ABSTRACT

Title of Thesis:	HYDROLOGIC EFFECTS OF CLIMATE AND LAND USE CHANGE IN SMALL MARYLAND WATERSHEDS
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The impact of a changing climate combined with a more urbanized world signals a change in watershed behavior. This work aims to quantify the change in watershed runoff due to both climate change and land use shifts by modeling changes in peak flow rates, duration of storm runoff, and the time to peak flow in response to storms of differing frequencies. GISHydro and WinTR-20 were used in tandem to model the effects of urbanization and increased rainfall predicted at mid-21st century on six small watersheds in two geographic regions of Maryland. Results indicate that climate change is the more influential factor in altering runoff for events from 50% to 1% annual exceedance probability; however, land use change is most prominently felt during the more common storms. Furthermore, a non-linear relationship is observed between the effects of impervious surface and rainfall on the runoff potential of the watersheds.

HYDROLOGIC EFFECTS OF CLIMATE AND LAND USE CHANGE IN SMALL MARYLAND WATERSHEDS

by

Austin Jack Milligan

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List of Abbreviations

CN – Curve Number

IDF – Intensity-Duration-Frequency

SCM – Stormwater Control Measures

Tc – Time of Concentration

Chapter 1: Introduction

Climate change is a global phenomenon that affects us all, in many complex and interconnected ways. Poverty, disease, mass migration, fires, increased flooding, and decreased food security all are symptoms of a rapidly warming climate. There are a great number of questions to answer in order to understand and curb global climate change; this study will explore several of them regarding the causes and impacts of changing watersheds in Maryland. The increased frequency and severity of storms are at the heart of this work, as well as the effects these events have on the natural and built environment.

Storms are a natural occurrence and bring with them the rainfall necessary to keep flora and fauna alive, but also flooding and destruction at times. Storms are a crucial part of our ecosystem, but their deleterious effects are becoming more severe due to warmer climate conditions. Due to the expected increased frequency and severity of storm patterns, it is important to analyze the effects that this extra rainfall will have on certain watersheds. Not only will peak flows be higher, potentially leading to larger floods, but these flows bring with them increased erosion, sediment content and pollutants. In conjunction with these increased flows, development is happening throughout the world as our population continues to grow, previously habitable land becomes inhospitable and migration patterns become more pronounced.

In addition to shifting weather patterns, changing land use/land cover alters a watershed’s response to precipitation. In particular, increased impervious cover, due to pavement and buildings, decreases the fraction of arriving precipitation that infiltrates into the soil and increases immediate surface runoff.

This work aims to quantify the behavior of 6 watersheds across Maryland, impacted by both shifting land use and changing climate, through analysis of the change in peak flow rates, times to peak, and total time of runoff. The effects of developing the land on the Eastern Shore of the state of Maryland were compared to development further inland, near the city of Frederick in the Piedmont physiographic region. These areas are different topographically, and while Frederick will experience stronger storms in the future, they will not be subject to complete inundation by rising sea levels, as the low-lying areas in and around the Eastern Shore will be.

The results can be compared across watersheds zoned for development that specifically include SCMs designed to mitigate the ecological impact of urbanization, and may thus prove useful for any future work that focuses on the effects of implementing SCMs in developing watersheds.

Chapter 2: Literature Review

Studies have been performed on land use and consequent flow rate change in the state of Maryland, however many go a step further. In addition to identifying the changes in flow rates, past research often uses this knowledge to predict the impact that increased water volume will have on delicate riparian ecosystems. "Human-induced changes to natural landscapes have been identified as one the greatest threats to freshwater resources." (Palmer et al., 2002). Not only does development lead to more impervious surface, which in turn leads to more vehicle activity and therefore pollutant runoff (Palmer et al., 2002), but changing weather patterns will only make storms more severe in the future; this excess water will have even less of an opportunity to infiltrate into the soil than it does now, exacerbating the effects of climate change. The problem is therefore twofold: storms that are more intense will drown regions in more rainfall than they are used to, and the natural coping mechanisms of these environments will be hindered due to a lack of infiltration from development. This will greatly increase the peak flow rates and flooding capabilities of these urbanizing watersheds.

In addition to land-based ecological harm, higher flow rates due to increased storm severity can also contribute to oxygen deprivation in the Chesapeake Bay, the United States' largest estuary, resulting in mass population loss across multiple species. Currently, around 50% of the world's population lives within 100 km of a coastline, which is expected to increase with population and urbanization (Kaushal et al., 2008). Connecting nitrogen runoff to algal blooms in the Chesapeake Bay, Kaushal et al. (2008) found that in years of drought, algal blooms are less prevalent in the bay and therefore oxygen levels are higher. In contrast, wet years were found to correlate with higher levels of algae throughout the Chesapeake Bay, in large part due to nitrogen runoff from agricultural land across the six states in the Bay's watershed. Low oxygen levels can kill massive amounts of aquatic life, not only harming the ecosystem itself, but also any human livelihoods that depend on a healthy Bay. It is therefore vital to be able to predict how changing land use and increased storm severity will impact stormwater flow rates throughout Maryland.

In addition to research on the effects on both land and aquatic ecosystems, work has been done to investigate the amount of headwater streams that are covered due to urbanization. According to the EPA (2018), "Headwater streams are the smallest parts of river and stream networks, but make up the majority of river miles in the United States. They are the part of rivers furthest from the river's endpoint or confluence with another stream." Urbanizing areas frequently avoid disturbing prominent water bodies; however, headwater streams are often ignored, leading to increased nitrogen levels, pollution and a decrease in fish and invertebrate life (Elmore, 2008).

Elmore (2008) found that "20% of all streams were buried, with streams in low-residential and suburban areas outside Baltimore City exhibiting 19% burial rates.". Although Elmore (2008) explicitly examined areas around Baltimore City, headwater streams are pervasive across Maryland's landscape. Erosion and habitat loss are known to be associated with increased water volume in riparian areas (Rogers, 2019), so research on runoff from small watersheds could also quantify the amount of increased water volume in these environments, leading to future insights regarding the level of water flow needed to alter an environment.

Figure 2.1: Erosion in a Riparian Area (Rogers, 2019)

The connection between increased stormwater runoff, pollution rates and the degradation of natural ecosystems is well-documented, however it is not explicitly known how well humans are able to mitigate the damage done by urban development. Measures are being implemented to decrease the impact of development on the environment; however, “Green stormwater infrastructure implementation in urban watersheds has outpaced our understanding of practice effectiveness on streamflow response to precipitation events.” (Hopkins et al., 2019). Although we are designing more sustainably, it is not known what effects (particularly long-term (>5 years)) development has on watersheds as a whole in terms of base and peak flow rates, time to peaks, time of concentration and overall runoff volume and duration (Hopkins et al., 2019). Stormwater control measures (SCMs), like sand filters and bioretention ponds, are designed to capture and treat water from storms with certain frequencies and duration (2-yr/24-hr, for example). However, the behavior of water bodies is still affected in regions of development due to piping systems that divert stormwater, a lack of infiltration in the developing area, and the potential for exceedance of the storm for which the SCMs are designed.

The lack of knowledge about how effective these SCMs are is dangerous given the fact that a changing climate will bring with it more intense storms carrying more rainwater than is accounted for in current designs. Not only will SCMs have to mitigate the excess runoff due to land use change, but the bioretention ponds and sand filters must be designed to cope with more extreme rainfall events. Currently, this is not the case; "existing storm water infrastructure designs based on present climate are likely to be inappropriately sized and mostly underdesigned to control future storm events of the same frequency." (Moglen, 2014). Under designing these SCMs could lead to increased flooding in developing areas, property and livelihood damages, and pollutant level increases. These effects will be more severe in regions that have mostly flat land, a high water table and are near the ocean, such as the Eastern Shore of Maryland.

In the coming years and decades, humans will be forced to combat rising sea levels and ocean temperatures, heavier precipitation events, coastal erosion and more severe storm surge (USGCRP, 2018). These challenges will hit the Eastern Shore of Maryland harder than any other part of the state, due to its proximity to the ocean as well as the fact that the fourth national climate assessment conducted by the U.S. Global Change Research Program report states: "Lasting damage to coastal property and infrastructure driven by sea level rise and storm surge is expected to lead to financial losses for individuals, businesses and communities, with the Atlantic and Gulf Coasts facing above-average risks." (USGCRP, 2018). The importance of quantifying the increased runoff potential due to both urbanization and climate change is therefore paramount to the design and construction of resilient infrastructure and residential areas in regions of elevated risk, such as the Eastern Shore.

Climate change is an undeniable truth that will change the face of the planet over the coming years and decades. It is important that future climate models be as accurate as possible to ensure that communities and countries can be well-prepared for this inevitable environmental shift. However, it is impossible to curtail uncertainty completely. "Projections from models are inherently uncertain, because a model can never fully describe the system that it attempts to specify." (Knutti, 2008). Uncertainty is especially prevalent when modeling large systems, such as future rainfall predictions, as these predictions are rooted in overall climate change, which can be impacted by political decisions, policies, war, public outcry and other unforeseen events. Current observations play a key role in determining model boundary conditions, and over the last few decades humans have observed that they are a factor in a warming climate, leading to greater oceanic evaporation and subsequent storm intensity. Although it is agreed upon that humans have an impact on the Earth's climate, it is difficult to determine quantitatively just how different storms in the future will be compared to storms observed today. As greenhouse gas emission rates rise and fall, they are but one boundary condition that could change dramatically in the next few years, thus altering the future climate model predictions (Knutti, 2008).

This study uses WinTR-20 to model the watershed response to storms under both current climate conditions and future climate predictions. WinTR-20 is a rainfall-runoff model developed by the Natural Resources Conservation Service (NRCS, n.d.). It is programmed to incorporate observed precipitation distributions analyzed and published by the National Oceanic and Atmospheric Administration (NOAA, 2004 [2006], 2017) (Merkel et al., 2015). Site-specific distributions can be formulated within WinTR-20, allowing the user to include precipitation values specific to the study location. This will be important moving forward, as half of the study sites contained in this work lie on the Eastern Shore of Maryland, while the other half are located in Frederick County, two areas that see marked differences in rainfall distribution.

Chapter 3: Methods

Section 1: Study Sites

Sites were selected for study inclusion through manual identification of development zoning using publicly available county-wide zoning maps for Frederick and Worcester counties in Maryland (Map Atlases, n.d.). Following manual selection, GISHydro (UM CEE, 2021) was used to delineate and describe the selected watersheds. In site selection, the ratio of the area of development to the overall watershed size was particularly important. Several study sites that fit the general requirement of development were excluded because the area slated for development made up to small a fraction of the total watershed area. After confirming that the watersheds were appropriate in size (relative to the amount of development), the built-in GISHydro land use definitions and zoning maps were compared to the current estimates, to ensure that the models had the same (or similar) future land use designations as the zoning maps. The zoning maps are updated every few years, while the future land use data in GISHydro was input a decade ago.

An integral part of this study is to determine several watersheds that will yield useful results from the research. Each study watershed must meet a few basic criteria. Firstly, the watersheds chosen must be forecast to either develop or remain undeveloped both according to the county and GISHydro. The importance of this is that the research will surmise whether the changing climate or changing land use (development) will be more impactful on the water flow rates during storms in the future. Peak flow rates are of particular interest in this research (especially on the Eastern Shore) due to their impacts on the built environment, which may include flooding and inundation, washing out of poorly built structures, and an inability of residents or emergency services to safely travel along roadways.

Second, the watersheds must have either a significant land use change or no change, and the change/no-change pairs must lie in the same region. This is important to note because it would not be accurate to say that land use change does or does not matter when determining the flow rates caused by future storms when an area in the Piedmont (Frederick County) without development is compared to one on the Coastal Plain (Eastern Shore) with development. The soil types, topography and rainfall data are all different when comparing these areas, so to get meaningful results it is imperative that two contrasting watersheds be from the same general region of Maryland.

Finally, the Eastern Shore of Maryland is of special interest because it is particularly susceptible to the effects of climate change due to its low elevation and flat land. Rising sea levels as well as the increased frequency and severity of storms will disproportionally affect the landscape the Eastern Shore (Boesch et al., 2018). The increased flow rates paired with sea level rise predictions on the Eastern Shore should influence the decisions of residents to either build more resiliently or potentially move. The water table is already high in the area and will rise just at the same time that urbanization and storm severity increase, posing a challenge to everyday life of residents. According to the 2018 sea level rise projections for the state of Maryland, “The likely range (66% probability) of the relative rise of mean sea level expected in Maryland between 2000 and 2050 is 0.8 to 1.6 feet, with about a one-in-twenty chance it could exceed 2.0 feet and about a one-in-one hundred chance it could exceed 2.3 feet" (Boesch et al., 2018). This multi-foot rise in sea level will greatly affect the low-lying areas of the Eastern Shore, an area where inundation is already becoming commonplace. These combined effects led to the choice of study watersheds on the Eastern Shore. Figures 3.1 – 3.4 illustrate conditions on Maryland's Eastern Shore in March of 2021. They show inundation throughout the region and a house on Taylor's Island in Dorcester County.

Figure 3.1: Inundation on the Eastern Shore (Photo Credit: M. Milligan, 2021)

Figure 3.2: High Sea Level/Water Table (Photo Credit: M. Milligan, 2021)

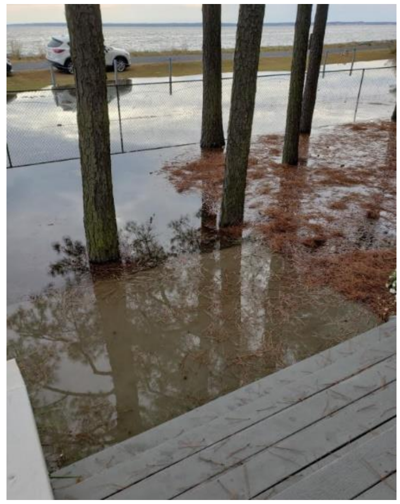


Figure 3.3: Home Flooding on Taylor's Island in Dorchester County, MD (Photo Credit: M. Milligan, 2021)

Figure 3.4: Inundated Home in Dorchester County, MD (Photo Credit: M. Milligan, 2021)

On the Eastern Shore, the county of Worcester has areas predicted to have significant growth as well as areas where there is no plan for development. The city of Snow Hill is zoned to have a large swath of previously undisturbed land become urbanized area (Department of Comprehensive Planning, 2006). This change in land use pairs well with a heavily forested area near St. Luke's Rd that will see no development. Again, GISHydro was used to pinpoint the specific watersheds within the developing and non-developing areas. These watersheds were confirmed to act as the zoning maps described.

In Frederick County, watersheds near Panorama Dr. and Sumantown Rd. were chosen due to the residential development occurring around Panorama Dr. and the relatively stagnant growth near Sumantown Rd. These areas were found using the zoning atlas for Frederick County (Map Atlases, n.d.), and confirmed in GISHydro's ultimate land use map.

1. Snow Hill – Eastern Shore (Development)

The Snow Hill region slated for development is broken up into two distinct watersheds denoted A and B which share a border: the areas are 1 and 1.32 square miles, respectively. The locations are shown in Fig. 3.5. Both watersheds, A and B, have development taking place, although site A has considerably more development planned (Figures 3.6 and 3.7).

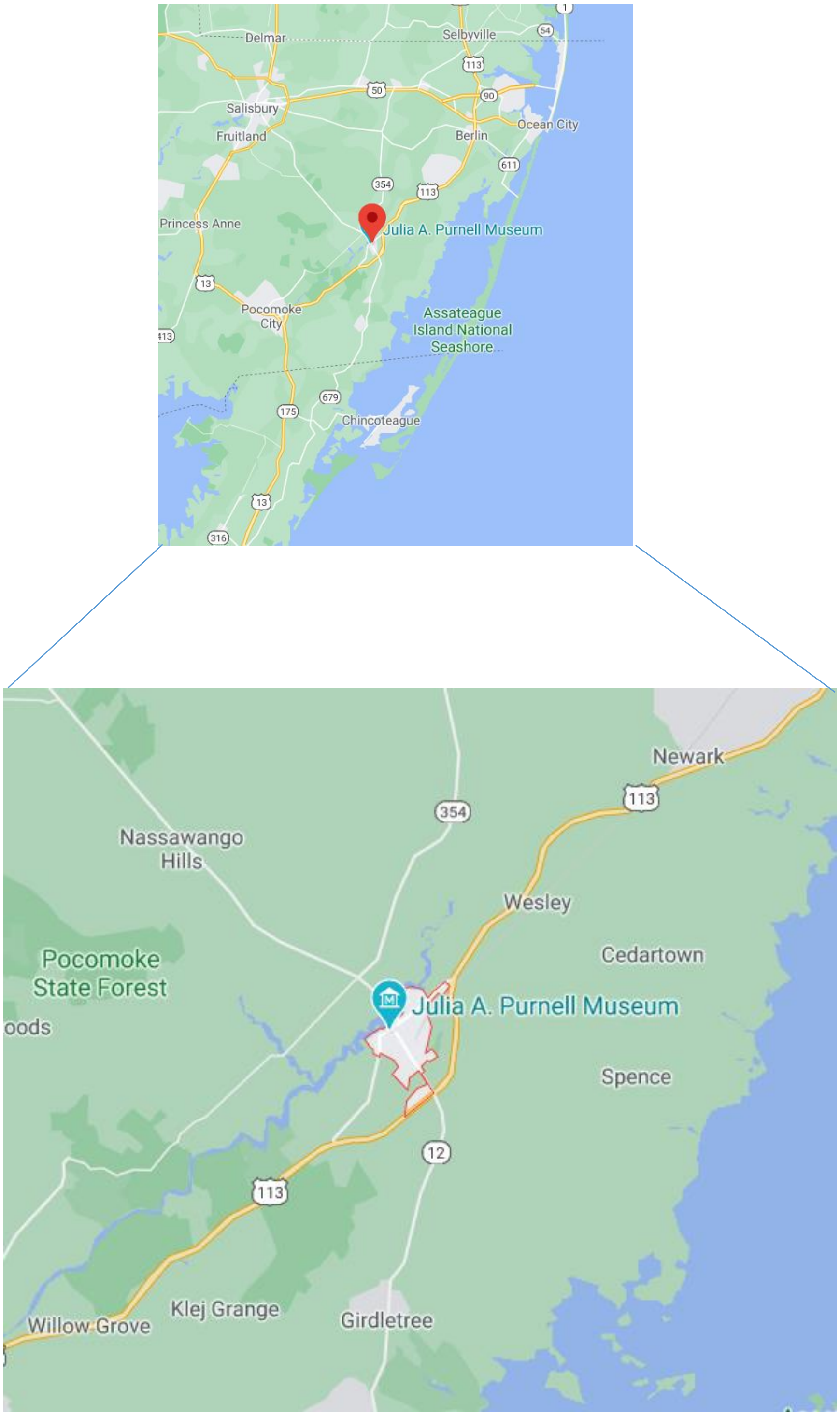


Figure 3.5: Snow Hill Watershed Location (Google Maps)

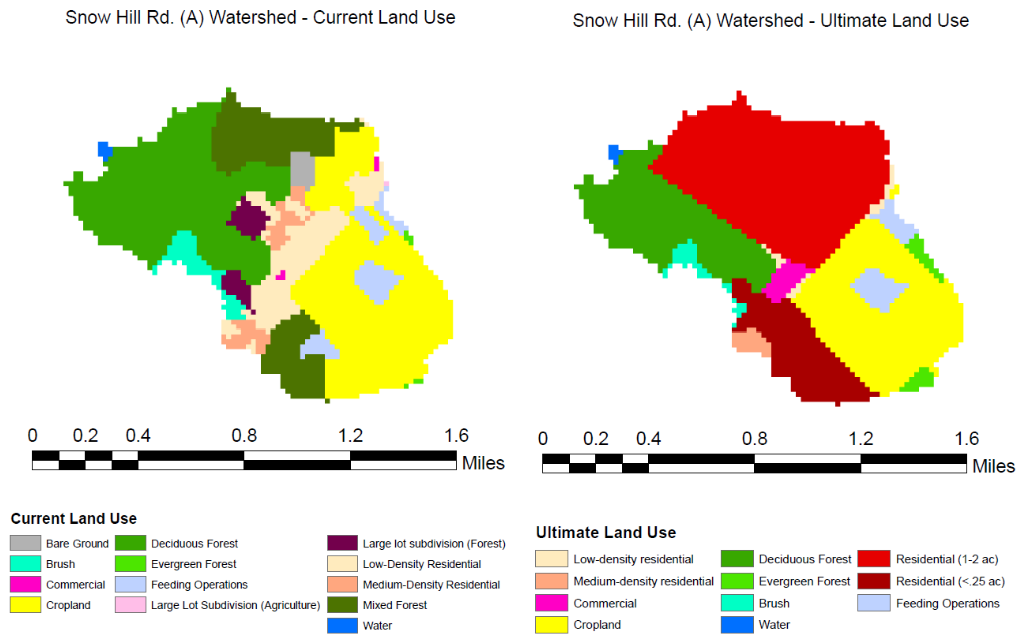


Figure 3.6: Land Use Conditions in Snow Hill (A)

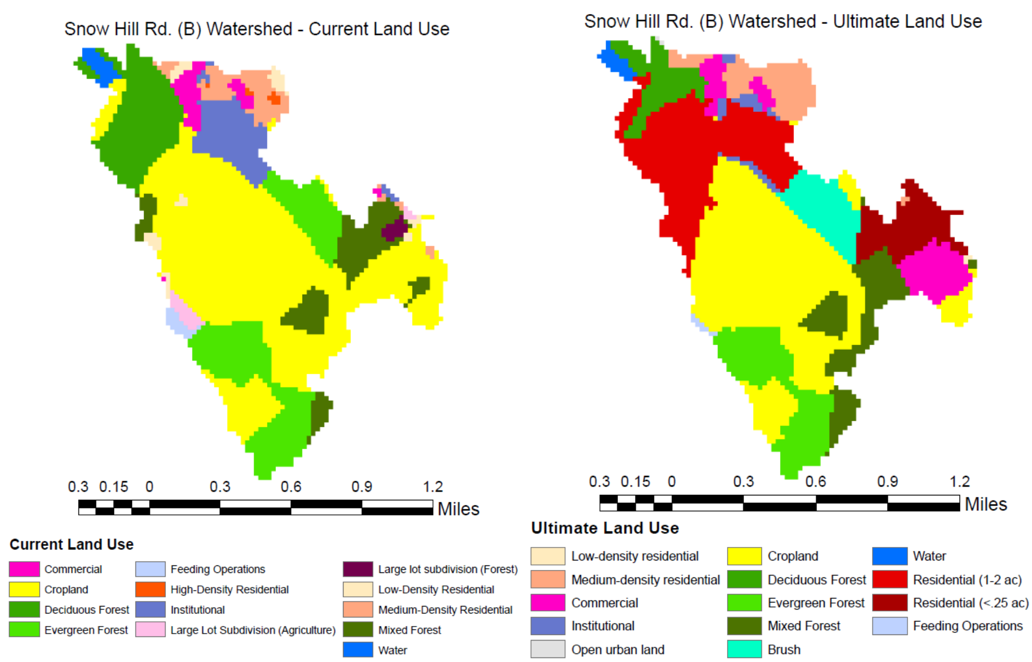


Figure 3.7: Land Use Conditions in Snow Hill (B)

2. St. Luke's Rd.

The St. Luke's Rd. watershed encompasses the headwaters of a small tributary to the Pocomoke River (Fig 3.8). St Luke's Rd. is collector road that travels south east from Salisbury towards Snow Hill. The northern end of the watershed engulfs the road, giving it the name. The size is substantially larger than either of the two Snow Hill watersheds, at 6.18 square miles. This area was chosen because of its proximity to Snow Hill and the fact that no development is planned throughout the watershed (Fig 3.9). It is about 6 miles from Snow Hill (Fig. 3.8); therefore, it can be modeled with the same precipitation data as the Snow Hill watersheds.

