SLEUTH Modeling of Urban Growth around the C&O Canal National Historic Park

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INTRODUCTION

The national park system, established in 1872 to preserve America's natural and cultural heritage (Gantenbein, 2004), is comprised of 397 natural parks, historic parks and sites, and monuments (US Dept. of the Interior (a), 2011). Throughout its history, the National Park Service has been tasked with protecting these American treasures. However, many threats to the national park system have arisen including unchecked human development in close proximity to the borders of many park sites (Taylor, 2011).

Increased human development in all forms, from industrial to commercial to residential to transportation continues, to infringe on the boundaries of national park sites (National Parks Conservation Association, 2011). While development cannot occur inside the boundaries of a given park, development in areas adjacent to a park can destroy the natural habitats of plants and animals, block out or detract from scenic vistas and attract increasing numbers of people to parks (Giesser, 1993). As new residential development near parks rises, ease of access for people and thus increased visitation results. Increased park visitation leads to more traffic congestion, air and noise pollution, and trash and litter (Giesser, 1993). A potential effect of this is that people will enjoy visiting a park so much they will "love it to death" (C&O Canal Trust).

The growth of existing urban areas is also a concern. Further commercial development yields increased impervious surface area and adverse effects for parks in terms of water pollution due to storm water run-off (Sprague et al., 2006). Larger urban areas also yield air pollution from automobile traffic and industrial processes (Giesser, 1993). Air pollution from urban areas both near to and far from national parks results in dirty air, acid rain, and haze; haze is present in all parks in the lower 48 states detracting from scenic views for 90% of the year (Giesser, 1993).

Since the original goal of the national park concept and, later, the National Park Service was to preserve natural and cultural beauty, the areas that are currently protected represent the best glimpses of America's past undisturbed condition. Because national parks represent our best view into the past, they can serve as a good focal point for the study of how current land use practices threaten natural areas by allowing comparisons to be made with our parks to see the effects that human influences have caused.

Study Area: C&O National Historic Park

The Chesapeake and Ohio Canal National Historic Park runs parallel with the Potomac River, originating in Cumberland, Maryland and terminating in Washington, D.C. Along its 184.5 mile length, the C&O Canal borders Maryland, West Virginia, and Virginia with the final 10 miles of the Canal travelling through the Washington, D.C. suburbs of McLean, Arlington, and Georgetown (Figure 1).

