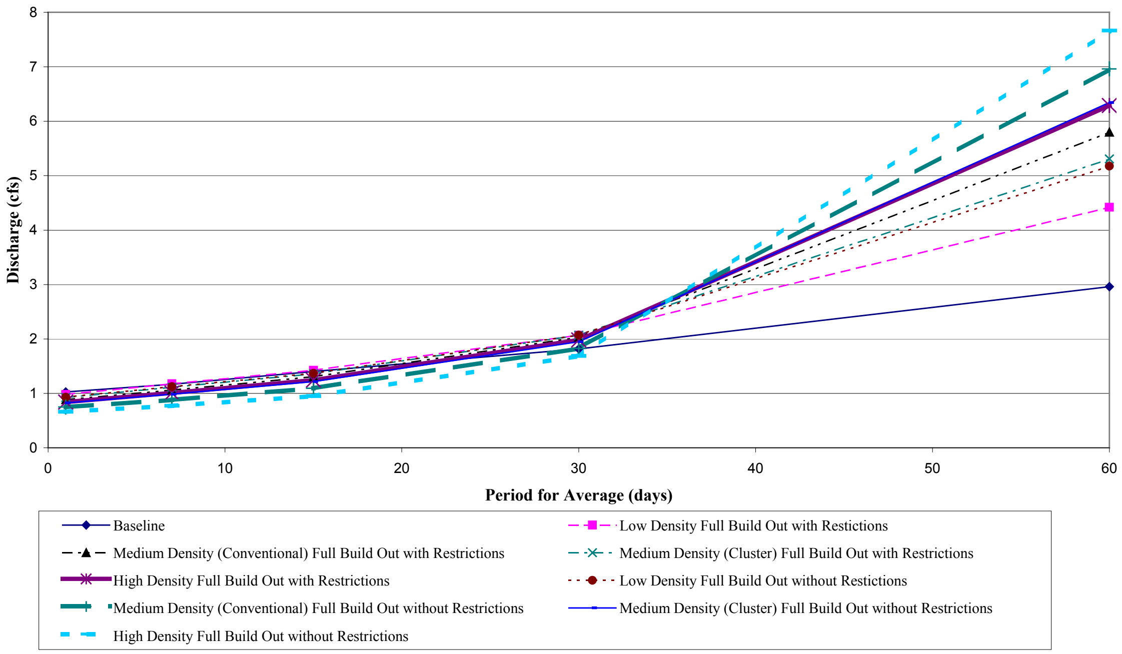

Figure 3.12 Low flow values for 50 year return period for the scenarios.

3.7 Summary and Conclusions

The HSPF model is used to simulate streamflows using 43-year of continuous hourly rainfall to examine effects of different residential development scenarios. The effects are examined in terms of the shifts in flood frequency curves, change in number of flood events of varying return periods, low flow statistics, and change in Log Pearson 3 probability density. The higher density and higher impervious fraction scenarios deviate the most from the baseline flow regime. Both extremes, high flows and low flows, are more common in the more densely developed scenarios. These deviations from the baseline condition can prove detrimental to the health of a stream as its character changes and equilibrium is upset (Poff et al. 1997).