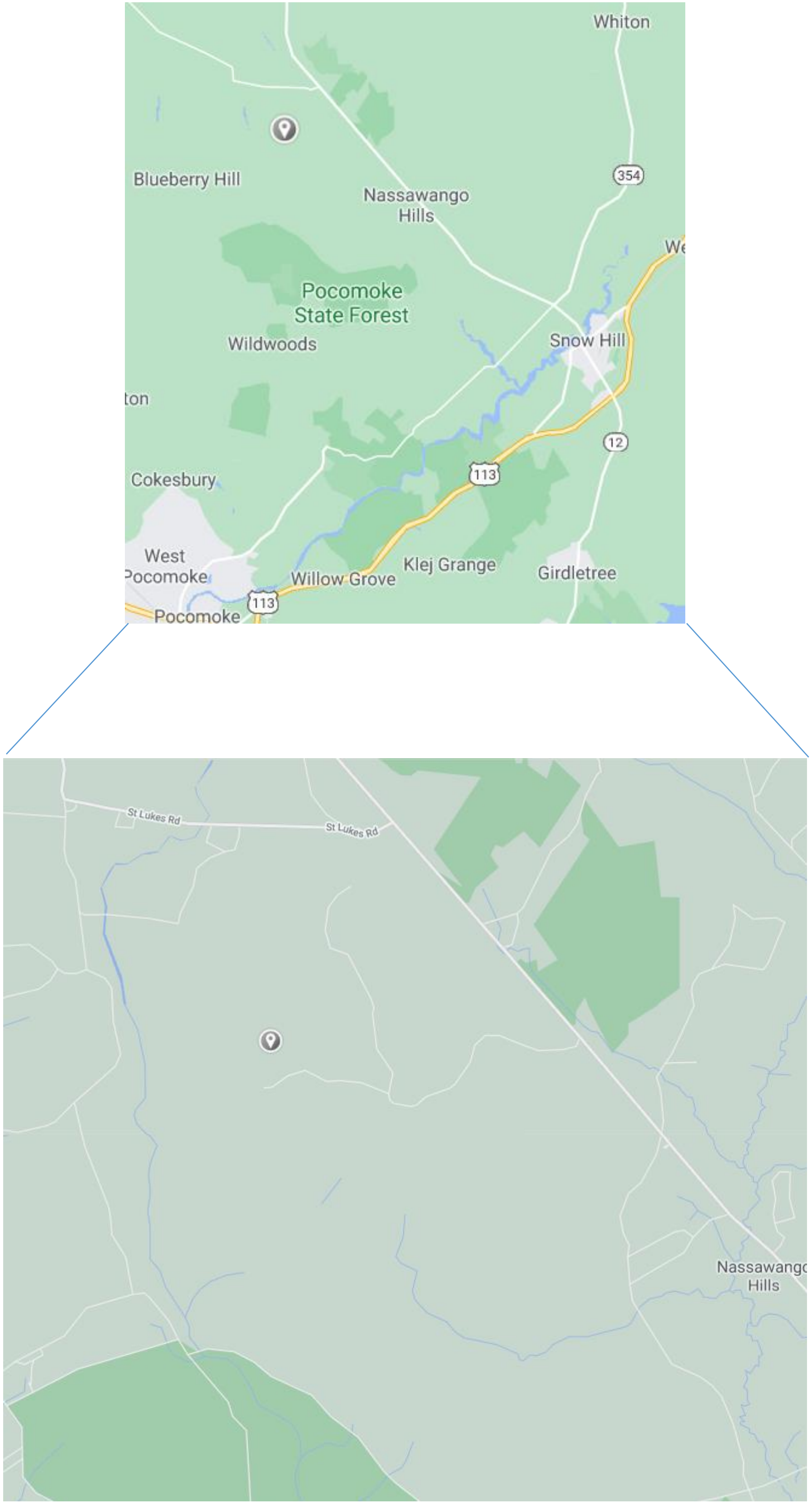


Figure 3.8: St. Luke’s Rd. Watershed Location (Google Maps)

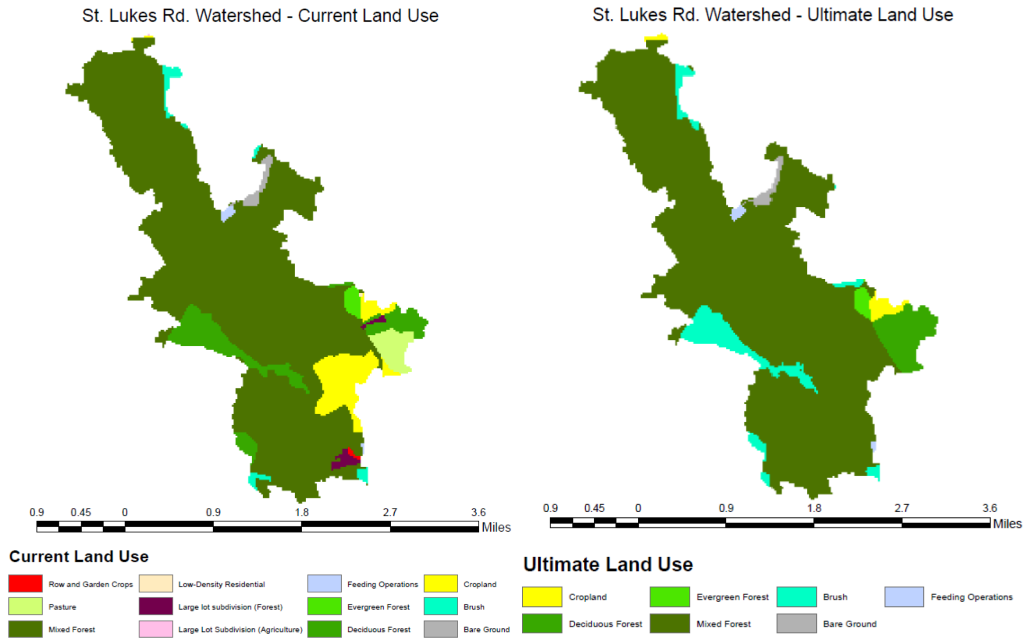


Figure 3.9: Land Use Conditions in the St. Luke's Rd. Watershed

3. Sumantown Rd.

The Sumantown Rd. watershed, located west of the city of Frederick, is divided into two study sites that share a border. The first site, denoted "Sumantown Rd. A", has an area of 0.64 square miles, while its counterpart, "Sumantown Rd. B" has a larger area of 4.48 square miles. The area is undergoing changes but not necessarily urban or suburban development (Figs. 3.11 and 3.12). The future land use data in GISHydro has different categories than the current data, so land that was previously denoted as "Low-density Residential" can now be broken up into residential areas by lot size. This change in designation will alter the curve number (CN) slightly even though there is not any major development planned for the region.

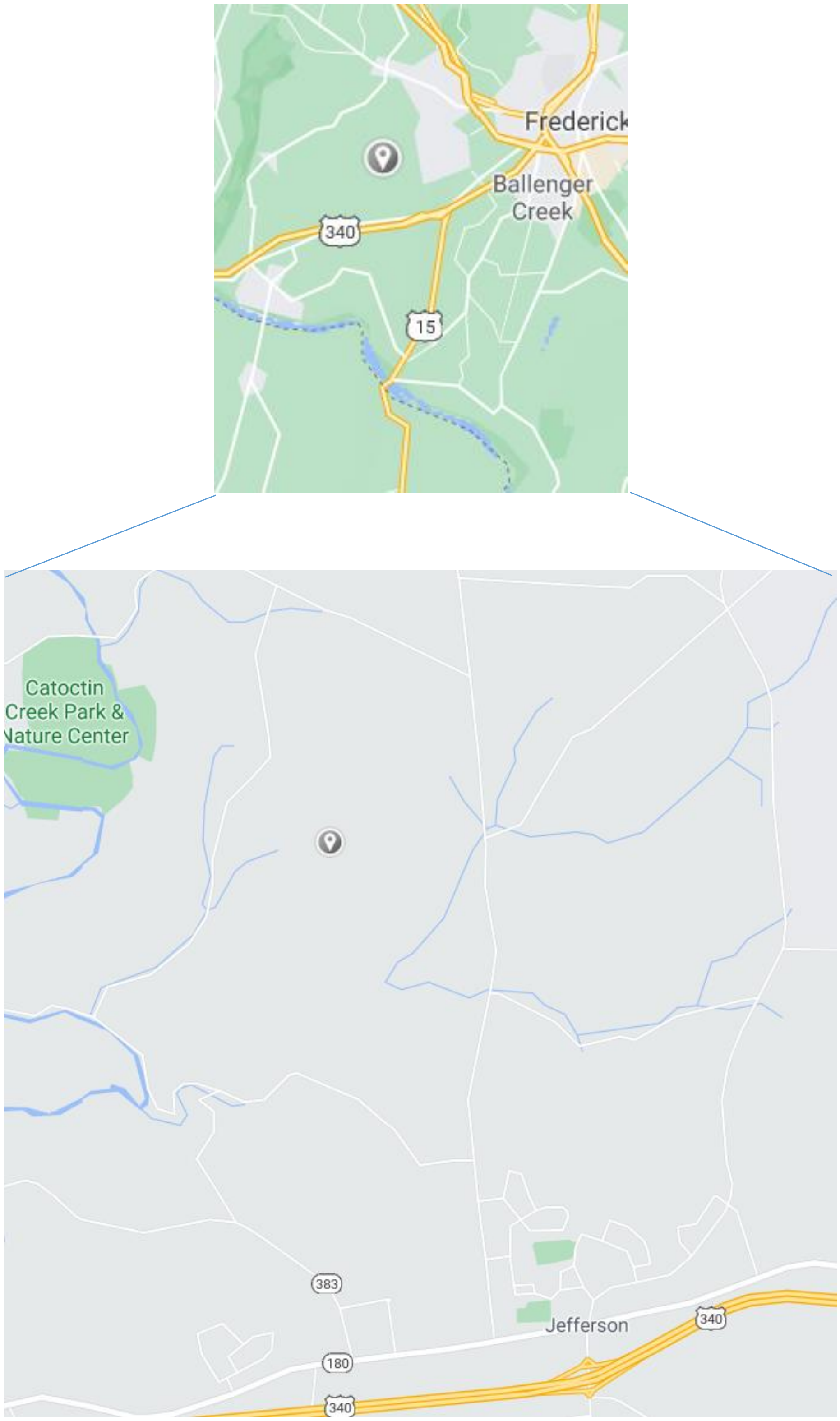


Figure 3.10: Sumantown Rd. Watershed Location (Google Maps)

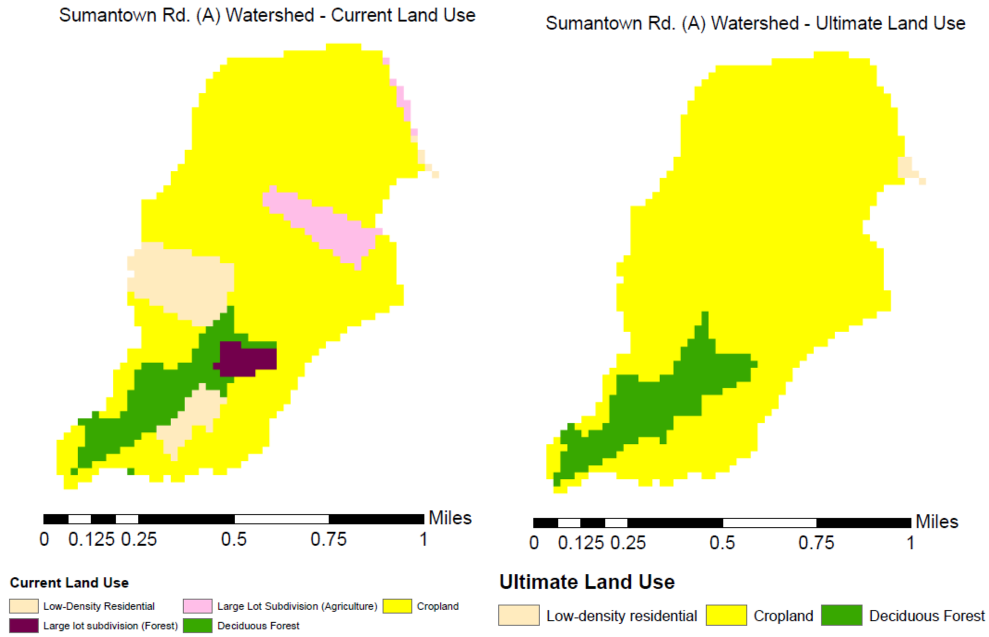


Figure 3.11: Land Use Conditions in the Sumantown Rd. (A) Watershed

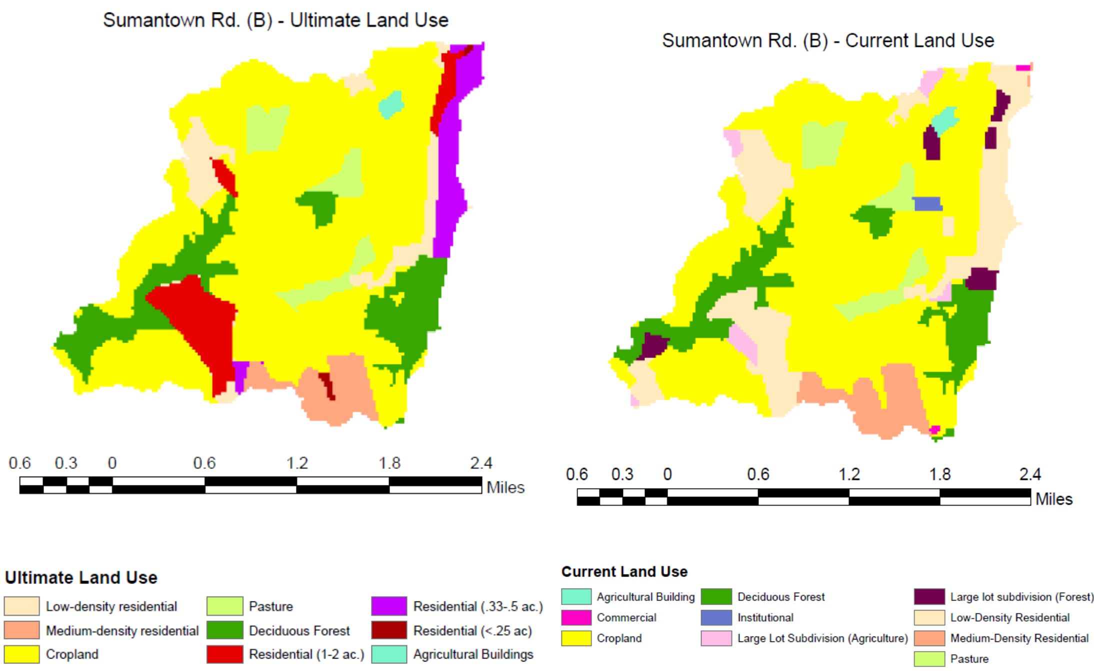


Figure 3.12: Land Use Conditions in the Sumantown Rd. (B) Watershed

4. Panorama Dr.

The Panorama Dr. watershed is also near the city of Frederick, although to the east (Fig. 3.13). It is about 17 miles east of the Sumantown Rd. watershed and therefore in a similar hydrometeorological zone. Panorama Dr. is 3.42 square miles in area and is arguably the watershed undergoing the most change. A large swath of deciduous forest is zoned to be developed into residential areas of lot sizes 0.25 - 0.33 acres (Fig. 3.14). This change is expected to alter the hydrologic behavior of the watershed, including higher peak flows, less time to peak, less overall runoff duration, and more polluted runoff.

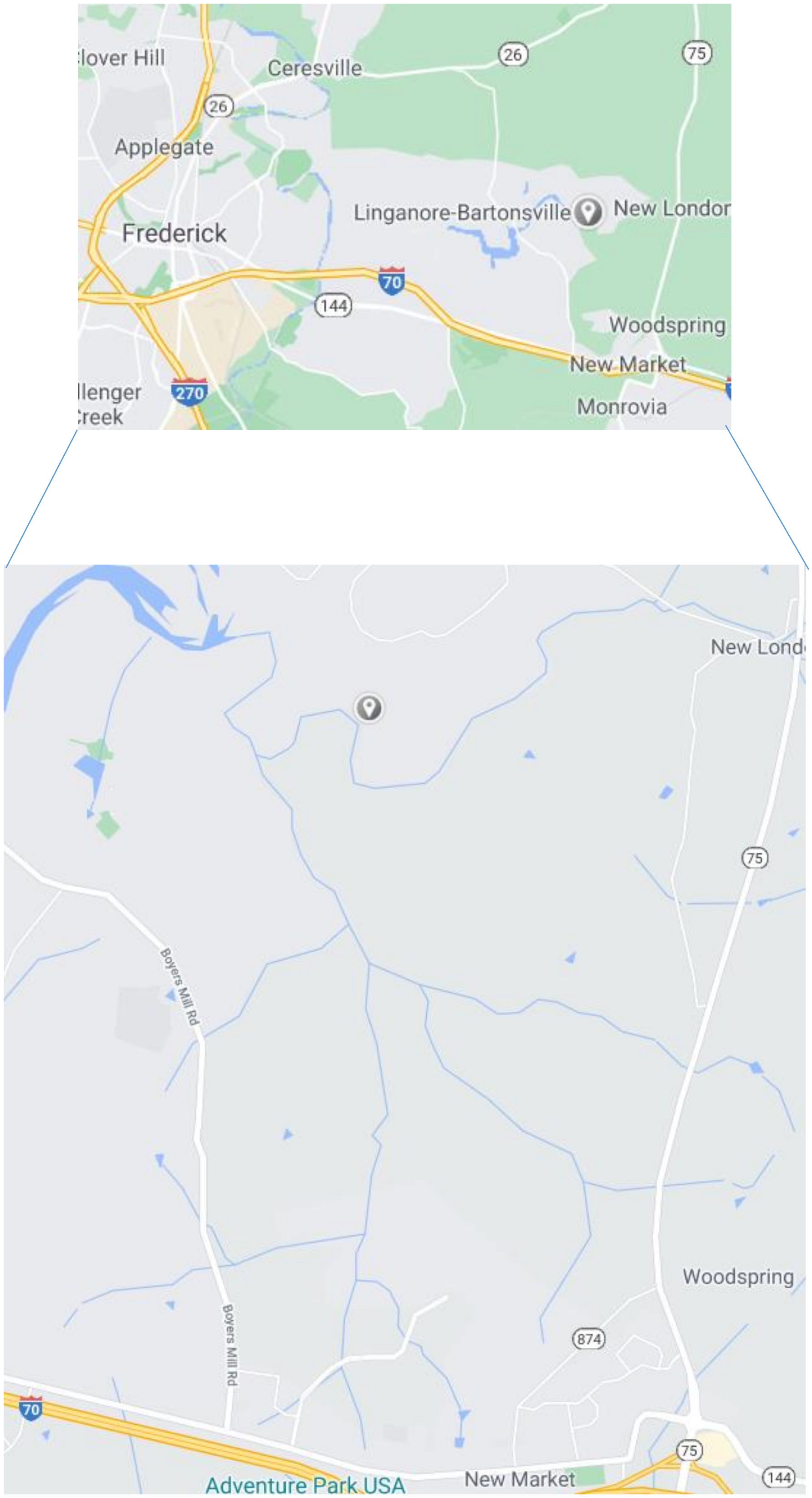


Figure 3.13: Panorama Dr. Watershed Location (Google Maps)

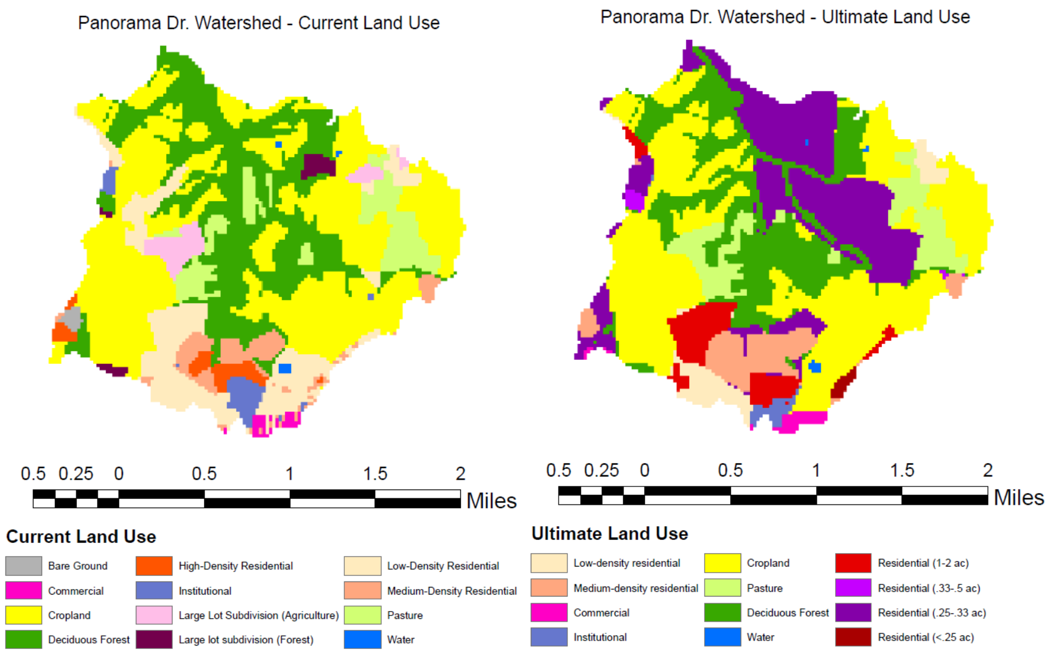


Figure 3.14: Land Use Conditions in the Panorama Dr. Watershed

Section 2: Process

Two specialized programs, GISHydro and WinTR-20, were used for this analysis. GISHydro is a program developed by the Department of Civil and Environmental Engineering at the University of Maryland that works with WinTR-20 (a single storm routing and runoff analysis program) to develop predictions of storm events in the state of Maryland. WinTR-20 requires several inputs from GISHydro to formulate predictions, including land cover, soil type, slope, and watershed area. With the implementation of GISHydro, calculations to predict flows after a storm in Maryland using WinTR-20 can be done in a fraction of the time it would take if the land had to be surveyed for each prediction. GISHydro draws on the land-soil-topographical database for the state of Maryland (using SSURGO soils data) and incorporates these values into the parameters required for each WinTR-20 simulation (Maryland Hydrology Panel, 2016).

One of the most important steps in accurately modeling flow rates in each watershed is the calibration of the model. To do this, GISHydro calculates the Thomas Discharges within each watershed. These discharges represent peak flow estimates for each level of storm severity, from a 1.25 to a 500-year event (1.25, 1.5, 2, 5, 10, 25, 50, 100, 200, 500). The regression equations used to compute these estimates vary based on the location of the watershed – the Eastern Shore (including Worcester County) uses a different set of equations than Frederick County. This set of regression equations for 4 sections of the state (Eastern Coastal Plain, Western Coastal Plain, Piedmont-Blue Ridge, and Appalachian Plateau) was derived following investigation of multiple gauging stations throughout each area (Maryland Hydrology Panel, 2016).