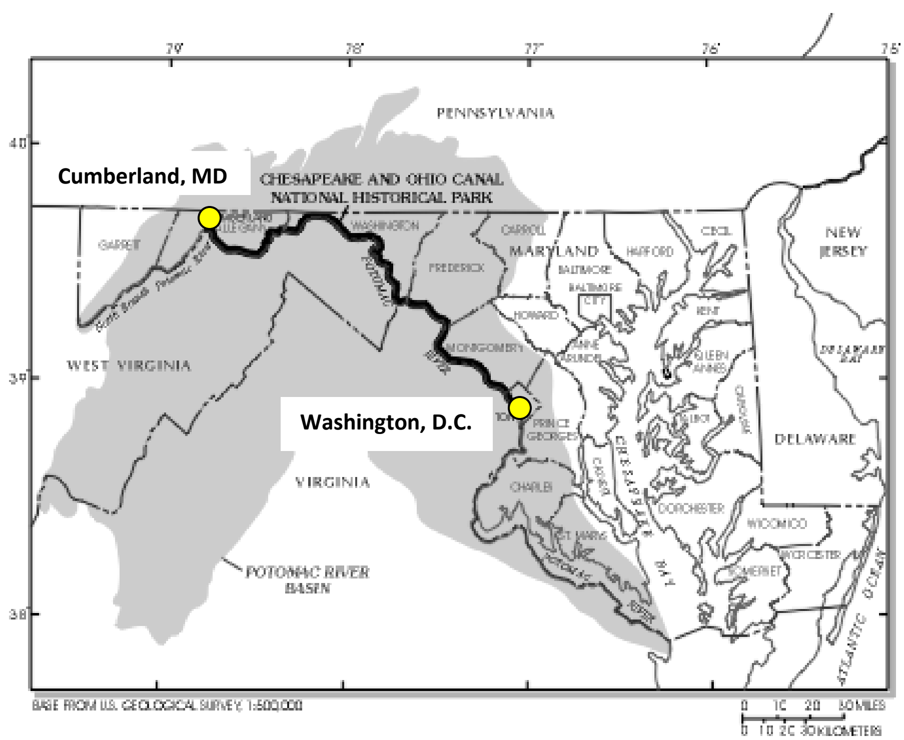

Figure 1: C&O Canal National Historic Park Courtesy: USGS

The C&O Canal was built between 1828 and 1859 and was in operation from 1831 to 1924, (Mackintosh, 1991). The primary economic function of the Canal during its years of operation was to transport coal from the Allegheny Mountains to Washington, D.C. (Hahn, 1984). However, canal operations ceased in 1924 due to many severe floods that damaged the canal beyond the financial resources available to make repairs (US Dept. of the Interior (b), 2011). In order to preserve the canal, the federal government purchased it in 1938 and placed it under control of the National Park Service (US Dept. of the Interior (b), 2011). The C&O Canal was first deemed a national monument in 1961 and then a national historic park in 1971 (US Dept. of the Interior (a), 2011).

Due to the fact that the C&O Canal is so long, it borders three states and traverses a major metropolitan area, it is becoming increasingly susceptible to the pressures of human development. There are currently approximately five million people living in the greater Washington, D.C. region and it is estimated than an additional one million people will move into this area by the year 2020 (C&O Canal Trust). As the population of this region increases, landscapes surrounding protected areas like the C&O Canal become further human dominated as land is converted to urban and agricultural land uses (Gimmi et al., 2011). The effects of this land conversion include increased impervious surfaces, sedimentation of waterways, nutrient loading, riparian buffer loss, and habitat fragmentation. These factors all stand to threaten the original goal behind the creation of national parks like the C&O Canal; the protection and preservation of America's natural areas.

The problems of population growth and urban development are compounded by the fact that protected natural areas may actually foster further development (Gimmi et al., 2011). The aesthetic and recreational amenities that preserved areas provide have been shown to change residential patterns (Hammer et al., 2004), which is accompanied by housing growth and road development (Forman and Alexander, 1998; Forman et al., 2003). as more people desire to live in closer proximity to natural areas.

Human growth and development are threatening many of our country's protected areas including the C&O Canal National Historic Park. While patterns of growth and development in the vicinity of protected areas can be observed based on historic trends, it is also important to be able to identify future growth patterns in order to plan for potential adverse impacts. The SLEUTH urban and land use change model is a tool that can aid in the forecasting of urban growth and land use change patterns. In this study, the SLEUTH model was used to identify areas where urban development is likely to occur within the study area.

PURPOSE

As populations surrounding the C&O Canal National Historic Park continue to grow, so too will urban development, to the detriment of important natural resource lands like this one (Chesapeake Bay Program, 2009). Identifying areas where rapid development has been occurring is an important step in creating and implementing monitoring and conservation efforts in order to ensure the future preservation and conservation of the C&O Canal Park for future generations. The SLEUTH model is an excellent method by which to visualize possible scenarios of development in the C&O Canal study area, so that policies can be enacted to preserve the park lands.

OBJECTIVES

The following questions were addressed in this study:

- What are the historical patterns of urban growth around the C&O Canal study area between 1984 and 2001?
- What is the potential for future urban growth in the C&O Canal study area, from 2006 to 2025?
- What are the implications of projected urban growth for the C&O Canal study area?

METHODS

Implementation of the SLEUTH model occurs in two stages: calibration and forecasting. In the first stage, calibration, historic growth patterns are simulated; in the second stage, forecasting, those simulated historic growth patterns are projected into the future.