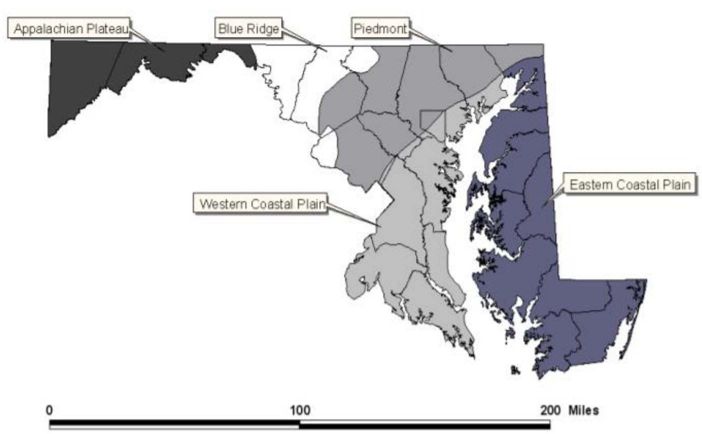


Figure 3.15: "Hydrologic Regions Defined by Dillow (1996) and Used by Moglen and others (2006) and Thomas and Moglen (2015)" (Maryland Hydrology Panel, 2016)

The equations used by GISHydro incorporate watersheds of varying sizes, impervious land cover percentages and soil types. Each equation includes the drainage area, impervious coverage and slope of the watershed being analyzed, but does so with different weights assigned to each parameter. Additionally, these Thomas discharges (named after Wilbert O. Thomas Jr., who created these equations with co-author Glenn E. Moglen) include standard error measurements and the equivalent years of record. Equivalent years of record are defined as “the number of years of actual streamflow record required at a site to achieve an accuracy equivalent to the standard error of prediction of the regional regression equation” (Maryland Hydrology Panel, 2016). Tables detailing these equations for each region of Maryland as well as the calculation for the equivalent years of record are listed in the Appendix.

WinTR-20 tends to overpredict flows (Maryland Hydrology Panel, 2016) and therefore the models for each watershed must be compared with the regression equation estimates for their region. Each model contains prediction intervals that accompany the regression equations that signify the level of deviation between the estimated flow and the extremes around this value. The Maryland Hydrology Panel recommends calibration to a level of the 67% regression equation prediction window, meaning the analysts estimate a 67% probability that the true value of the discharge lies within the specified bounds (Maryland Hydrology Panel, 2016). When calibration is required, the time of concentration (Tc) in the watershed must be changed. To do this, the Manning’s roughness coefficient (n) of the prominent channel can be altered from the default .05 value to one signifying a rougher or smoother channel; increasing the value indicates a rougher channel and therefore a longer Tc, whereas decreasing the value has the opposite effect. The Manning coefficient relates to Manning's equation, equation (3.1) used to find the velocity of water in a channel:

$$V = (1.49/n)*R^{2/3}S^{1/2} \tag{3.1}$$

where V (ft/s) is the velocity of the water; R (ft) is the hydraulic radius; n is the Manning's roughness coefficient; and S (ft/ft) is the slope of the channel.

A WinTR-20 model was initially developed and calibrated for each watershed under current climate. Then the precipitation input was replaced with depths and distributions representing the future climate. The scenarios listed in Table 3.1 were performed for each study watershed; the WinTR-20 model provides the watershed runoff response to a design storm of a particular return period (of annual exceedance probability, AEP). Because watershed runoff is a nonlinear function of precipitation, the AEP of the calculated peak discharge is not necessarily the same as that of precipitation.

Table 3.1: Summary of Modeled Events

	Current Land Use	Ultimate Land Use
Current Precipitation IDF	"Baseline"	"Land Use Change"
Future Precipitation IDF	"Climate Change"	"Climate + Land Use Change"

Note: All models: 2-, 10-, 25-, 50- and 100-year Return Periods (50%, 10%, 4%, 2% and 1% Annual Exceedance Probability), 24-hour Precipitation Duration

The tools and steps required to model climate and land use change impacts on runoff for each watershed were as follows:

Using GISHydroNXT:

1. Delineate the watershed
2. Gather spatial data in the watershed, including soil types and land uses.
3. Assemble current precipitation data in design-storm format.
4. Calculate regression-based peak discharge for selected return periods (Thomas discharges).
5. Calculate watershed time of concentration (Tc).
6. Generate input data for WinTR-20 for each storm return period and duration (2,10,25,50,100-yr return periods with 6,12,24 hr durations each).
7. Calibrate and run WinTR-20 model for current land use with current precipitation ("Baseline") and ultimate land use with current precipitation ("Land Use Change").

Using stand-alone WinTR-20:

8. Use WinTR-20 precipitation import tool to format future-climate IDF estimates.
9. Create new WinTR-20 input files with future-climate precipitation input replacing current precipitation.
10. Run WinTR-20 for current land use with future precipitation ("Climate Change").
11. Run WinTR-20 for ultimate land use with future precipitation ("Land Use + Climate Change").

Using Python:

12. Extract appropriate features from WinTR-20 outputs for each storm (return period and duration (Custom script written by the author)).
13. Visualize storms in each watershed together to assess the impact of future development and precipitation on peak flow rates/timings.

Using Microsoft Excel:

14. Extract parameters from WinTR-20 model output
    a. Peak flow rate
    b. Time to peak
    c. Duration of runoff
15. Normalize the peak flow rates (Divide by watershed area for comparisons among watersheds of unequal size)
16. Visualize results
    a. Peak flow rate
        i. Normalized peak flows
        ii. Percent change between baseline and other scenarios
    b. Time to peak
        i. Percent change between baseline and other scenarios
    c. Duration of runoff
        i. Percent change between baseline and other scenarios

An example of the calibration results, in step 7, including the final Manning's n value for the Snow Hill (A) region is shown in Fig. 3.16. The remainder of the calibration graphs may be found in the Appendix.

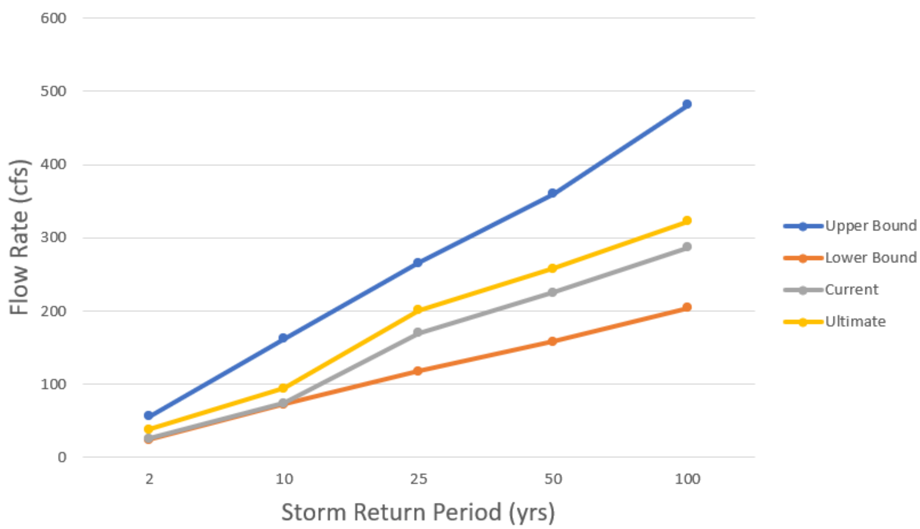


Figure 3.16: Snow Hill (A) Calibration Envelope (n = 0.085)

Another major part of this research was the retrieval and application of future precipitation data. Research conducted under a separate project by Dr. Kaye Brubaker's group led to the development of these future precipitation estimates (Charochak, 2019). The future precipitation estimates are based on model output from the NARCCAP, the North American Regional Climate Change Assessment Program (Mearns et al. 2007, updated 2014). The NARCCAP is an international program which uses regional climate models (RCM's) in conjunction with atmosphere-ocean general circulation models (AOGCM's) to produce future climate projections across the United States and the majority of Canada (UCAR, 2007). The NARCCAP models provide precipitation values on a 5-km grid at 3-hour intervals. Twelve AOGCM-RCM pairs were interpolated to a 750-m grid (to match GISHydro), ensemble-averaged and downscaled to shorter durations using ratios from NOAA (2004

[2006]). These projections represent climate change impacts on the years 2040 to 2071, assuming a carbon emissions scenario at the "higher end" of those being considered at the time the experiments were conducted (UCAR, 2007).

The modeling and analysis steps were performed on the six study watersheds described at the beginning of this chapter. The properties of the watersheds are summarized in Table 3.2.

Table 3.2: Watershed Properties

Watershed	Area (mi^2)	Tc (hr)	CN Current Land Use	CN Ultimate Land Use
Snow Hill A	0.99	4.67	67.0	71.7
Snow Hill B	1.32	5.26	72.6	72.2
St. Luke's Rd.	6.18	7.09	69.4	67.3
Panorama Dr.	3.42	1.56	77.5	78.2
Sumantown A	0.64	0.86	75.7	76.3
Sumantown B	4.48	1.52	74.0	73.9

Note: Calculated by GISHydroNXT

Chapter 4: Results

The hydrographs for each watershed using (a) current land use and precipitation data (Baseline), (b) current land use with future precipitation data (Climate Change), (c) ultimate land use with current precipitation data (Land Use Change) and (d) ultimate land use with future precipitation data (Land Use + Climate Change) were generated using WinTR-20. From the hydrographs, three summary measures were extracted: peak discharge, full duration of runoff, and time to peak. It is important to note that the future precipitation data only allowed for the analysis of 24-hr duration storms, so when comparisons were made between the current and future climate conditions, each storm of a given return period had the same duration of 24 hours.

The peak flow analysis revealed that land use change in two of the developing watersheds (Snow Hill A and Panorama Dr.) increased the peak flow of each return period storm (2, 10, 25, 50, 100-yr). This was not the case for the Snow Hill B watershed, however, which showed a slight decrease in each model. Similarly, in the watersheds that were not developing (and in the St. Luke's Rd. watershed case, becoming less developed due to ultimate land use containing more deciduous forest) the peak flows were unaffected or decreased. These peak flow changes at their most prominent instance increased by 36.2% (Snow Hill A, 2-yr). In contrast, the St. Luke's Rd. watershed saw its peak flow rate drop by 12.4% for the 2-yr return period storm, and the flow remained below the current land use conditions model for each event.

In the Climate Change experiments, the 6 watersheds retained their current land use designations and were modelled using future climate conditions. These conditions increased the overall precipitation seen by each watershed by up to 5.93, 23.09, 23.14, 20.54 and 16.56 percent for the 2, 10, 25, 50 and 100-yr return period storms, respectively (Tables 4.1 through 4.5).

Table 4.1: 24-hr Duration, 2-yr Rainfall Event Precipitation Depth Change

Watershed	Current Climate (in)	Future Climate (in)	Change (%)
Snow Hill A	3.41	3.57	4.69
Snow Hill B	3.42	3.57	4.39
St. Luke’s Rd.	3.37	3.57	5.93
Panorama Dr.	3.01	3.11	3.32
Sumantown A	2.98	3.08	3.36
Sumantown B	2.97	3.08	3.70

Table 4.2: 10-yr, 24-hr Duration Storm Precipitation Depth Change

Watershed	Current Climate (in)	Future Climate (in)	Change (%)
Snow Hill A	5.32	6.45	21.24
Snow Hill B	5.34	6.45	20.79
St. Luke’s Rd.	5.24	6.45	23.09
Panorama Dr.	4.61	5.33	15.62
Sumantown A	4.46	5.05	13.23
Sumantown B	4.45	5.05	13.48

Table 4.3: 25-yr, 24-hr Duration Storm Precipitation Depth Change

Watershed	Current Climate (in)	Future Climate (in)	Change (%)
Snow Hill A	6.68	8.09	21.11
Snow Hill B	6.69	8.09	20.93
St. Luke's Rd.	6.57	8.09	23.14
Panorama Dr.	5.77	6.59	14.21
Sumantown A	5.49	6.17	12.39
Sumantown B	5.50	6.17	12.18

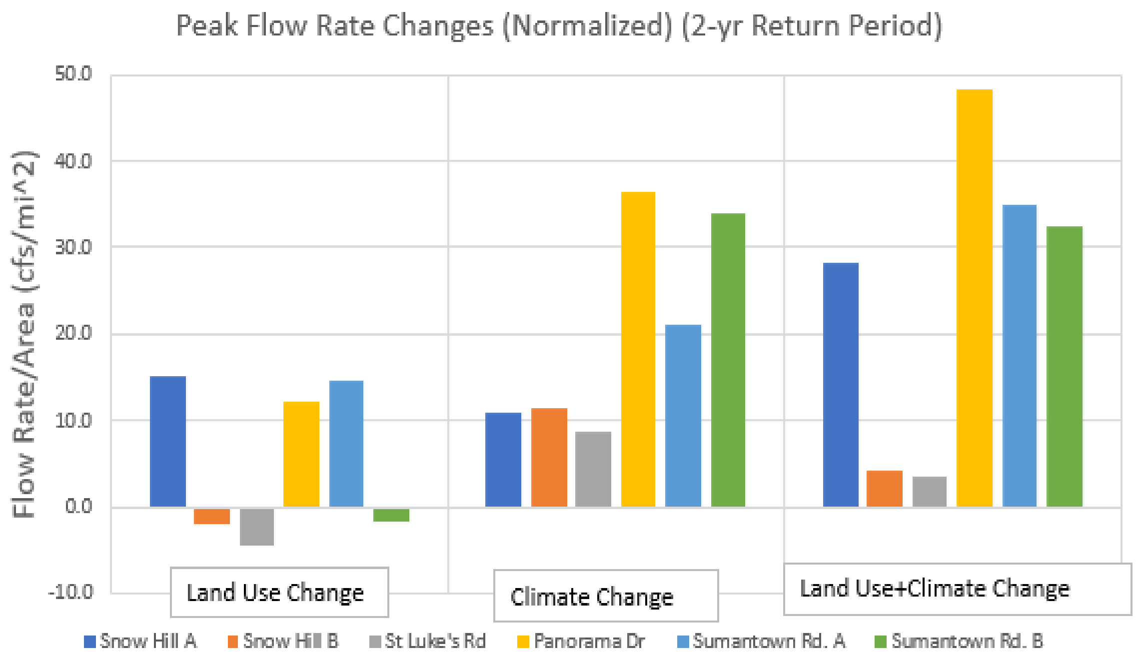
Table 4.4: 50-yr, 24-hr Duration Storm Precipitation Depth Change

Watershed	Current Climate (in)	Future Climate (in)	Change (%)
Snow Hill A	7.87	9.33	18.55
Snow Hill B	7.88	9.33	18.40
St. Luke's Rd.	7.74	9.33	20.54
Panorama Dr.	6.79	7.55	11.19
Sumantown A	6.38	7.01	9.87
Sumantown B	6.42	7.01	9.19

Table 4.5: 100-yr, 24-hr Duration Storm Precipitation Depth Change

Watershed	Current Climate (in)	Future Climate (in)	Change (%)
Snow Hill A	9.20	10.56	14.78
Snow Hill B	9.21	10.56	14.66
St. Luke's Rd.	9.06	10.56	16.56
Panorama Dr.	7.96	8.51	6.91
Sumantown A	7.38	7.86	6.50
Sumantown B	7.45	7.86	5.50

The changes in peak discharge compared to Baseline for all six watersheds under land use change alone, precipitation change alone, and combined land use and precipitation change, are shown in Fig. 4.1 through 4.5. Each figure presents the results for a different return period. The normalized peak flow rate change (upper bar graphs) considers the area of the watersheds.



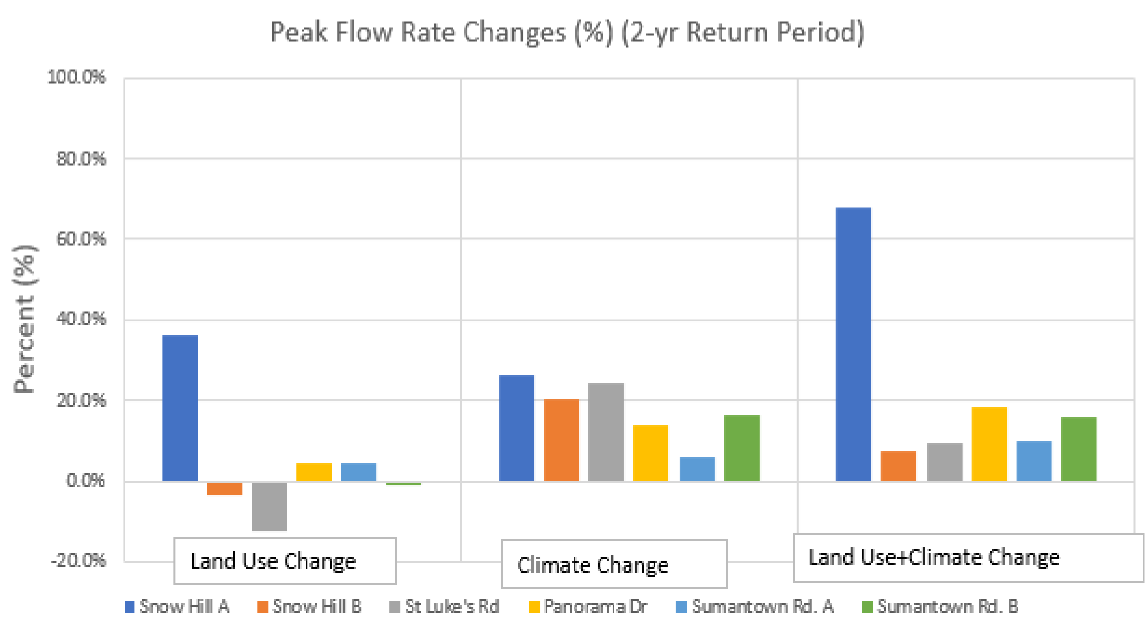


Figure 4.1: Peak Flow Rate Analysis of 24-hr Duration, 2-yr Return Period

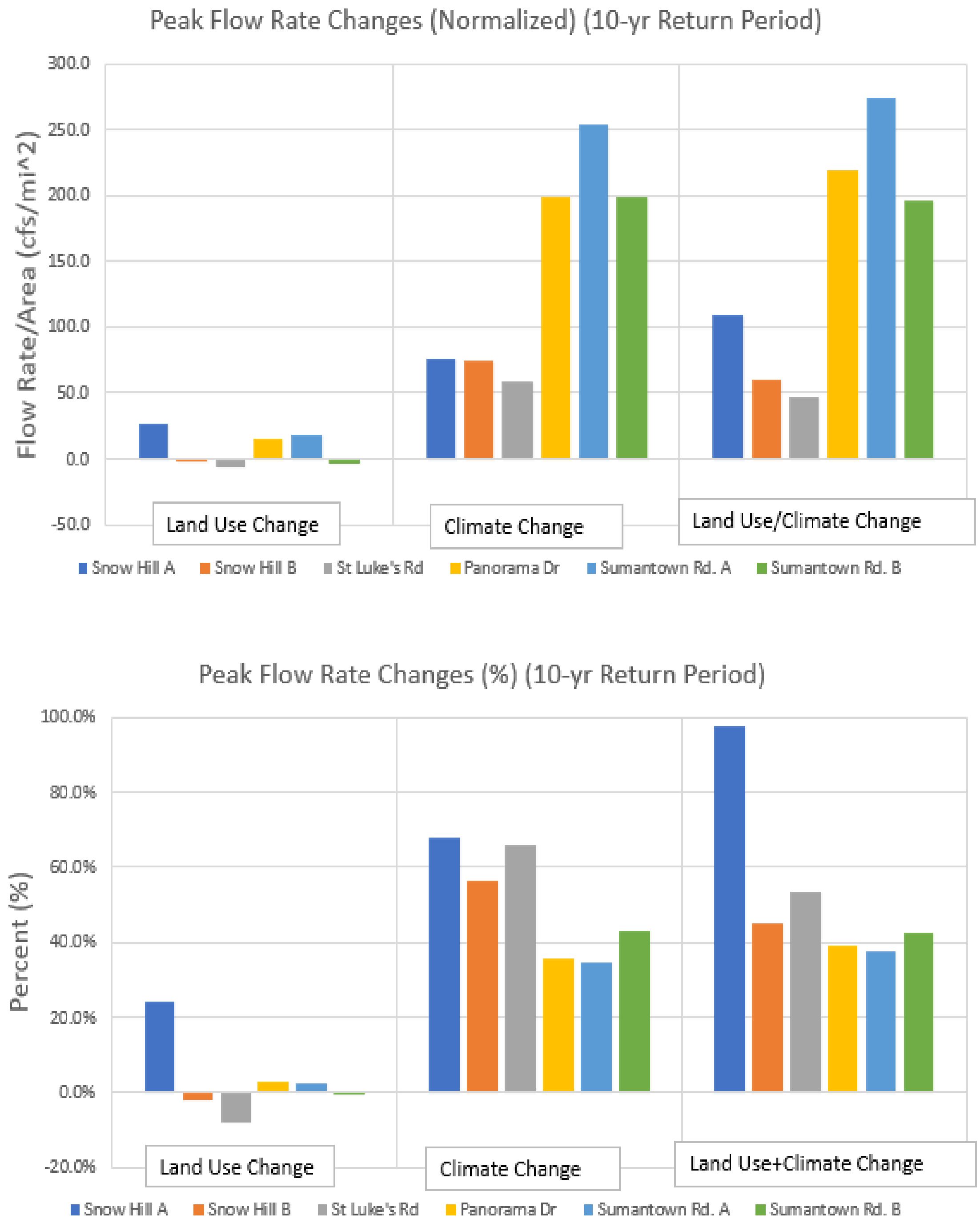


Figure 4.2: Peak Flow Rate Analysis of 24-hr Duration, 10-yr Return Period

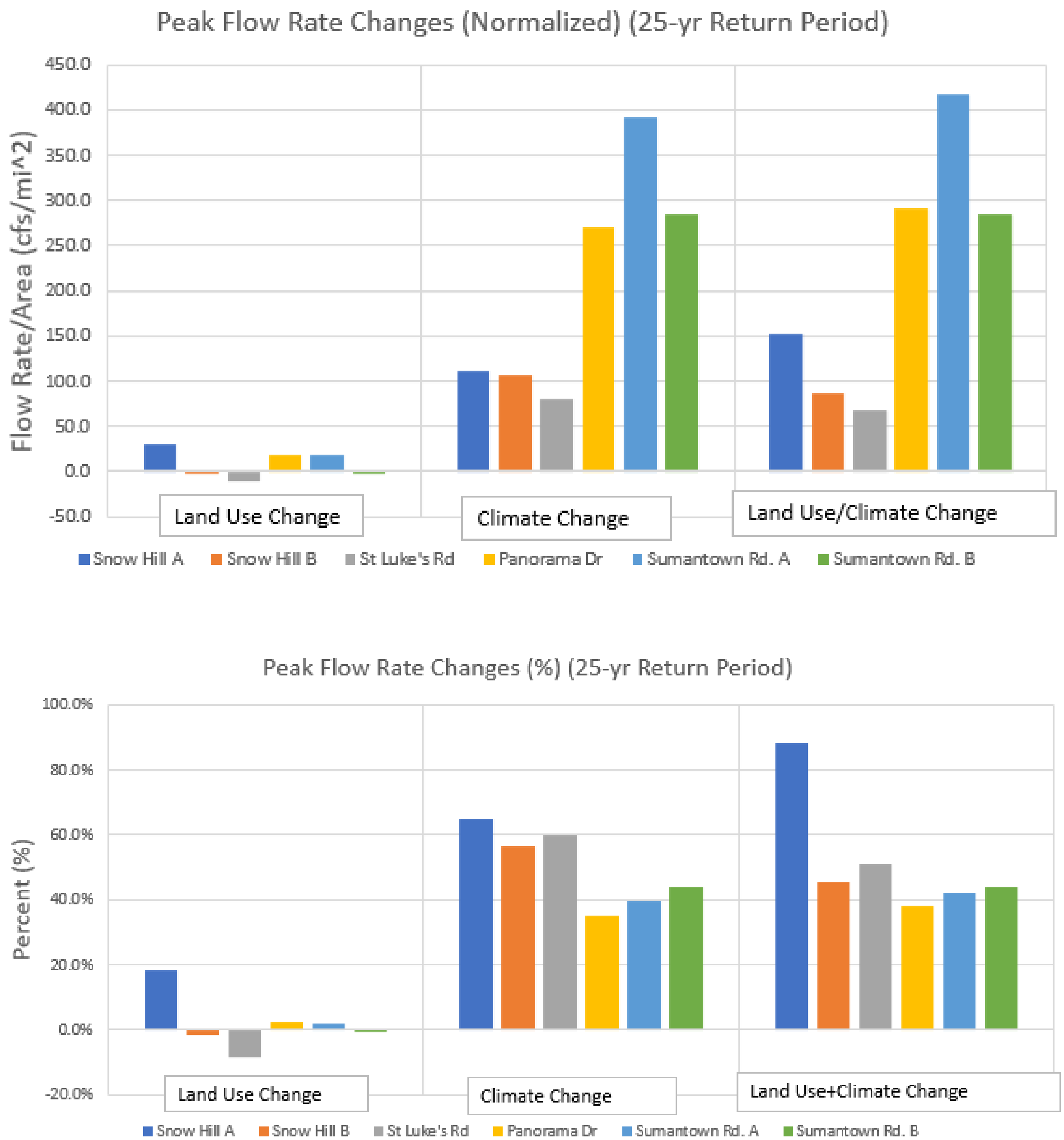
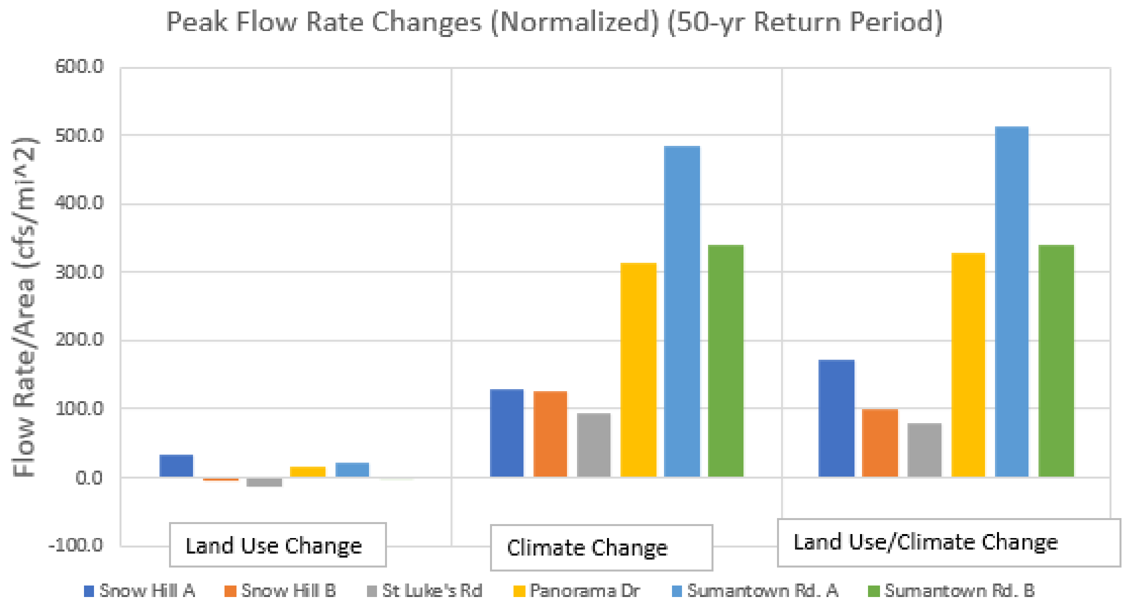


Figure 4.3: Peak Flow Rate Analysis of 24-hr Duration, 25-yr Return Period



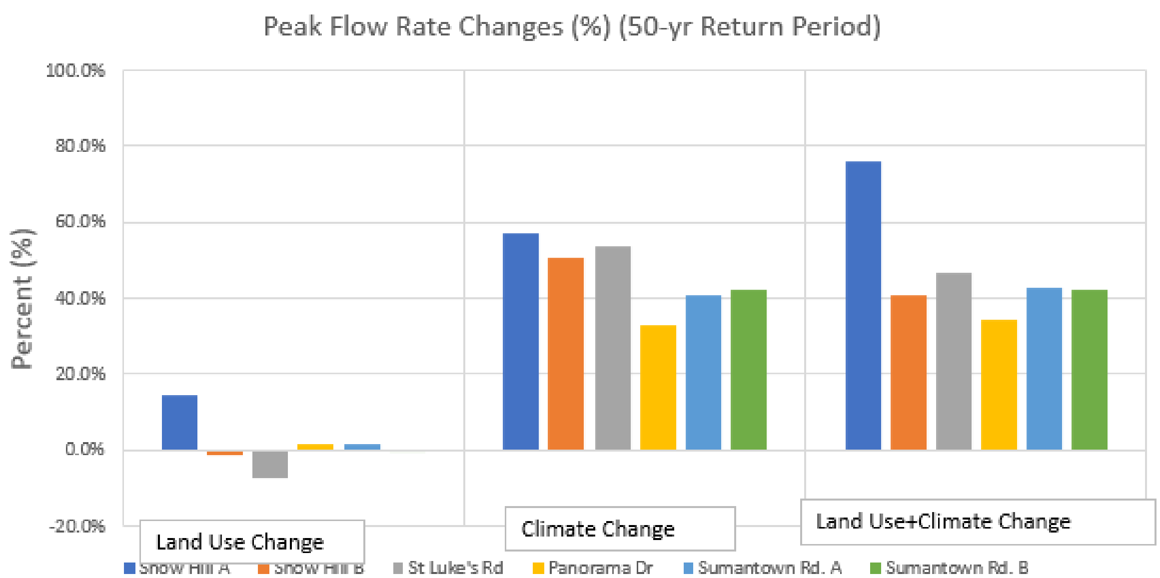


Figure 4.4: Peak Flow Rate Analysis of 24-hr Duration, 50-yr Return Period

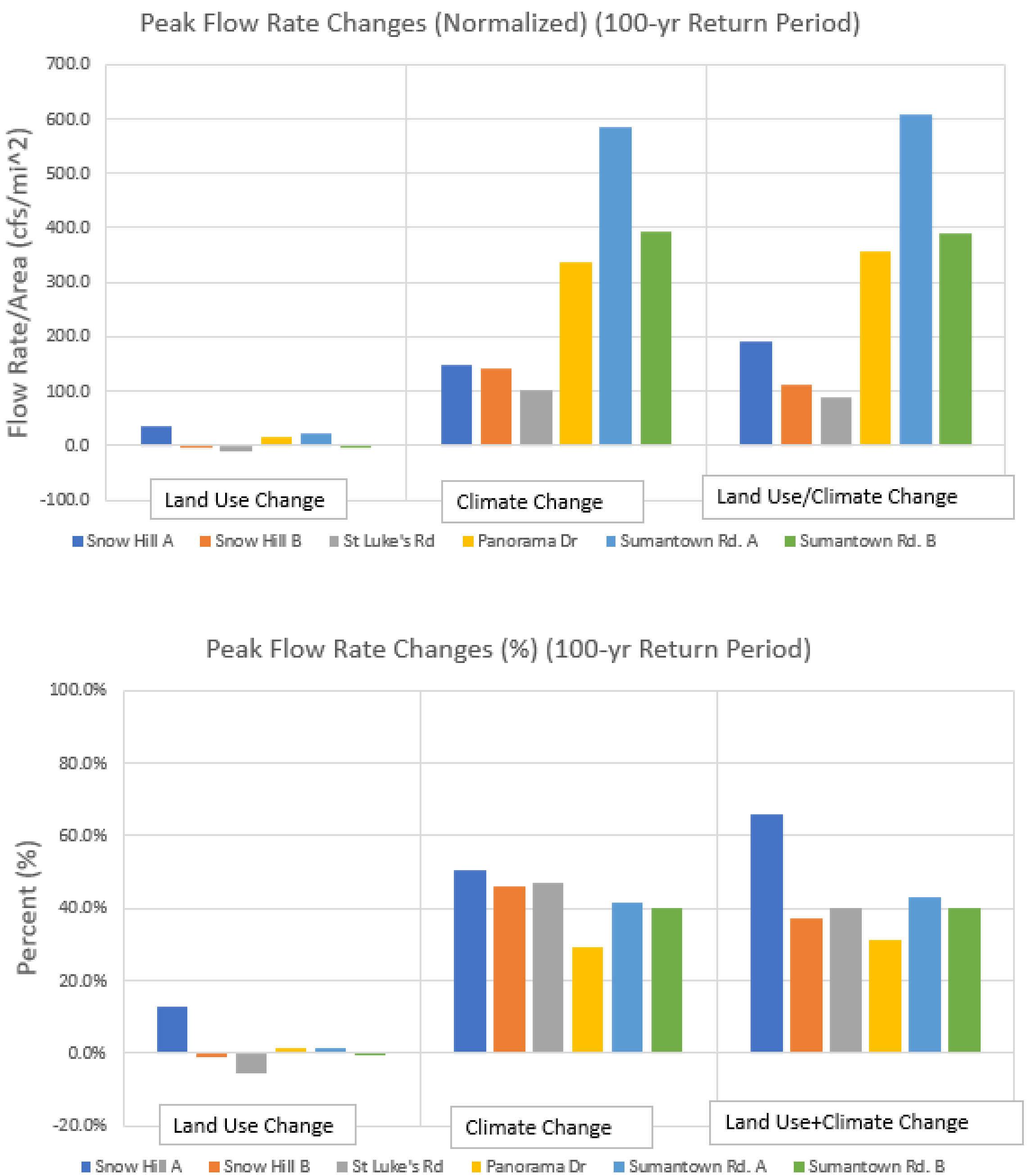


Figure 4.5: Peak Flow Rate Analysis of 24-hr Duration, 100-yr Return

The effect of climate change on each watershed is noticeably more impactful than the effect of development. In only a single case (Snow Hill A 2-yr, 24-hr storm) is the peak flow rate higher due to land use change as opposed to climate change. The percent difference between the two increases is only 10.1%, which is low when compared to the percent difference between any other watershed in any scenario. Additionally, the effects of land use change on St. Luke's Rd., Snow Hill B and Sumantown Rd. B show a decrease in peak flow rate for each return period (gray, orange and green bars in Figs. 4.1 through 4.5). These decreases, however, are overshadowed by the larger effect of climate change in each scenario.

Overall, when both types of change are considered, the peak flow rate change is not a simple additive value of the individual land use and climate change effects; rather there is a non-linear hydrologic response that occurs due to the compounding effects of shifting land use and climate. This is especially true for high-frequency events (2/10-yr models) that occur on watersheds with significant development. The Snow Hill A watershed has an increased peak flow rate due to land use alone of 36.2%, an increase due to climate change alone of 26.3%, and a combined increase of 67.6%. The relationship between increased development and increased precipitation is deeper than just the sum of the individual effects. Additionally, not only developing watersheds will experience a substantial increase in peak flows, as the St. Luke's Rd. watershed is one of those most affected by the changing climate: a 60% increase in peak discharge for the 10- and 25- year events (gray bars in Figs. 4.2 and 4.3) and 50% for the less frequent events (gray bars in Figs. 4.4 and 4.5).

More severe peak flow rates are emblematic of transforming watersheds; however, they are only one of several variables used to predict how a watershed will change over the coming years and decades. The time it takes to reach the peak flow rate as well as the total time of measurable runoff from a single storm event are both important qualities to inspect to gauge how a watershed will act. The changes between these variables were extracted from the WinTR-20 output files and graphed to show the impact of changing land use and climate.

Figures 4.6 through 4.10 show the change in runoff duration relative to the Baseline. In each case, the design storm is 24 hours. The duration of runoff was determined as the point when the discharge hydrograph reaches 0 in the WinTR-20 output. In each figure, the top bar graph gives the change (hours) in runoff duration compared to Baseline, and the bottom bar graph gives the same information, expressed as a percent of the baseline value.

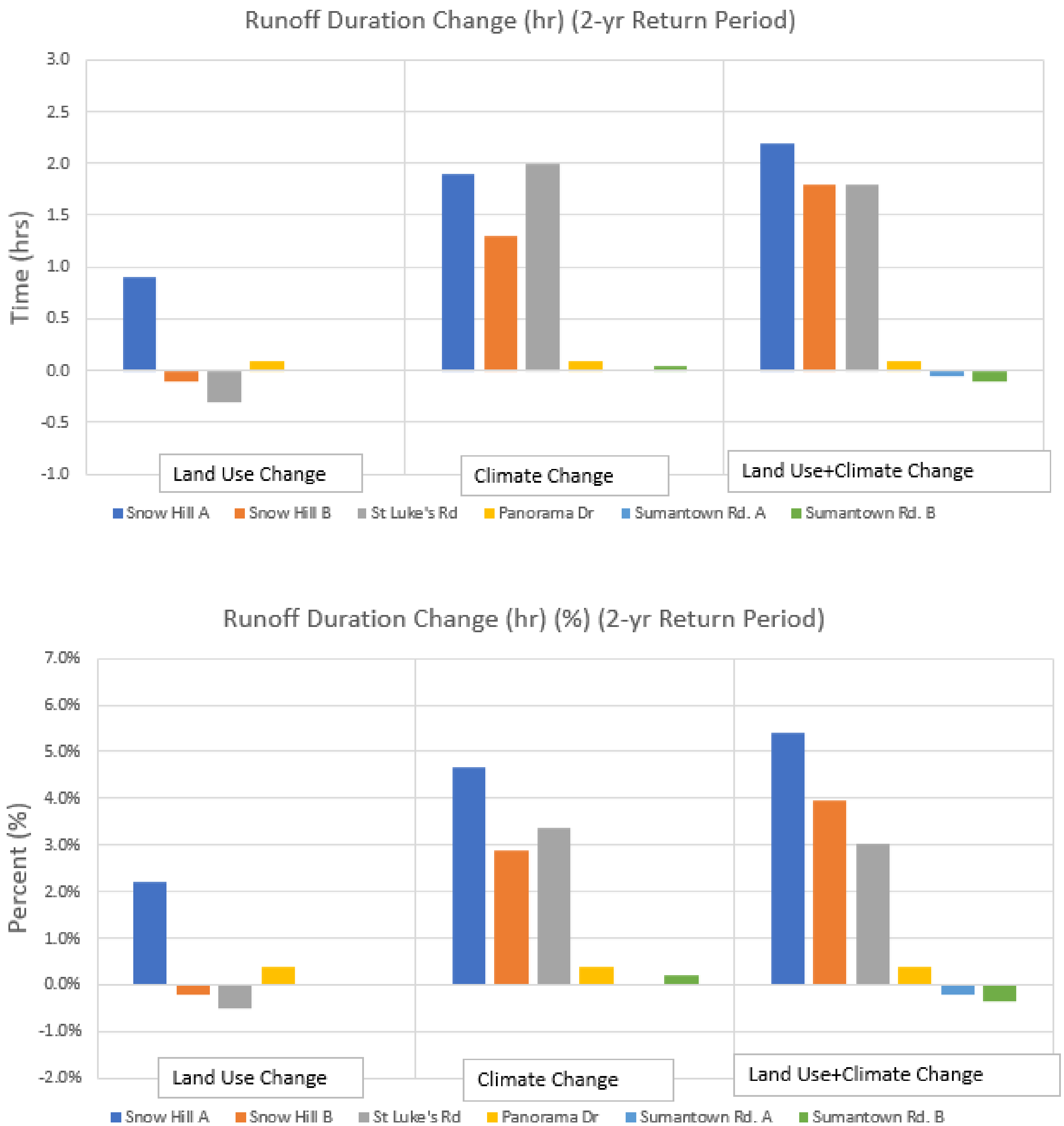
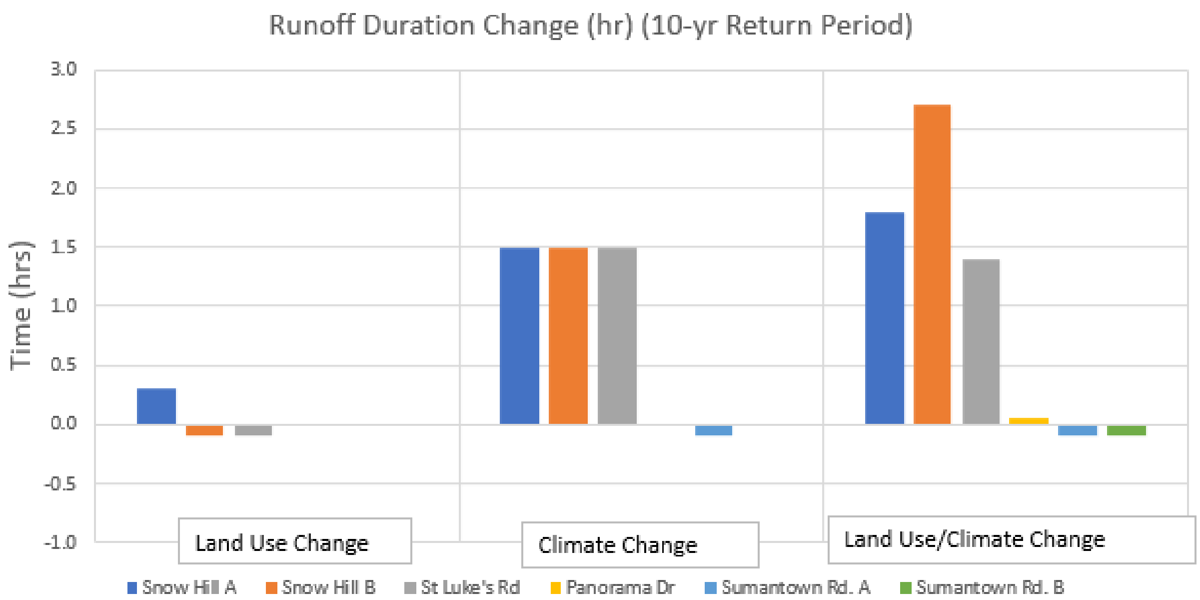


Figure 4.6: Runoff Duration Analysis (2-yr, 24-hr storm)



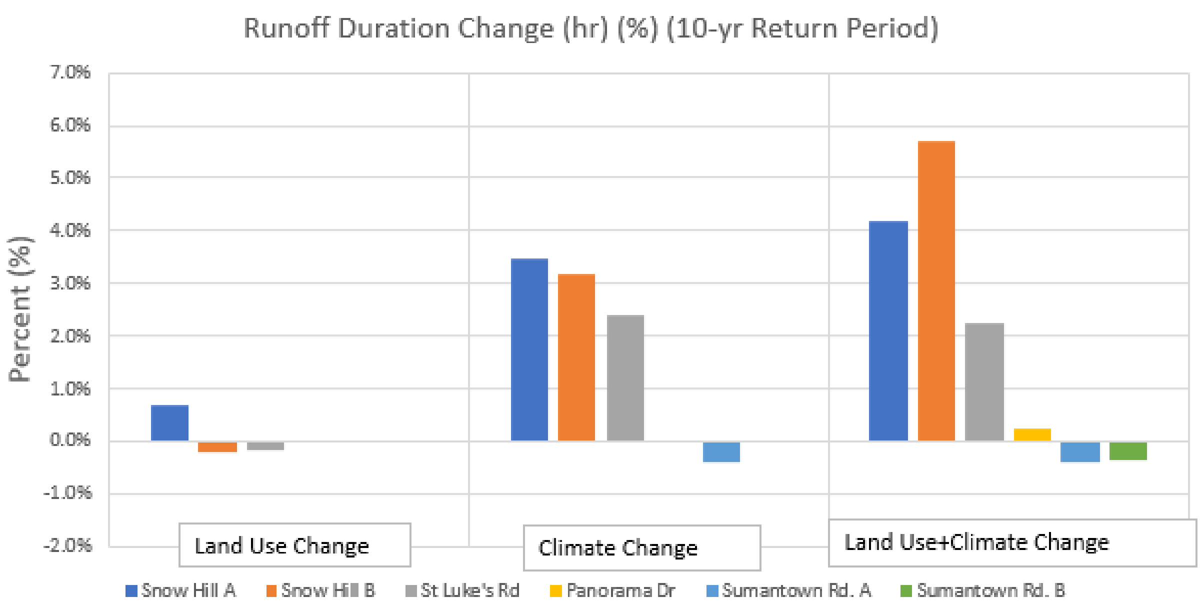


Figure 4.7: Runoff Duration Analysis (10-yr, 24-hr storm)

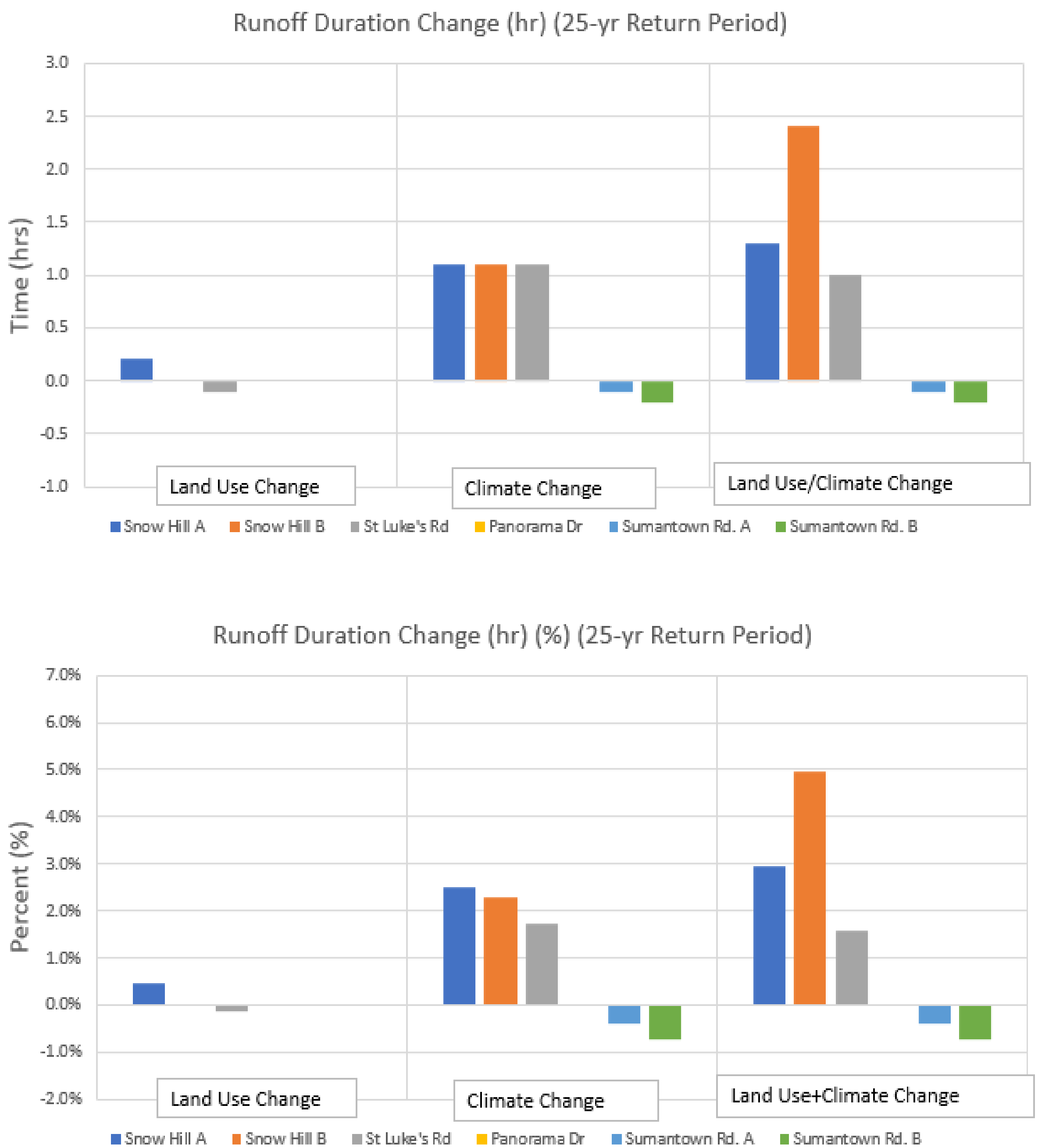


Figure 4.8: Runoff Duration Analysis (25-yr, 24-hr storm)