Four types of growth are simulated by SLEUTH: spontaneous new growth, development of new urban areas, edge growth stemming from urban centers, and road-influenced growth. The first growth step, spontaneous growth, defines the random urbanization of a non-urbanized cell of land. Next, new spreading center growth determines whether any of the new, spontaneously urbanized cells will become a new urban spreading center. Edge growth then defines the part of the growth that stems from existing spreading centers. The final step is road-influenced growth, which is determined by both the existing transportation network and the urbanization predicted by the previous three steps. These four growth types comprise a single growth-cycle (Clarke, 2011).

Each of the above growth types is defined through five growth coefficients or parameters: slope (slope resistance), diffusion (spontaneous new growth of low density urban land use), breed (new spreading centers or new urban areas), spread (expansion of the urban edge), and road-gravity (road-influenced). These parameters are calibrated by comparing the study area's historical growth patterns with simulated land cover change, and the resulting coefficient values are then applied in the forecasting mode (Clarke, 2011).

Data Inputs

SLEUTH requires an input of several grayscale .gif image files. Each image must be derived from rasters of the same projection, extent, number of rows and columns, and following the prescribed naming format.

The data inputs required by SLEUTH to simulate historic patterns of development are:

- Maps showing historic patterns of development over time from at least two time periods
- A historic transportation network for at least two instances in time
- A slope layer derived from a digital elevation model (DEM)
- An exclusion layer depicting areas where development cannot occur (i.e. water, protected lands, etc.)

Historic patterns of development:

The urban area inputs were derived from Chesapeake Bay Watershed Land Cover Data Series (CBWLCD) datasets using reclassification in a GIS environment. Land use classifications from within the CBWLCD dataset were developed open space, low intensity urban, medium intensity urban and high intensity urban classes. These were the best indicators of developed lands within the aforementioned datasets. These were derived from the data years 1984, 1992, 2001, and 2006. The resultant dataset was reclassified into a binary raster dataset, with 0 denoting no development, and 1 denoting urban area.

Slope:

The slope inputs for slope were derived from publicly available USGS Digital Elevation Model. These data were transformed into a raster file that portrayed percent slope instead of elevation values via GIS capabilities. The resultant dataset had values that were greater than

100% slope. This was an artifact of the nearest neighbor calculations, and thus values greater than 100% were calculated in very steep areas of our study extent. SLEUTH excludes steep areas from development, so this likely did not create errors within our results.

Transportation network:

The road input layer was derived from a United States Census TIGER dataset for SLEUTH input, our roads raster was also reclassified into a binary dataset, with 0 denoting areas that are not road surfaces, and with 1 denoting areas with road surfaces.

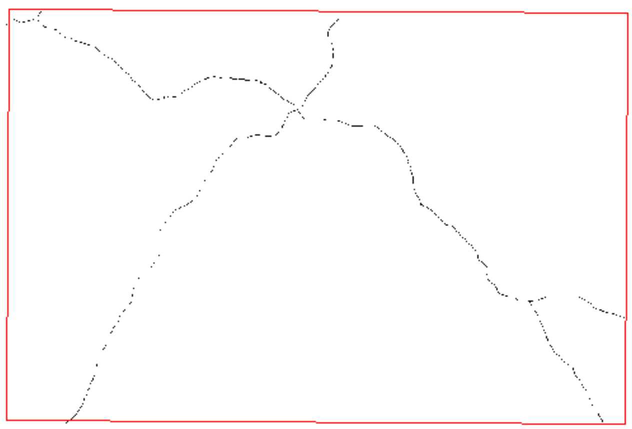

Figure 2. The roads input layer.

Excluded Areas:

The excluded areas input for SLEUTH were derived from multiple datasets. The CBWLCD datasets provided the water portions of the excluded layers, a National Park Service Boundary Dataset and an ESRI Federal Lands Dataset provided the areas in which development are prohibited in general. These were combined in a GIS environment, and reclassified as a binary dataset, with 0 denoting areas that are developable and 1 denoting areas that preclude development (water and areas protected by government).

Figure 3. Excluded areas include water, state, and federal lands.

SLEUTH Model Calibration

The goal of the calibration mode is to narrow-down values for the four growth parameters that most accurately simulate historic trends in land-cover change within a given study area. The parameter values are combined in 3,125 unique permutations, and the user must identify the best set of parameter values for most closely simulating the historical patterns of urban (Jantz and Morlock, 2011).