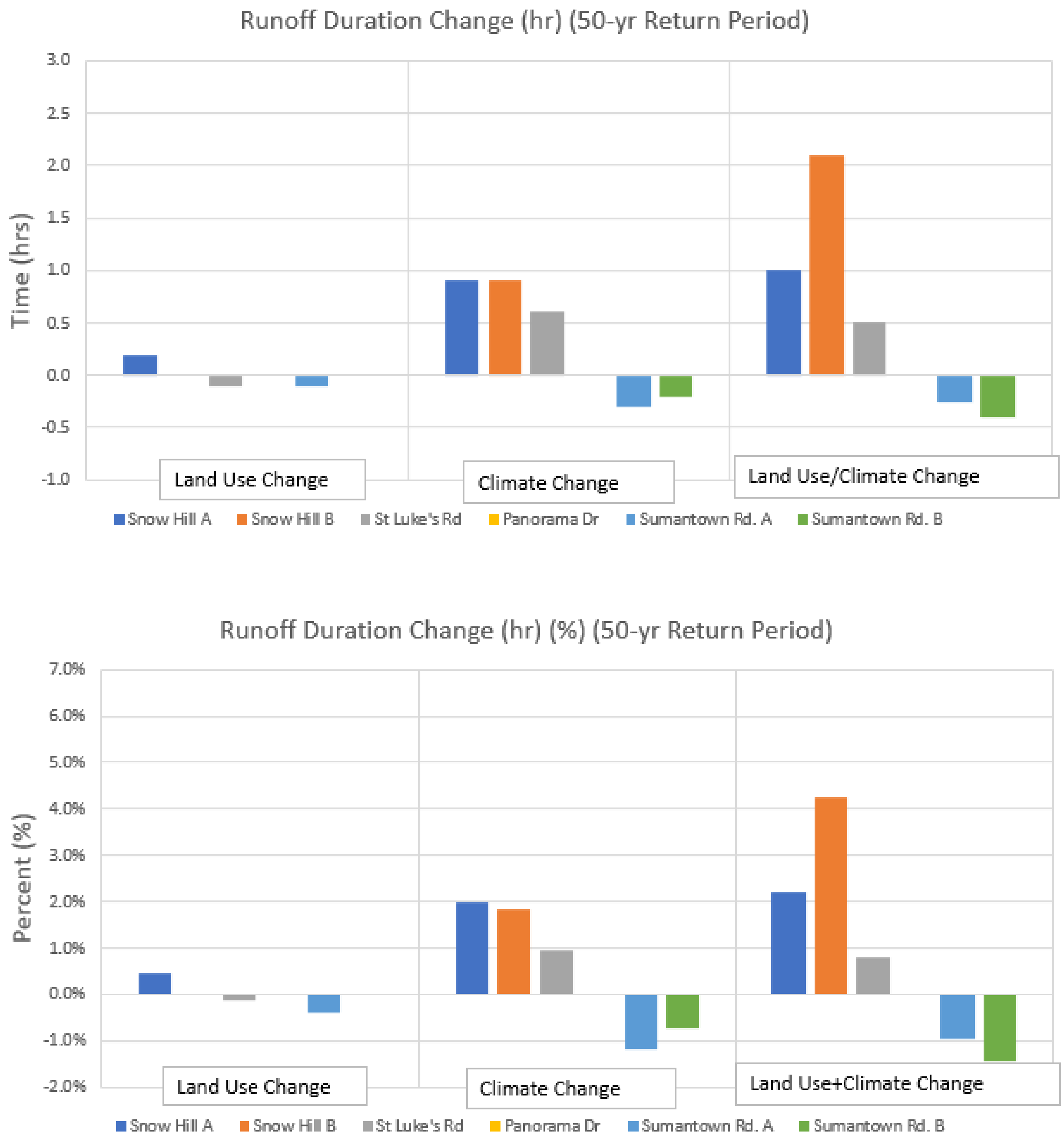


Figure 4.9: Runoff Duration Analysis (50-yr, 24-hr storm)

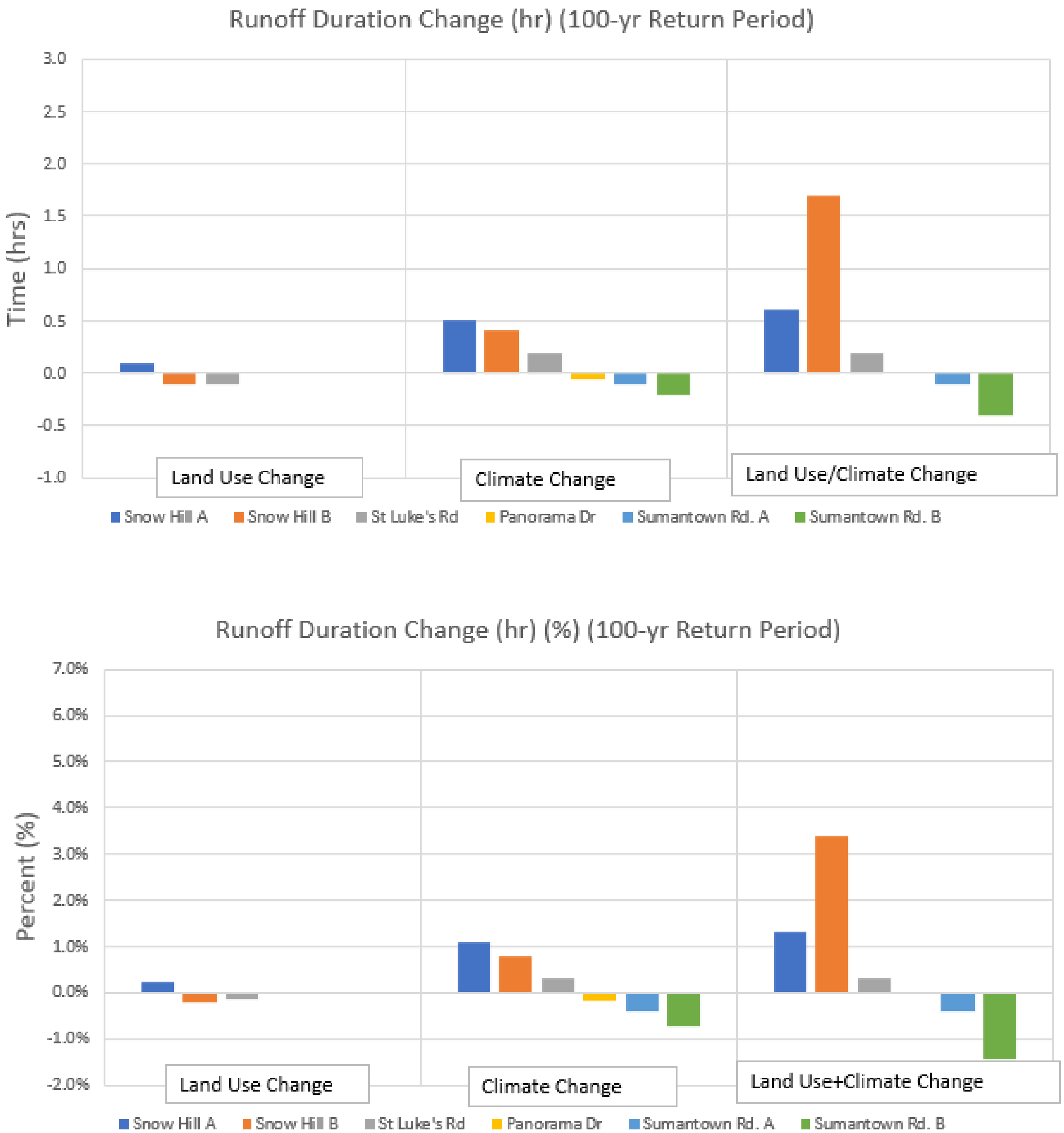


Figure 4.10: Runoff Duration Analysis (100-yr, 24-hr storm)

The runoff duration changes are different in sign and magnitude between the watersheds on the Eastern Shore and the watersheds in Frederick County. In (almost) every model the duration either increased or had a negligible deviation from the current land use and climate model. On the Eastern Shore, the watersheds showed nearly ubiquitous increases in runoff duration, with the Snow Hill B watershed having the largest increase of 5.7% during the 10-yr, 24-hr storm. Conversely, the watersheds in Frederick County only varied by 1.4% at their most, due to the changing land use and climate model for the Sumantown B watershed during the 100-yr, 24-hr storm. These longer runoff durations were consistent for each storm along the Eastern Shore apart from the Snow Hill B and St. Luke's Rd. watersheds when only land use was taken into account. In these instances, the change in runoff duration was less than a percent for each watershed, and in some cases there was no change at all. In the Frederick County watersheds, the runoff duration decreased for each return period apart from the 2-year event. Although the decreases were not as drastic as the Eastern Shore increases, they were consistent across the Frederick (Piedmont) region.

The time for each watershed to reach the peak flow was taken from each model. The magnitude as well as the percent change in time-to-peak from the current conditions (both land use and climate) to the ultimate land use and/or future climate conditions is shown in Figs. 4.11 – 4.16. Again, the top bar graph in each figure gives the change (hours) in time-to-peak compared to Baseline, and the bottom bar graph gives the same information, expressed as a percent of the baseline value.

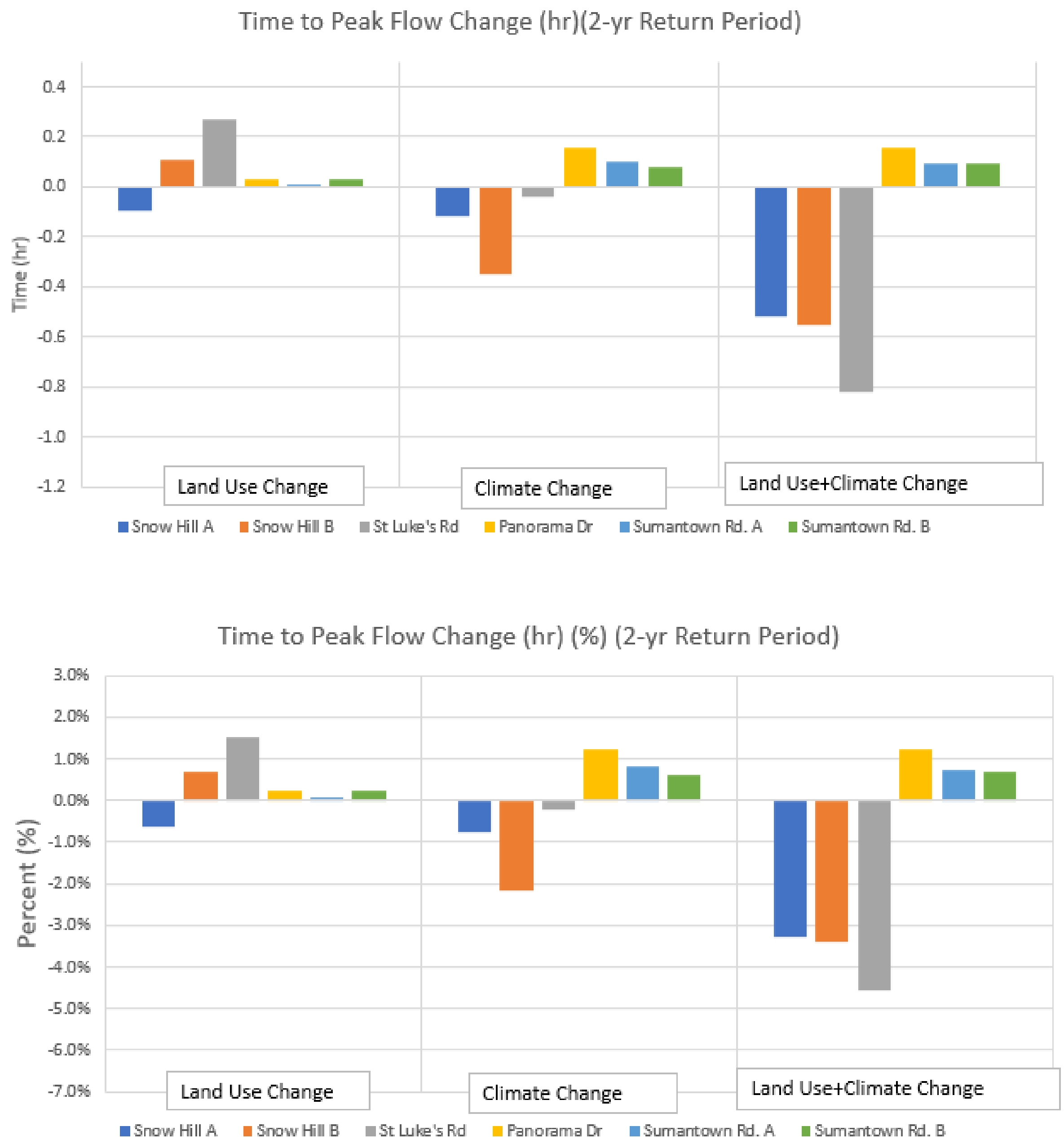
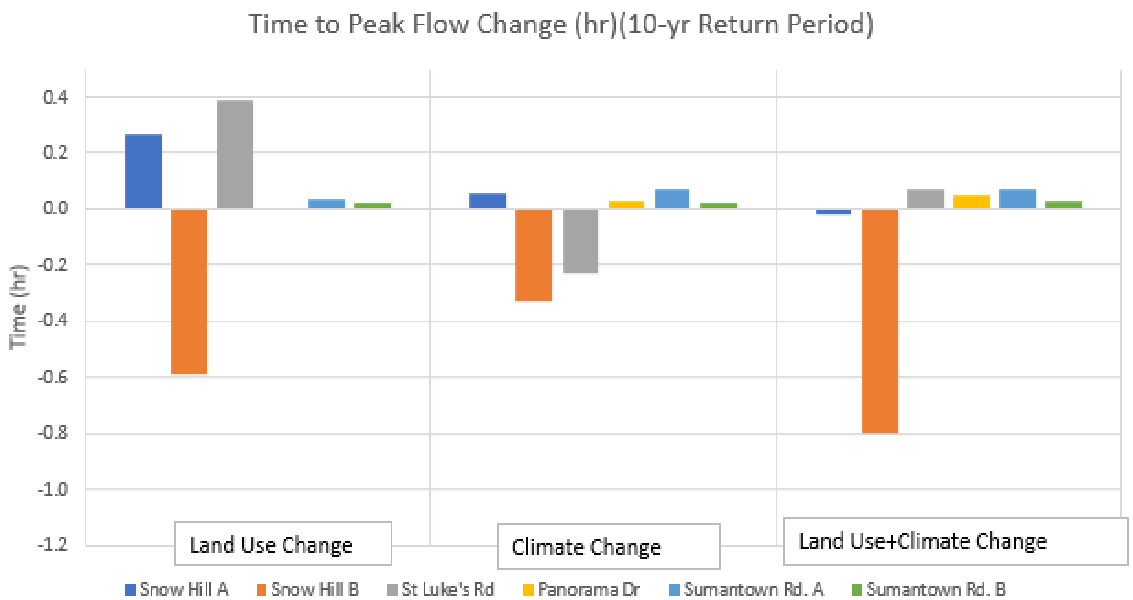


Figure 4.11: Time to Peak Flow Analysis (2-yr, 24-hr storm)



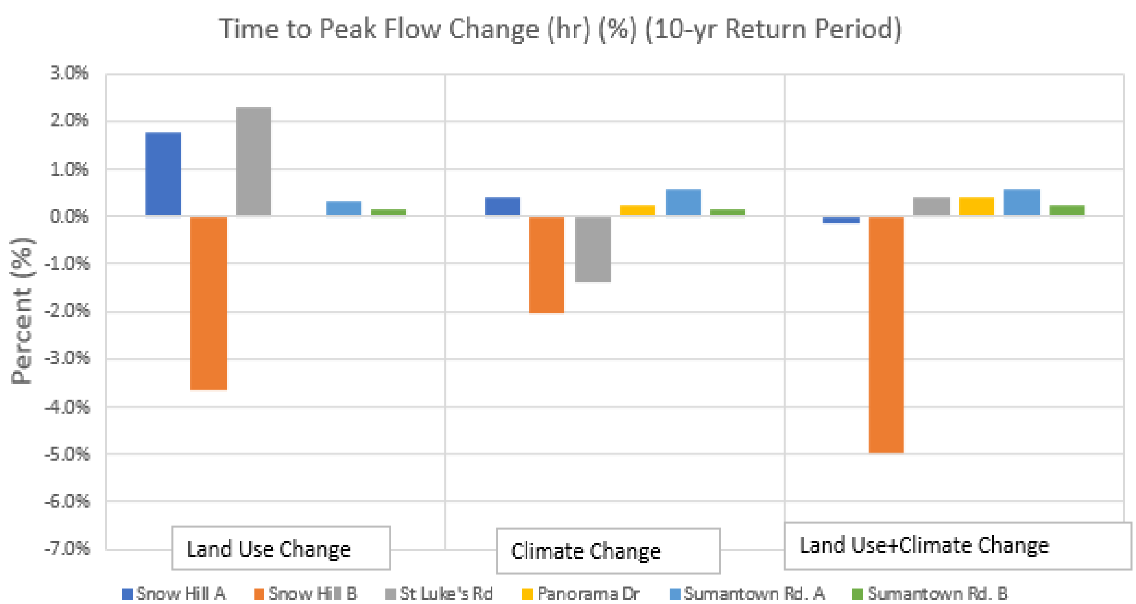
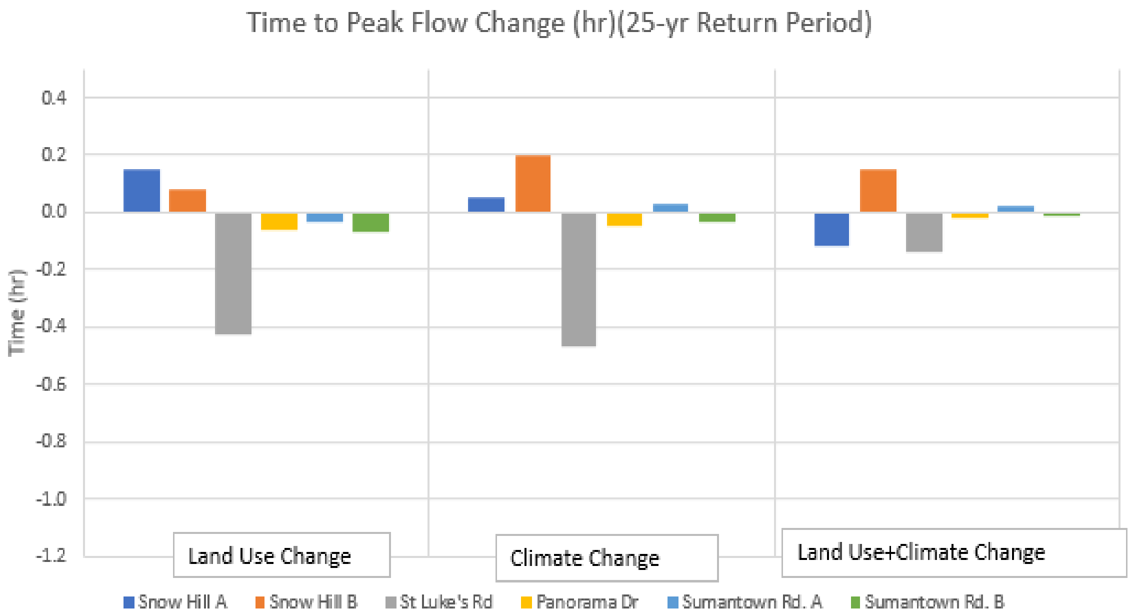


Figure 4.12: Time to Peak Flow Analysis (10-yr, 24-hr storm)



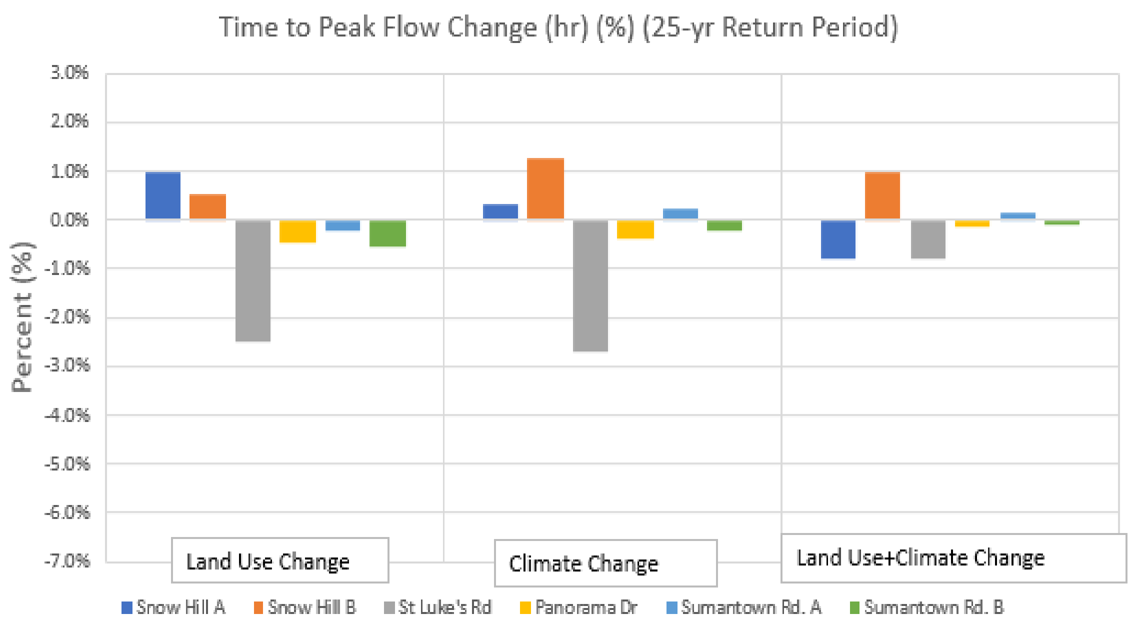
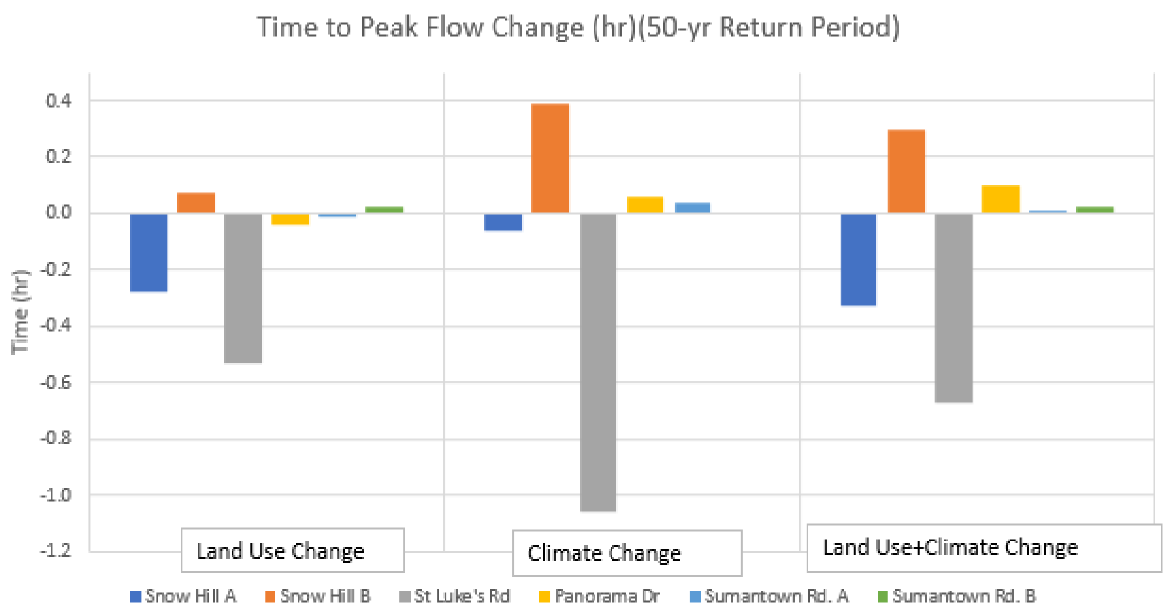


Figure 4.13: Time to Peak Flow Analysis (25-yr, 24-hr storm)



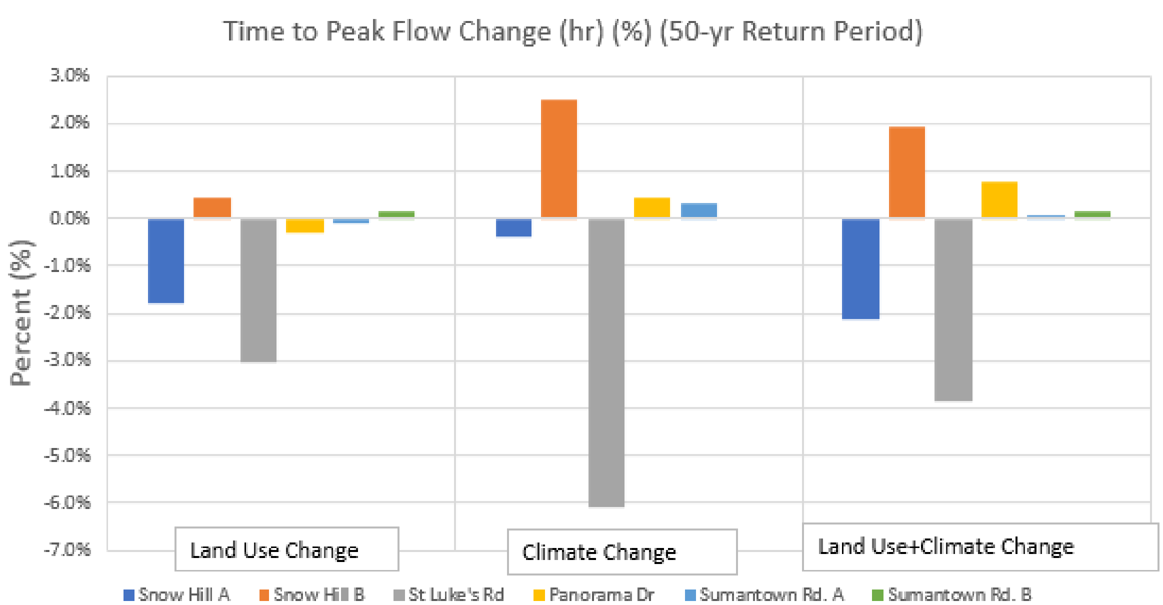
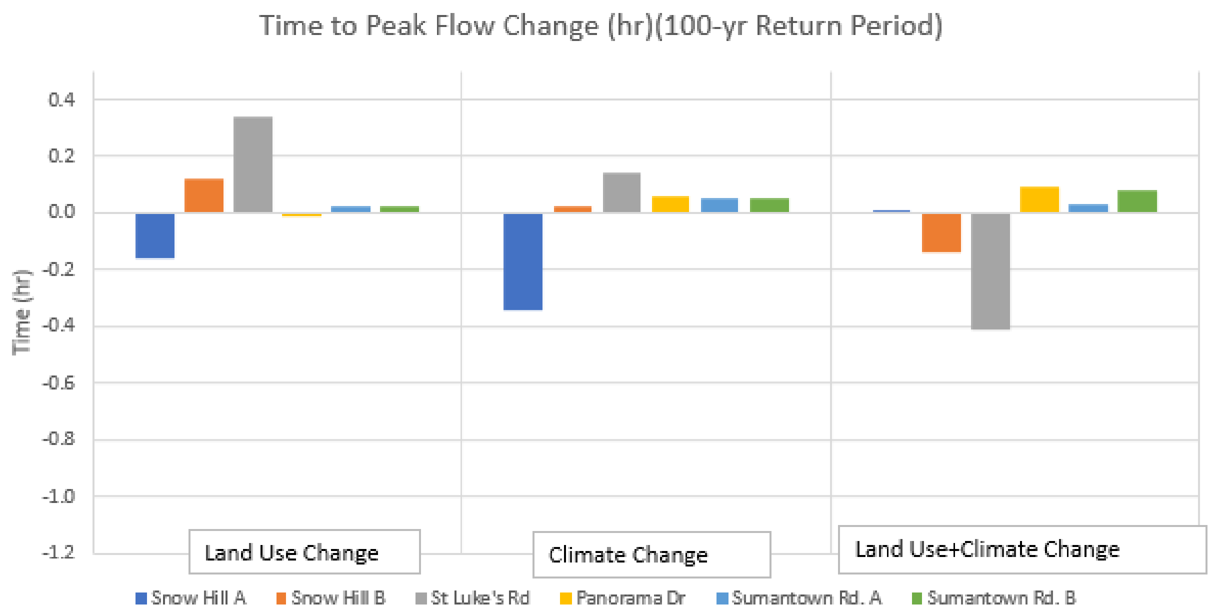


Figure 4.14: Time to Peak Flow Analysis (50-yr, 24-hr storm)



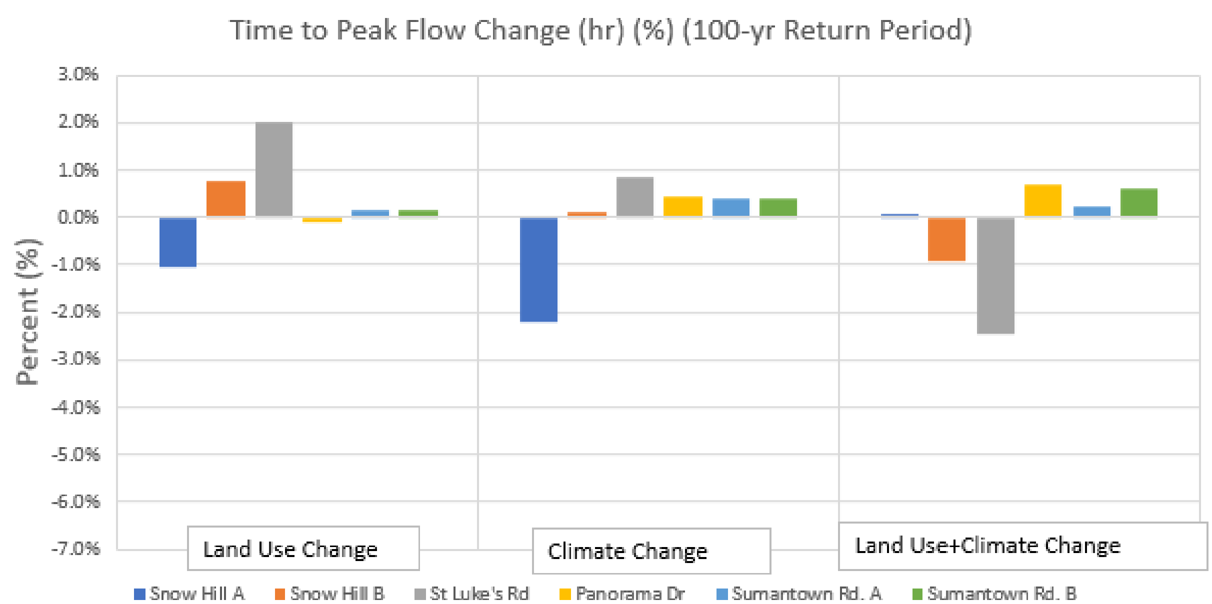


Figure 4.15: Time to Peak Flow Analysis (100-yr, 24-hr storm)

The results of the peak flow timing analysis show that each watershed behaves differently, even in the same general region. Although they are all receiving more water from the predicted precipitation, not every watershed has a decreased time to peak; in fact, each watershed for each scenario (besides the Sumantown A watershed) has both increased and decreased times to peak over the full 5-storm analysis. The Sumantown A watershed is the single exception; it displays a slight increase of up to 0.9% for each storm frequency in the Land Use + Climate Change model as well as the climate change only model. A few important points to make about these graphs are the sudden changes between return periods for each watershed. The Sumantown and Panorama watersheds remain rather consistent, however both Snow Hill watersheds as well as the St. Luke’s Rd. watershed show significant variability in their peak flow timings when the frequencies change from 2 to 10, 25, 50 and 100 years. Particularly interesting is the spike in the 10-yr storm for Snow Hill B (Fig. 4.12), where each peak flow timing decreased – in the most extreme case by over 4 percent. It is important to note, however, that the shift in peak flow timings do not correlate to increased rainfall or development; the variable is much more random than both peak flow rates and storm runoff duration.

The summary results described above were derived from the runoff hydrographs generated by WinTR-20. A custom Python script extracted and plotted selected hydrographs from multiple WinTR-20 output files. In these hydrographs it is possible to see each change: the differing peak flow rates, the shifting runoff durations, and the altered times to peak flow for each watershed due to changing land use, changing climate, and their combination. As examples, the 2-, 10- and 100-year return period storms for the Snow Hill A and Panorama Dr. watersheds are shown in Figs. 4.16 through 4.21; the remainder can be found in the Appendix.

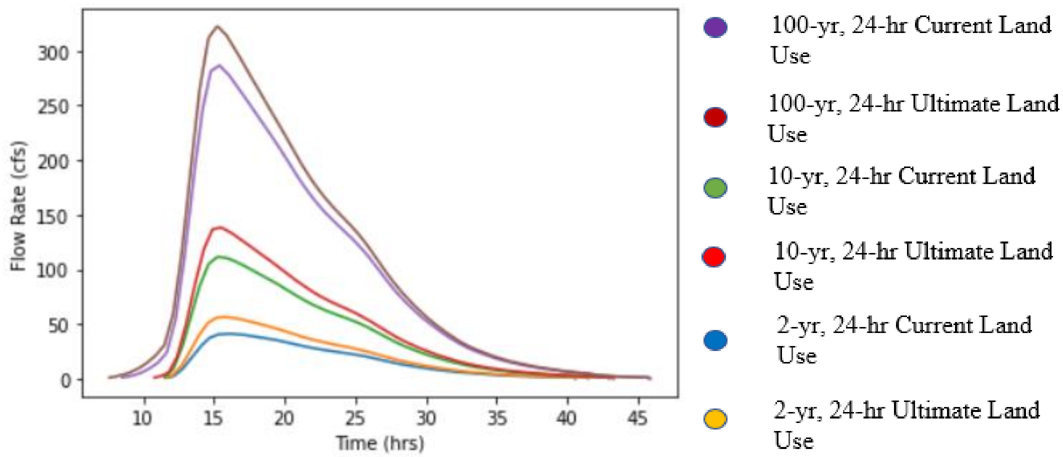


Figure 4.16: Current vs. Ultimate Land Use (Snow Hill A)

Figure 4.16 shows the increase in overall runoff volume and peak discharge in response to current precipitation when part of the Snow Hill A watershed is developed. The increases in peak discharge correspond to the blue bar in the left-hand bar graphs in Figs. 4.1, 4.2 and 4.5. The ending time of discharge corresponds to Figs. 4.6, 4.7, and 4.10.

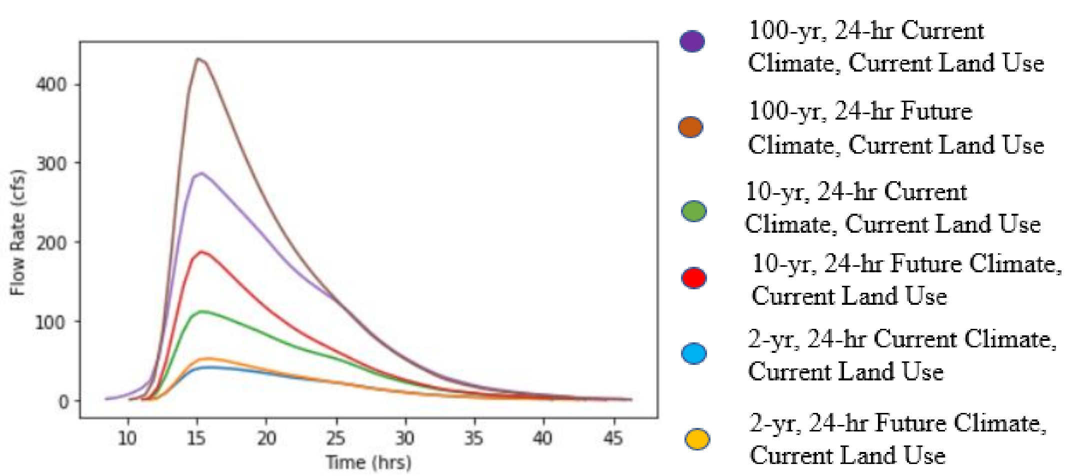


Figure 4.17: Current vs. Future Climate (Snow Hill A)

Figure 4.17 illuminates the larger impact that climate change has on the watersheds compared to land use change. The noticeable difference between the peak flows of the return period pairs can be seen in Figs. 4.1, 4.2, and 4.5 when comparing the left-hand blue bar with the middle blue bar.

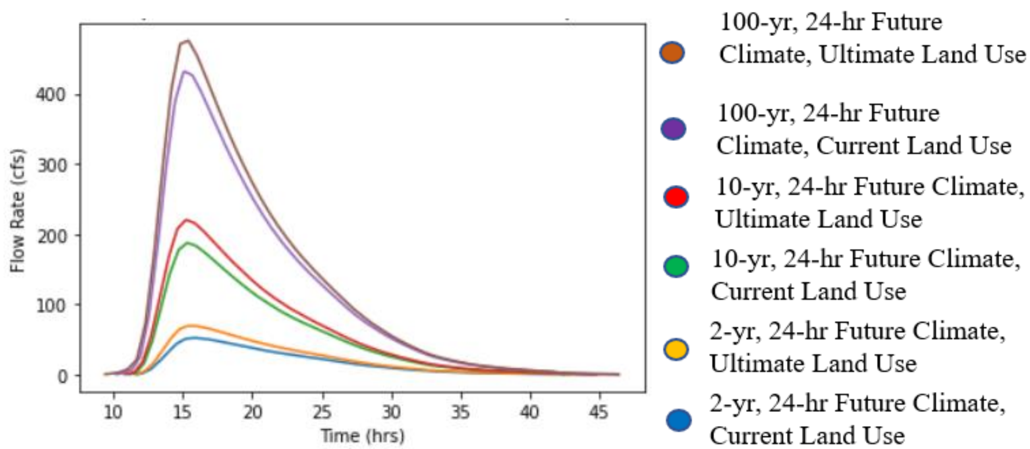


Figure 4.18: Future Climate – Current vs. Ultimate Land Use (Snow Hill A)

Figure 4.18 illustrates the general finding that land use change has less impact than climate change when the two influences are combined. The differences between the peak discharges in the pairs of curves reflect the differences between the yellow bars in the middle (Climate Change only) and the right-hand (Land Use + Climate Change) bar graphs in Figs. 4.5, 4.2, and 4.1.

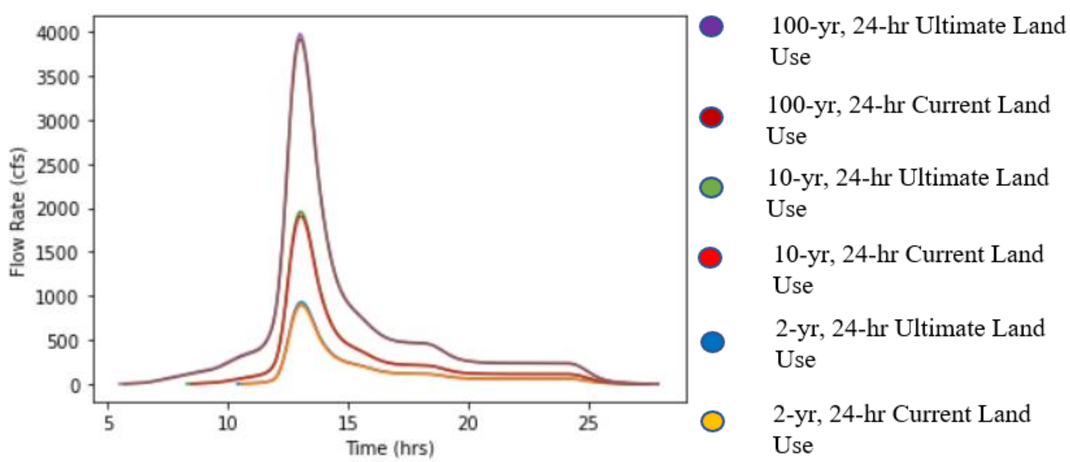


Figure 4.19: Current vs. Ultimate Land Use (Panorama Dr.)

Despite the fact that the Panorama Dr. watershed is slated for development, Figures 4.19 and 4.20 show barely perceptible differences between the current and ultimate land use, for both current (Fig.4.19) and future (Fig. 4.20) precipitation. Figure 4.21 shows the dominant effect of climate change on the peak discharge in this location. The differences between the peak flows of the return period hydrograph pairs correspond to the yellow bars in the middle bar graphs in Figs. 4.5 (100-ear), 4.2 (10-year), ad 4.1 (2-year).

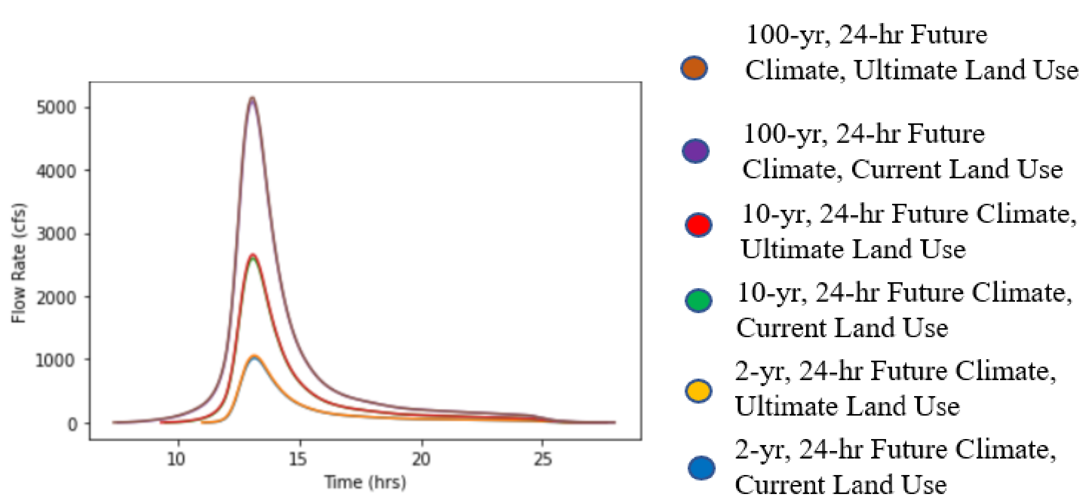


Figure 4.21: Future Climate – Current vs. Ultimate Land Use (Panorama Dr.)

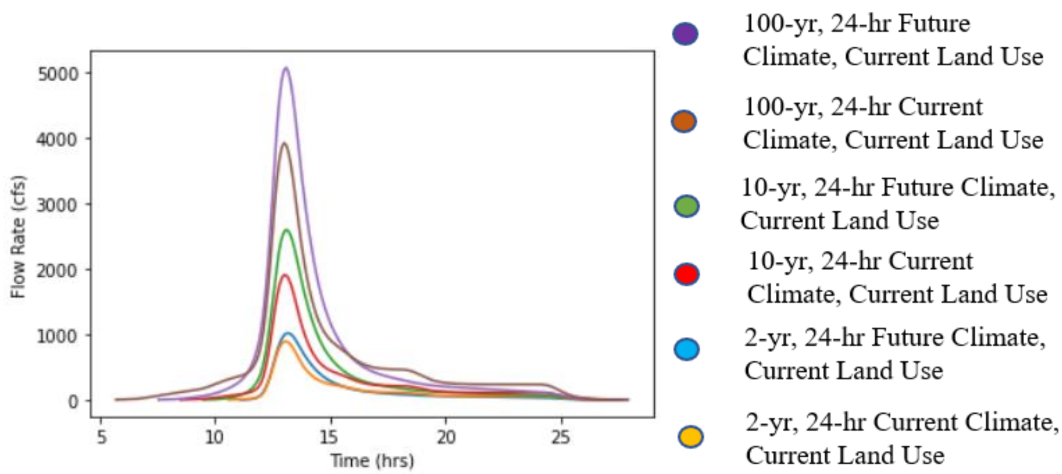


Figure 4.20: Current vs. Future Climate (Panorama Dr.)

Chapter 5: Discussion

Section 1: Increased Rainfall

The results from modeling the six watersheds in two geographic regions of Maryland using ultimate land use conditions and future precipitation data can be explained in a variety of ways. Further investigation of the increased peak flow rates due to urbanization as well as future precipitation data may be the simplest to understand and will shed light on the reasons behind altered runoff durations and peak flow timings. The peak flow rates increase for each watershed when future precipitation estimates are added. What is most interesting when looking at these increases is why the watershed with the least development (St. Luke's Rd.) has some of the highest percent increases in its peak flow rate. An initial explanation is simply because the watershed is receiving a greater increase of rainfall than either of the other non-developing watersheds (Sumantown A/B). The St. Luke's Rd. watershed is on the Eastern Shore of Maryland; a region that typically receives more rain than the more inland Frederick County. Furthermore, the future-climate estimates predict the St. Luke's Rd. watershed will receive a greater increase in rainfall than any other watershed for every return period. Comparing these increases to the Frederick County watersheds, St. Luke's Rd. has almost twice the increase (and in the 100-yr event almost 3 times the increase) in rainfall in terms of percentage.

More rainfall is a clear predictor of more runoff, but if the St. Luke's Rd. watershed is receiving two to three times the percent increase that the Frederick County watersheds are, why does the increase in peak flow not demonstrate the same relationship? The answer comes down to a key hydrologic concept – infiltration. The

St. Luke's Rd. watershed is large and mainly wooded, consisting of 91.3% forest that increases to 97.9% when ultimate land use is considered. Despite the fact that 77.3% of the soil is type D (the lowest-grade soil that can produce the most amount of runoff due to the high clay content), the sheer amount of wooded land in the watershed allows the rainfall to remain stagnant on land as long as possible. This residence time is long enough to allow the water to infiltrate the soil, even though it is the densest soil type. The infiltration greatly decreases the total amount of runoff seen in the watershed and essentially consumes rainfall that otherwise would be turned into runoff. When enough water has infiltrated the soil, the soil is said to be fully saturated – a state that implies no further infiltration can occur. Due to the increased rainfall when future climate data is taken into account, the soil may approach this fully saturated state. However, because the watershed has so much infiltration potential (due to the large amount of forest cover), the soil continues to saturate throughout the storm duration, mitigating the impact that the greatly increased rainfall would otherwise have. As more rainfall falls on the watershed due to climate change, there is more water that will run off compared to the current climate conditions. This extra water will lead to the lengthening of total runoff duration, as surface flow will continue even after the majority of the rain has fallen.

Section 2: Land Use Change

This infiltration concept can also be seen in the developing Snow Hill A watershed, although this time with respect to changing land use. This watershed is the clearest example of how more impervious surface due to development can impact a watershed's behavior. When only land use change is considered, the Snow Hill A watershed sees an increase in its peak flow discharge by up to 32.6%. The reason for this increase is due to previously undeveloped land being paved over or permanently changed. This watershed is predicted to see an impervious land use change of 11.1%: the current conditions show Snow Hill A with 5.4% impervious surface coverage while the ultimate conditions show 16.5% coverage. This means that each rain drop that would have fallen on 11% of the watershed's soil will now fall on developed residential areas.