Calibration parameters

The *spread coefficient* is the most important growth rule (C. Jantz, personal communication, December 5, 2011); it is the most indicative of the total amount of urban area in a given time period. The area metric is based on the pixel count of the original urban data inputs. Run #3004 was chosen because the *areafract* value was the closest predictor of actual urban pixels in 2001, with an underestimation of 52,568 urban cells or about 12.5%. The underestimation is due to the spread coefficient value of 0; run #3004 was used again but with a spread coefficient value of 5, and again with 10, in hopes of reducing the amount of omission.

The *diffusion coefficient* growth rule is an indicator of low-density urban sprawl. The *Edgesfract* metric is based on the number of edge pixels. More edge pixels mean more low-density sprawl. The *breed coefficient* growth rule is an indicator of urban spreading centers. The *clusterfract* metric is based on the number of clusters, where a cluster is defined as a central raster cell and its eight surrounding cells being classified as urban. Run # 670 was chosen because the *clusterfract* value was the closest predictor of actual urban spreading centers in 2001, with an underestimation of about 1,823 urban clusters, or 4.6%.

For this project, two unique calibration runs were identified as potentially being able to accurately simulate historic patterns of growth between 1984 and 2001: run #670 and run #3004 (Table 1).

Table 1. Growth rules and corresponding growth coefficients for SLEUTH calibration

	breedcoeff	spreadcoeff	slp_resstcoeff	road_gravcoeff	controlyear	areadiff	arearatio
670	1	25	100	1	2001	79923	1.18
3004	100	1	1	100	2001	-52568.28	0.87
	edgesdiff	**edgesratio**	**edgesfract**	**clusterdiff**	**clusterratio**	**clusterfract**	
670	31846	1.13	0.13	-1823.85	0.95	-0.046	
3004	-3163.85	0.98	-0.013	3166	1.08	0.081	

Calibration output processing:

First, in order to calibrate the outputs from SLEUTH, a fishnet grid was created. The fishnet was created as a polygon file in ArcGIS with each grid square representing an area of $480m^2$. Typically fishnet grids are made up of either $500m^2$ or $1km^2$ squares (C. Jantz, personal communication, December 7, 2011). However, because our original urban rasters were 30m resolution, $480m^2$ fishnet grid cells were used because 480 is a multiple of 30. This will insure that an even number of urbanized raster cells can be counted in a given fishnet grid cell. The fishnet was used to calculate the area within each grid cell that was developed in the four study years: 1984, 1996, 2001, and 2006. This was accomplished using the **Zonal Statistics** toolset in ArcGIS.

Zonal statistics were used to count the number of pixels that SLEUTH utilized to determine the number of cells within each fishnet grid cell that had a probability of development. The outputs of the zonal statistics were then used to determine the total land area within each fishnet grid cell that was predicted to have been developed by the SLEUTH model. This was determined using the following formula:

$$\frac{\left(\left(\frac{Sum\ of\ cells\ with\ a\ probabilty\ assigned}{100}\right) X\ 900\, \frac{m^2}{cell}\right)}{Area\ (in\ Sq.m) of\ each\ fishnet\ grid\ cell}$$

This formula calculates the percentage of the area within each fishnet grid that was predicted to be developed in 2001. The results of these calculations were then compared to the *actual* percentage of developed area by subtracting the modeled value from the observed value. These calculations were repeated 6 times, once for each of the SLEUTH outputs. The SLEUTH runs that were tested can be viewed in Table 2 below. The main differences between these 6 models of growth are the spread variables, which were modified to better represent the observed growth within the study area. The spread variables are based on a scale from 1-100 where higher values indicate a stronger influence of that growth rule on the overall forecasted urbanization of a given area (Jantz and Morlock, 2011).