Not only is it easier for rainfall to be channelized and flow over the smoothly paved surfaces of these urbanized areas, but the soil underneath the asphalt and concrete cannot be used to store the rainfall and acts as though it were saturated. Table 5.1 lists the current and ultimate impervious area and the change (in units of percent) in each of the study watersheds. The three developing watersheds show increases, while the non-developing ones show small decreases in impervious area.

Table 5.1: Impervious Surface Presence

Watershed	Current Conditions (% Impervious Surface)	Ultimate Conditions (% Impervious Surface)	Change (%)
Snow Hill A	5.4	16.5	11.1
Snow Hill B	7.5	14	6.5
St. Luke's Rd.	0.5	0.4	-0.1
Panorama Dr.	7.7	12.8	5.1
Sumantown A	3.3	0.1	-3.2
Sumantown B	7	6	-1

Not all development plays such a decisive role in increasing peak flows, however, as the results from both the Snow Hill B and Panorama Dr. watersheds illustrate. Although both watersheds are zoned for development (increases of 6.5 and 5.1 percent impervious surface respectively) the residential areas are not being built upon forests and grasslands. Instead, these developments are occurring over cropland. Cropland has a surprisingly high curve number (CN = 83), even higher than the low-density residential designations that are planned throughout both watersheds (CN = 78 for Snow Hill B and 81 for Panorama Dr.). This curve number is a basic description of the runoff potential of a land use designation. Higher curve numbers indicate a higher percent runoff (such as pavement at 97) whereas lower numbers indicate a lower percent (such as forests at 60-70 depending on soil type). Due to the planned development having a lower curve number than the replaced cropland, the Snow Hill B and Panorama Dr. watersheds do not exhibit significant alterations to their watershed's behaviors as other watersheds that develop over more permeable soil with lower curve numbers.

Section 3: Runoff Duration

The third metric analyzed in this research was the duration of the runoff event. The results were very consistent for this analysis, as each watershed on the Eastern Shore displayed significant increases in their runoff durations when future climate estimates were used (up to 4.7%) while the Frederick County (Piedmont) watersheds showed little to no change despite the precipitation changes. These results are particularly interesting because they are not intuitive. More rainfall means more water must run off, effectively lengthening the total time of runoff. This is true in the case of Eastern Shore watersheds, however not so much in Frederick County. The reason behind this is in part connected to the times of concentration and the infiltration rates. Although the Tc values do not actually change between any conditions of any watershed in this research, what is happening at those points is just as important as the number itself.

The Tc value signifies the time associated with the longest path a water droplet will take in a watershed and is the largest ‘lag-time’ between rainfall and runoff. Incorporating the increased rainfall into the Eastern Shore watershed models may not have as much of an effect on the time to runoff due to the high forest cover percentages in each of the watersheds (49.6, 34.5 and 91.7 percent for Snow Hill A, B and St. Luke’s Rd. respectively). As previously discussed, the dense forest cover will allow the rainfall the time it needs to infiltrate into the soil. It is possible that the increased rainfall on the Eastern Shore was not enough to fully saturate the soils, even at the most remote part of the watershed (where time to runoff is Tc). This effect occurred so much so that the rainfall coming later in the storm continued to infiltrate the soil and either ran off slowly or was infiltrated into the subsurface. Conversely, the Frederick County watersheds have much less forest cover (10.8, 12.5 and 26.7 percent for Sumantown A, B and Panorama Dr. respectively). This absence of forest cover may not have allowed the water the time it needed to infiltrate the soil, meaning the measurable discharge from each storm frequency would reach zero around the same time when either future or current climate conditions were modeled, as the vast majority of the rain was falling on other land use types.

<u>Section 4: Land Use Change and Future Precipitation</u>

The combination of both future climate predictions and ultimate land use significantly impacts the behavior of each watershed. This is most apparent when comparing the peak flow rates of each watershed to its current conditions. The watersheds are most impacted by the changed precipitation, however when the land use change is factored in, the outcome is not a simple additive value of both individual land use and climate change models. This effect is more pronounced in storms with lower return periods (2/10 year) compared to the higher, less common storms (50/100 years). The main reason behind this phenomenon is once again infiltration. The 2- and 10-year storms have less cumulative rainfall than the 50- and 100-year storms. This means that the soil will be less saturated for the more common storms, causing the effect of development on the watershed to have a larger effect, as the new pavement behaves like fully saturated soil in that no infiltration can take place. Not only will more rainfall hit the pavement and turn into runoff that is not present in the current land use model, but the excess rainfall due to the future climate conditions will add to this volume, compounding the effect of paving over previously porous land.

As the storms become less common (50/100-year storms) the excess rainfall is enough that the amount necessary to saturate the soil is much more negligible when compared to the excess amount that is running off due to the sheer increase in water volume. Although the land use is still having an effect, the future climate and ultimate land use model shows a changing peak runoff value that is more representative of an additive value of the independent future climate and ultimate land use models. For example, in Snow Hill A, the land use only change for the 2-yr storm shows an increase in peak flow of 36.2%. For the Climate Change only scenario, this decreases to 26.3%. When both future precipitation and ultimate land use are used in the model, the peak flow rate increase becomes 67.6%. The discrepancy between the additive 62.5% and the actual 67.6% increase in peak flow rate is due to the effect of more rain falling on more impervious surface. This effect becomes less obvious at the 100-year return period. For the same watershed, the increase in peak flow rate due strictly to land use is 12.6%, while the future precipitation model shows a 50.6% increase for the 100-year storm. The additive percentage is 63.2%, while the results show an actual increase of 65.8%. The larger storm may therefore saturate the soil, or fall with such intensity, that it causes the watershed to act as if it were paved, allowing for every rain drop to run off. In the 2-year storm this is not the case, and the increase in peak flow is larger when both future climate and ultimate land use are considered because the land use change has an overall greater effect on less severe storms than more severe ones.

This inverse relationship between the effect of land use on peak flow and the severity of the storm is true in the reverse as well: the St. Luke’s Rd. watershed is an example. For the 2-year storm, land use change alters the peak flow rate by a negative 12.4% while the future climate data increases the flow by 24.4%. Therefore, the additive change is 12.0%, however the actual increase in peak flow is 9.5%, showing that the land use change has a more significant impact on the behavior of the watershed than expected. Doing the same analysis for the 100-year event, the land use change decreases the peak flow by 5.4% and the climate change increases it by

46.9%. The actual increase in peak flow rate when both parameters are modelled together is 40.1%, 1.4% less than the additive value of 41.5%. This 1.4 percentage difference is less than half the difference in the 2-year model, which amounts to 3.5%. Therefore, the 100-year response is more linear than the 2-year response when the land use and climate change alterations to peak flow are added together. This sparks an interesting question: at what point (if one exists at all) would the additive value be equal to the actual increase in peak flow rate? Given this information and the fact that more areas around the world are experiencing more severe storms more frequently, would it be possible to say that development has an almost negligible impact on peak flow rates during high-intensity storms if the soil would otherwise become saturated so quickly that it effectively acts as pavement in the first place? Furthermore, how will land use change and urbanization effect watersheds undergoing more significant development if the Snow Hill A watershed already sees a 5.1% peak flow rate discrepancy while only consisting of 16.5% impervious area?

Table 5.2: 2-yr, 24-hr Rainfall Event Peak Discharge Change (Normalized by Watershed Area)

Watershed	Current Conditions (cfs/mi^2)	Land Use Change Only (cfs/mi^2)	Change (%)	Climate Change Only (cfs/mi^2)	Change (%)	Land Use & Climate Change (cfs/mi^2)	Change (%)
Snow Hill A	41.8	57.0	36.2	52.8	26.4	70.1	67.7
Snow Hill B	56.2	54.2	-3.6	67.5	20.1	60.4	7.4
St. Luke's Rd.	35.5	31.1	-12.4	44.2	24.4	38.9	9.5
Panorama Dr.	261.1	273.2	4.6	297.5	13.9	309.4	18.5
Sumantown A	347.3	362.0	4.2	368.3	6.0	382.3	10.1
Sumantown B	205	203.3	-0.8	238.9	16.5	237.5	15.9

Table 5.3: 10-yr, 24-hr Rainfall Event Peak Discharge Change (Normalized by Watershed Area)

Watershed	Current Conditions (cfs/mi^2)	Land Use Change Only (cfs/mi^2)	Change (%)	Climate Change Only (cfs/mi^2)	Change (%)	Land Use & Climate Change (cfs/mi^2)	Change (%)
Snow Hill A	112.6	139.7	24.0	189.2	68.1	222.5	97.6
Snow Hill B	133.0	130.1	-2.2	208.2	56.6	193.0	45.2
St. Luke's Rd.	88.4	81.5	-7.8	146.7	66.0	135.7	51.0
Panorama Dr.	559.5	574.6	2.7	758.6	35.6	778.1	39.1
Sumantown A	731.7	750.2	2.5	986.1	34.8	1006.6	37.6
Sumantown B	463.6	460.6	-0.7	663.2	43.1	660.2	42.4

Table 5.4: 25-yr, 24-hr Rainfall Event Peak Discharge Change (Normalized by Watershed Area)

Watershed	Current Conditions (cfs/mi^2)	Land Use Change Only (cfs/mi^2)	Change (%)	Climate Change Only (cfs/mi^2)	Change (%)	Land Use & Climate Change (cfs/mi^2)	Change (%)
Snow Hill A	171.8	203.3	18.3	282.9	64.7	323.7	88.4
Snow Hill B	191.1	188.2	-1.5	299.2	56.6	278.2	45.5
St. Luke's Rd.	133.5	122.4	-8.3	213.7	60.1	201.6	51.0
Panorama Dr.	769.6	787.0	2.3	1040.2	35.2	1061.7	38.0
Sumantown A	987.2	1005.9	2.3	1379.7	39.8	1404.1	42.2
Sumantown B	648.4	646.0	-0.4	934.4	44.1	933.4	44.0

Table 5.5: 50-yr, 24-hr Rainfall Event Peak Discharge Change (Normalized by Watershed Area)

Watershed	Current Conditions (cfs/mi^2)	Land Use Change Only (cfs/mi^2)	Change (%)	Climate Change Only (cfs/mi^2)	Change (%)	Land Use & Climate Change (cfs/mi^2)	Change (%)
Snow Hill A	227.8	260.7	14.5	357.4	56.9	400.6	75.9
Snow Hill B	245.1	241.7	-1.4	369.7	50.9	345	40.8
St. Luke's Rd.	173.8	161.3	-7.2	267.1	53.6	254.7	46.5
Panorama Dr.	950.8	965.4	1.5	1263.7	32.9	1279.3	34.5
Sumantown A	1197.0	1217.3	1.7	1682.8	40.6	1711.4	43.0
Sumantown B	808.2	805.6	-0.3	1149.1	42.2	1148.0	42.0

Table 5.6: 100-yr, 24-hr Rainfall Event Peak Discharge Change (Normalized by Watershed Area)

Watershed	Current Conditions (cfs/mi^2)	Land Use Change Only (cfs/mi^2)	Change (%)	Climate Change Only (cfs/mi^2)	Change (%)	Land Use & Climate Change (cfs/mi^2)	Change (%)
Snow Hill A	289.5	326.0	12.6	436.1	50.6	480.1	65.8
Snow Hill B	305.9	301.9	-1.3	446.4	45.9	418.7	36.9
St. Luke's Rd.	219.0	207.3	-5.4	321.7	46.9	306.9	40.1
Panorama Dr.	1147.7	1164.5	1.5	1484.6	29.3	1502.8	30.9
Sumantown A	1416.3	1438.8	1.6	2001.7	41.3	2024.7	43.0
Sumantown B	978.9	977.7	-0.1	1371.0	40.1	1396.8	39.9

Chapter 6: Conclusion

The first insight from this work is that altered precipitation patterns due to climate change are likely to have a more profound impact on watersheds than anticipated land use change. The increasing rainfall is not something humans can actively decrease; however, it is something they can, and should, consider when planning new development. Urbanization and the subsequent increase in impervious surface is something new communities can account for when mitigating their effect on a watershed. The increased volume of water related to climate change, however, poses a much greater challenge in planning for future impact on watersheds and communities.

The second key insight from this work is that although land use change may not always be effective in changing watershed behavior, it is particularly influential when the developing land was previously undisturbed. Due to this, it is essential for land developers and local governments to conduct watershed studies and communicate with environmental agencies when zoning large areas for development, as the changing land use may greatly affect the runoff peak flows, durations, times to peak and overall volume of runoff in the watershed. Increased flow rates can lead to flash floods, washed out roads and inundation in low-lying areas. Furthermore, this work indicates that urbanization has a particularly acute influence over the runoff conditions during more common storms, even with only an 11.1% increase in impervious surface, from 5.4 to 16.5%. This means that although future rainfall will have a greater overall effect on watershed behavior, the newly urbanized area will cause greater amounts of runoff to be present in 2- and 10-year storms. It follows that not only will flooding be a more common occurrence in these areas, but pollution of nearby waterways will presumably increase due to the larger amount of runoff flowing over these neighborhoods, roads, and parking lots.

Both land use change and precipitation change will alter the volume and timing of watershed runoff. Development and infrastructure design should address both factors.

Chapter 7: Additional Information

Increasing the levels of pavement over a region is not the only factor impacting the behavior of watersheds. In addition to the obvious change in land use, areas designated as construction sites that will return to their natural state can also behave as though they are impervious surfaces. Among the study watersheds, Panorama Dr. is most susceptible to this phenomenon. In this watershed a large amount of deciduous forest is being converted into residential housing. Although these houses will likely have yards complete with grasses and native plants, the large equipment on-site during construction can severely impact the soils beneath the new sod.

Due to the immense weight of construction equipment, the soil can be compacted, significantly decreasing its porosity, and therefore causing the infiltration of stormwater into the soil to decrease. If enough pressure is applied to the soil at the surface, the water will no longer be able to infiltrate at all, essentially turning the soil into pavement from an infiltration standpoint. This effect on runoff is not accounted for in the look-up table curve numbers, so one might expect each future land use curve numbers in developing areas to be higher than currently predicted.

To counter the compaction of soils that is not accounted for in these models, one could argue there could be significant sustainable development happening as well. Sustainable development is a practice that includes designing and constructing a building with the surrounding ecology and environmental disruption in mind. Some development may include green roofs; roofs that contain rain gardens on top of them, so rainfall is able to be treated and possibly stored. This process would reduce the amount of runoff as well as the peak flow volumes due to the storage and evapotranspiration provided. However, it remains to be seen if the watersheds in this study are implementing such designs in the planned development. In further research, it may be interesting to see how much stormwater runoff is reduced in areas that have developed sustainably. This practice is more prominent in city development but not as commonplace in residential settings.

Similarly, watersheds that currently employ SCMs as well as watersheds zoned for development with SCMs should be studied to measure their effectiveness. Many new suburban communities implement bioretention ponds or sand filters to offset the amount of extra runoff created by paving over parts of the watershed, however the effectiveness of these practices remains largely unquantified. Additionally, conservation landscaping may be incorporated into the new development designs at a much higher proportion than green roofing. Conservation landscaping includes designing the landscape around houses to slow down and store rainwater, encourage native plant habitat, and bring life back to a disturbed watershed. These practices can be used by each individual homeowner and can effectively minimize the effect of urbanization on the watershed by decreasing peak flows through storage, halting erosion by planting native plants, and cutting down pollution levels in runoff by treating rainfall in yards rather than having it flow over sidewalks, roads and into piping systems. The Chesapeake Bay, which just received a D+ rating in the 2020 State of the Bay report (Portlock, 2020); conservation landscaping could contribute to restoring the Bay’s health.

Appendices

Appendix A:

Regression Equations for Calibration

Table A.1: Regression Equations for the Eastern Coastal Plain Region
Source: Maryland Hydrology Panel, 2016.

Eastern Coastal Plain Region Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 41.53\ DA^{0.815}\ (SA+1)^{-0.139}\ LSLOPE^{0.115}$	32.4	4.6
$Q_{1.50} = 78.75\ DA^{0.824}\ (SA+1)^{-0.144}\ LSLOPE^{0.194}$	32.3	4.1
$Q_{2} = 134.0\ DA^{0.836}\ (SA+1)^{-0.158}\ LSLOPE^{0.249}$	32.8	4.4
$Q_{5} = 477.5\ DA^{0.847}\ (SA+1)^{-0.184}\ LSLOPE^{0.385}$	35.1	7.0
$Q_{10} = 924.3\ DA^{0.844}\ (SA+1)^{-0.196}\ LSLOPE^{0.445}$	36.7	9.7
$Q_{25} = 1860.4\ DA^{0.834}\ (SA+1)^{-0.212}\ LSLOPE^{0.499}$	39.3	13
$Q_{50} = 2941.5\ DA^{0.824}\ (SA+1)^{-0.222}\ LSLOPE^{0.531}$	41.6	15
$Q_{100} = 4432.9\ DA^{0.812}\ (SA+1)^{-0.230}\ LSLOPE^{0.557}$	44.2	17
$Q_{200} = 6586.3\ DA^{0.800}\ (SA+1)^{-0.237}\ LSLOPE^{0.582}$	47.2	18
$Q_{500} = 10{,}587\ DA^{0.783}\ (SA+1)^{-0.247}\ LSLOPE^{0.610}$	51.6	19

Table A.2: Regression Equations for the Piedmont-Blue Ridge Region

Piedmont-Blue Ridge Region Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 283.3\ DA^{0.724}\ (LIME+1)^{-0.124}\ (IA+1)^{0.143}(FOR+1)^{-0.412}$	44.3	2.8
$Q_{1.50} = 352.4\ DA^{0.704}\ (LIME+1)^{-0.131}\ (IA+1)^{0.123}(FOR+1)^{-0.373}$	40.9	3.2
$Q_{2} = 453.4\ DA^{0.683}\ (LIME+1)^{-0.140}\ (IA+1)^{0.105}(FOR+1)^{-0.334}$	37.5	3.7
$Q_{5} = 746.8\ DA^{0.640}\ (LIME+1)^{-0.158}\ (IA+1)^{0.083}(FOR+1)^{-0.249}$	31.9	9.2
$Q_{10} = 972.3\ DA^{0.615}\ (LIME+1)^{-0.169}\ (IA+1)^{0.076}(FOR+1)^{-0.195}$	29.6	16
$Q_{25} = 1{,}327.6\ DA^{0.593}\ (LIME+1)^{-0.182}\ (IA+1)^{0.074}(FOR+1)^{-0.145}$	29.0	25
$Q_{50} = 1{,}608.2\ DA^{0.576}\ (LIME+1)^{-0.191}\ (IA+1)^{0.073}(FOR+1)^{-0.103}$	29.8	31
$Q_{100} = 1{,}928.5\ DA^{0.561}\ (LIME+1)^{-0.198}\ (IA+1)^{0.073}(FOR+1)^{-0.067}$	31.8	34
$Q_{200} = 3{,}153.5\ DA^{0.550}\ (LIME+1)^{-0.222}\ (FOR+1)^{-0.090}$	35.7	32
$Q_{500} = 3{,}905.3\ DA^{0.533}\ (LIME+1)^{-0.233}\ (FOR+1)^{-0.045}$	42.0	30

Note: $Nr = (S/SEp)^2R^2$ where Nr is the equivalent years of record, S is the standard deviation at the site being analyzed of the logs of yearly peak discharges, SEp is the standard error of prediction for each regression equation (in log units), and R^2 is a parameter estimated based on recurrence interval and skewness.

Calibration Envelopes

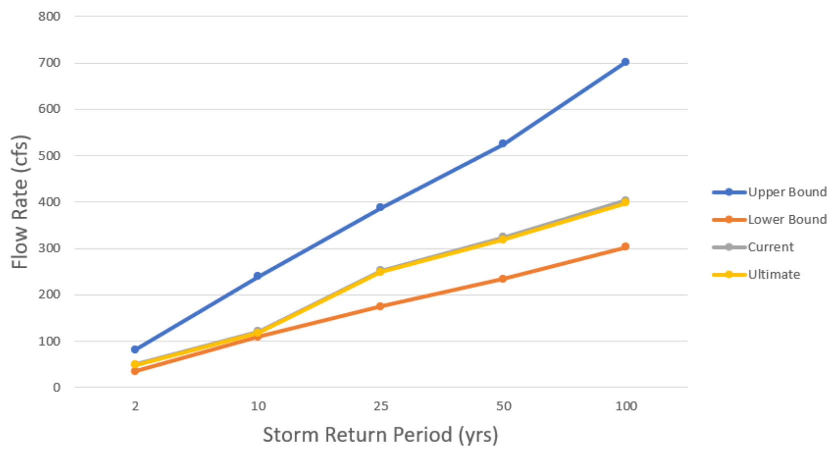


Figure A.1: Snow Hill (B) Calibration Envelope (n = 0.075)

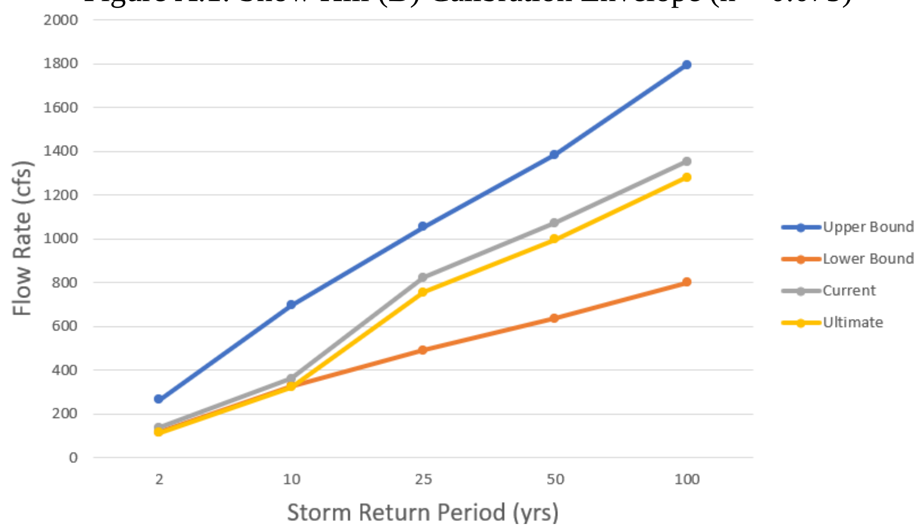


Figure A.2: St. Luke's Rd. Calibration Envelope (n = 0.03)

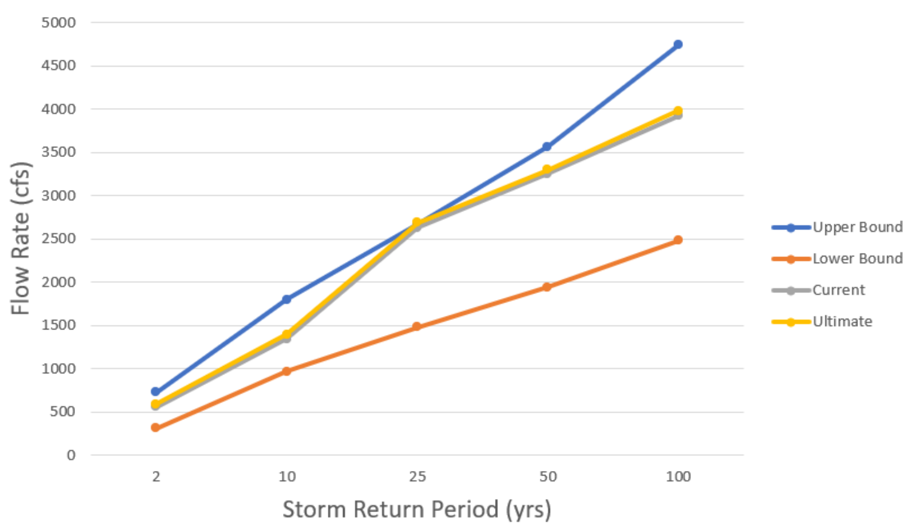


Figure A.3: Panorama Dr. Calibration Envelope (n = 0.065)

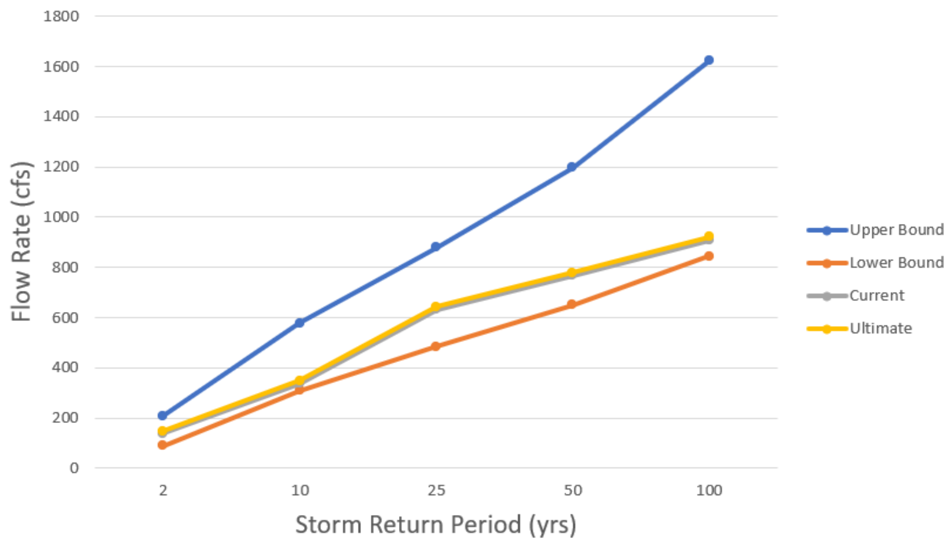


Figure A.4: Sumantown Rd. (A) Calibration Envelope (n = 0.05)

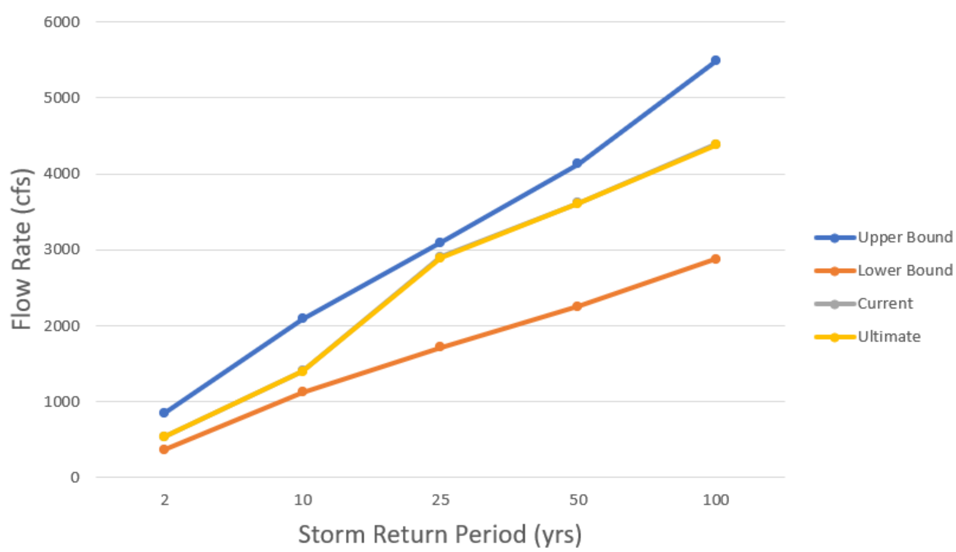


Figure A.5: Sumantown Rd. (B) Calibration Envelope (n = 0.05)

Appendix B:

Hydrographs

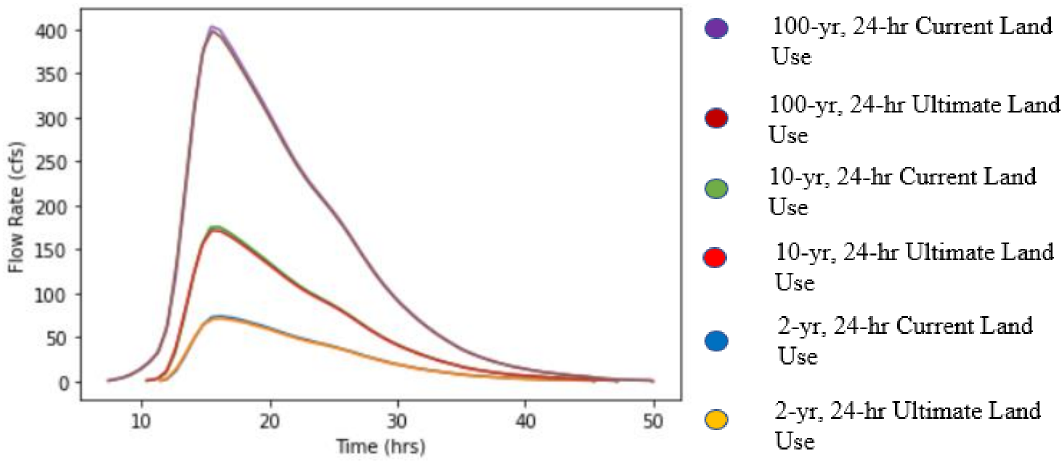


Figure A.6: Current vs. Ultimate Land Use (Snow Hill B)

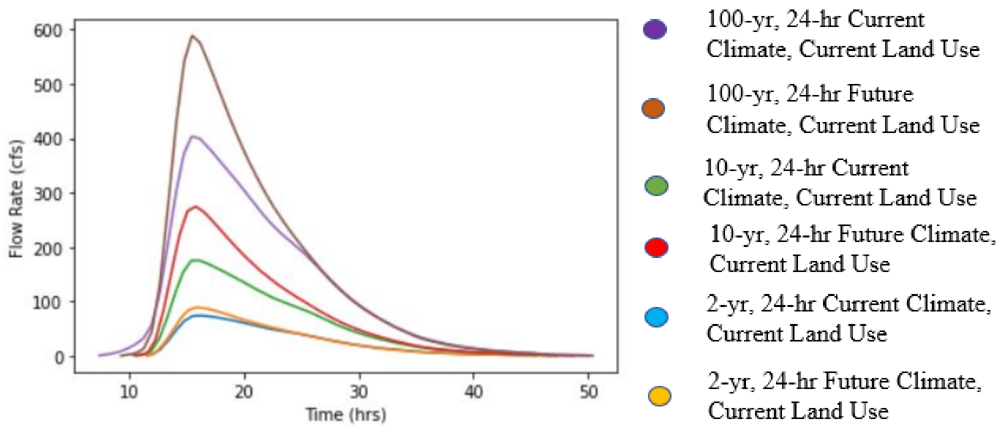


Figure A.7: Current vs. Future Climate (Snow Hill B)

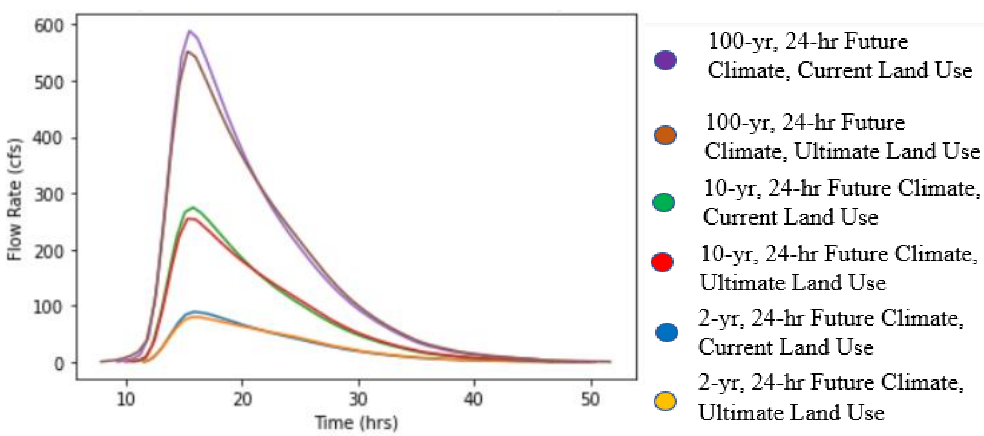


Figure A.8: Future Climate – Current vs. Ultimate Land Use (Snow Hill B)

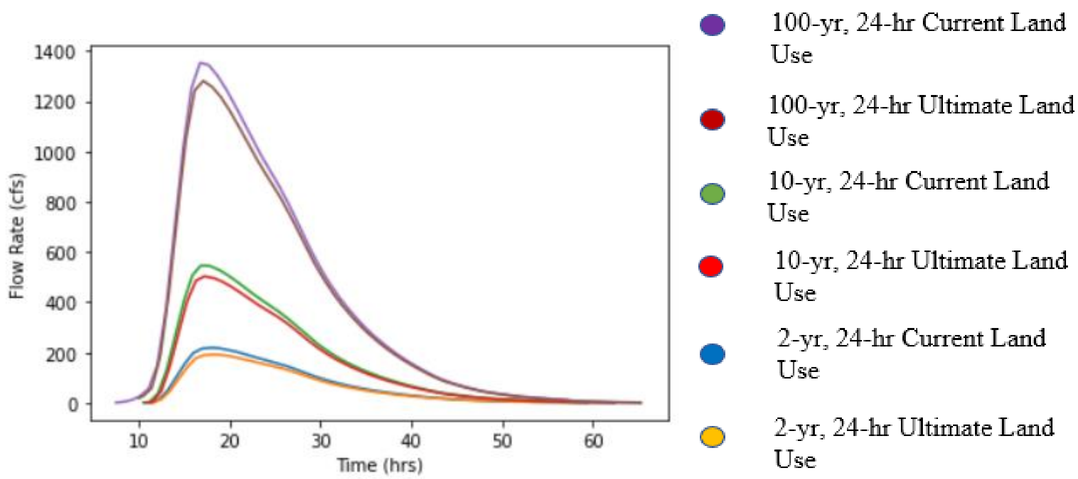


Figure A.9: Current vs. Ultimate Land Use (St. Luke's Rd.)

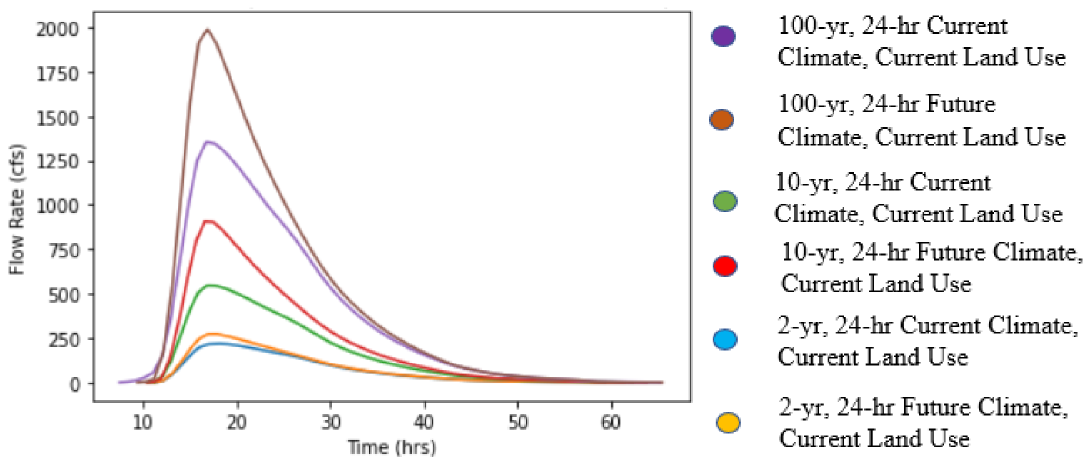


Figure A.10: Current vs. Future Climate (St. Luke's Rd.)

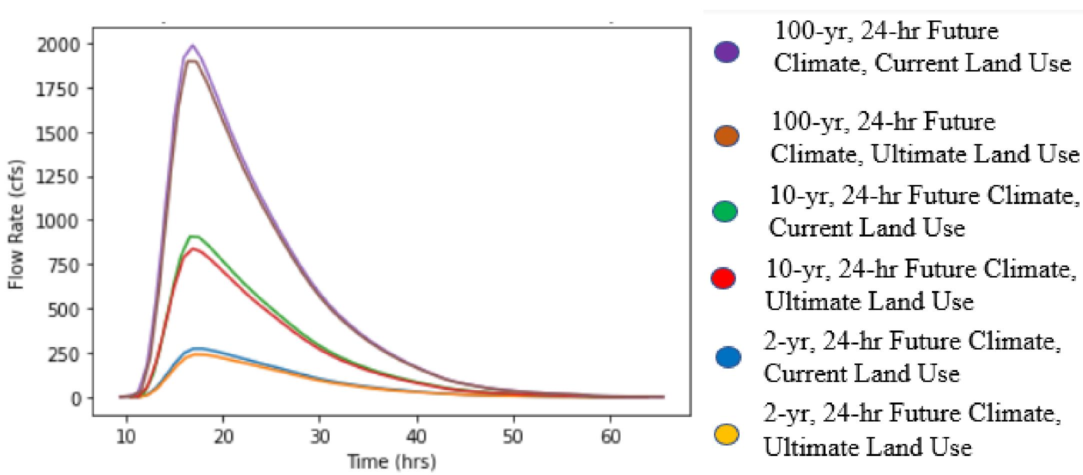


Figure A.11: Future Climate – Current vs. Ultimate Land Use (St. Luke's Rd.)

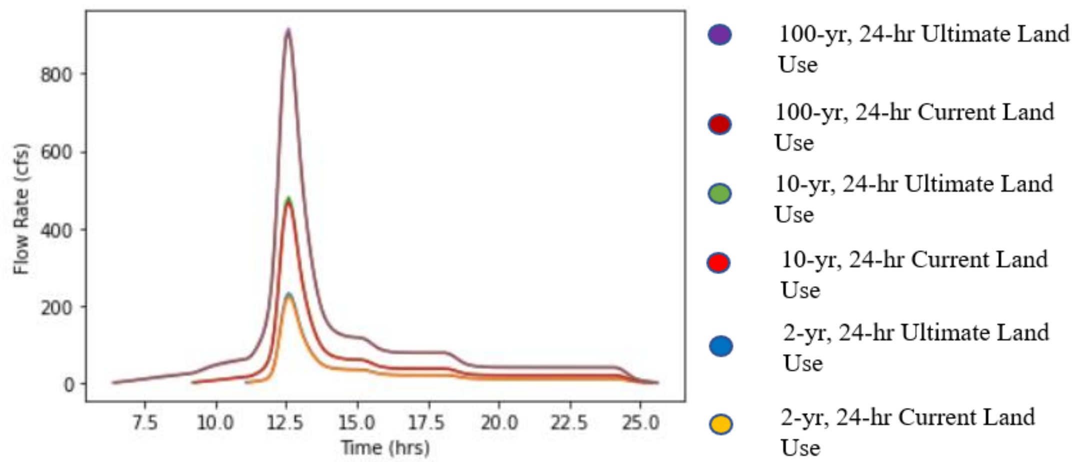


Figure A.12: Current vs. Ultimate Land Use (Sumantown Rd. A)

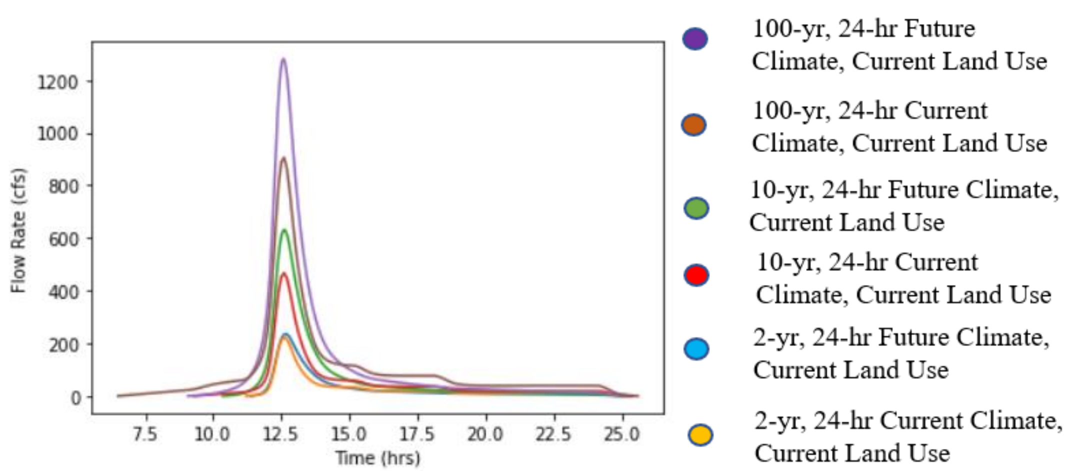


Figure A.13: Current vs. Future Climate (Sumantown Rd. A)

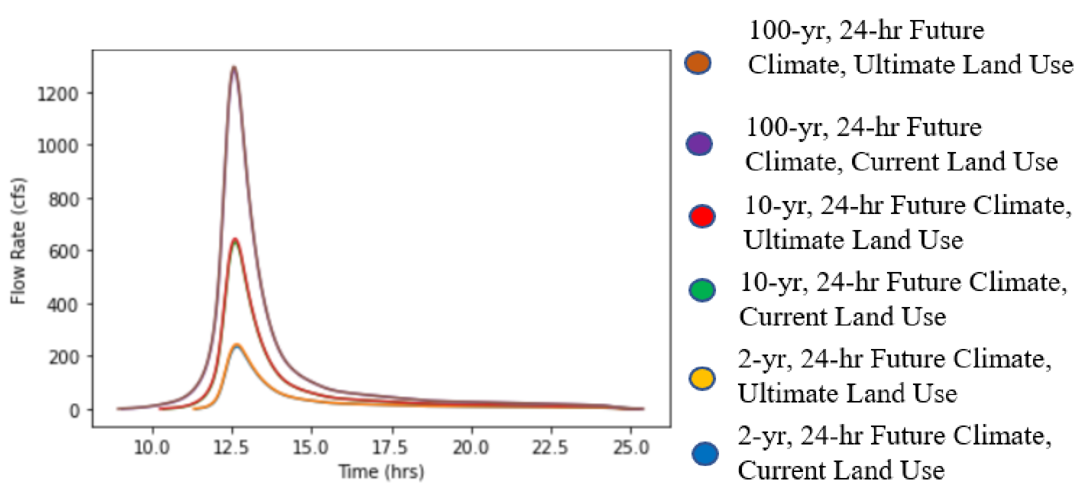


Figure A.14: Future Climate – Current vs. Ultimate Land Use (Sumantown Rd. A)

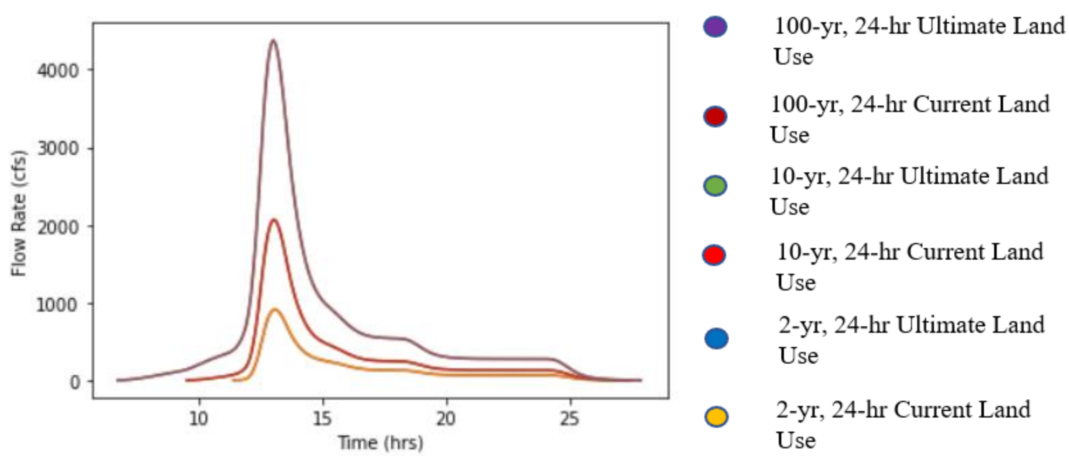


Figure A.15: Current vs. Ultimate Land Use (Sumantown Rd. B)

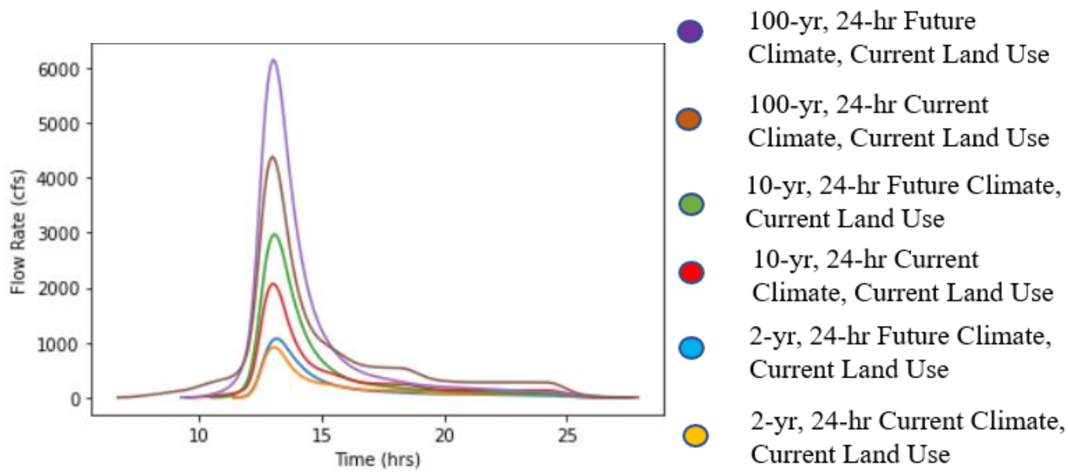


Figure A.16: Current vs. Future Climate (Sumantown Rd. B)

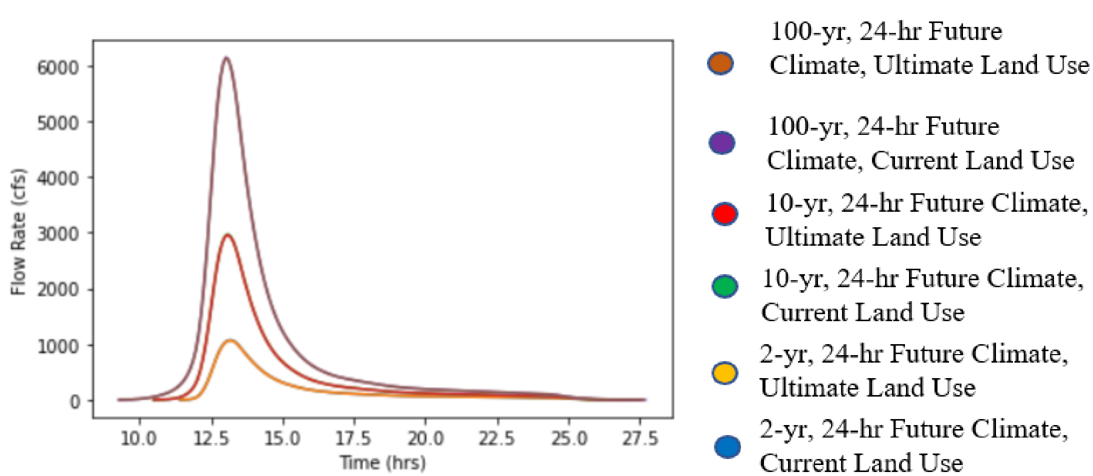


Figure A.17: Future Climate – Current vs. Ultimate Land Use (Sumantown Rd. B)

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