Table 2: The variables for the six different calibration runs tested in this study

Run	Diffusion	Breed	Spread	Slope	Road Growth
3004_00	100	100	1	1	100
670_00	25	1	25	100	1
3004_05	100	100	5	1	100
670_05	25	1	5	100	1
3004_10	100	100	1	10	100
670_10	25	1	10	100	1

SLEUTH Model Validation

The model for run #670_05 from the above table displayed the closest fit between modeled and observed development in the year 2001 based on all of the growth coefficients. This model was used to predict development in 2006 based on data inputs for 1992 and 2001. The output .gif file was processed in the same way previously described in the calibration section. The percentages of land which had a probability of development as assigned by SLEUTH were compared to the observed intensity of urban development in 2006.

RESULTS

Calibration

Based on the six model calibration runs that were performed, run #3004_00 (Figure 4) and run #670_05 (Figure 5) had the least amount of error associated with them in terms of under- or overestimation of actual developed land. While #3004_00 had the least amount of error overall, it was based largely on the spreading coefficient. However, #670_05 had only slightly more error (~1% more) but did a better job of incorporating the edge and cluster coefficients; thusly, it was chosen for the model validation.

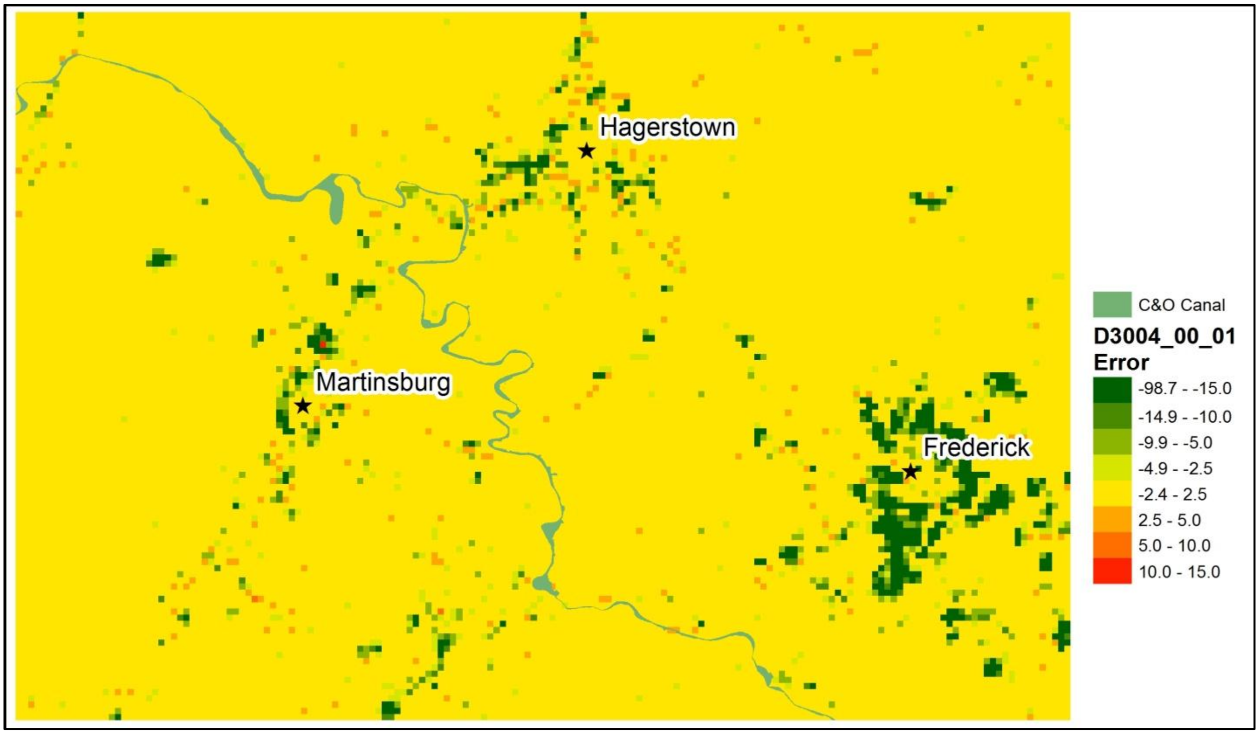

Figure 4. Output for model calibration run # 3004_00

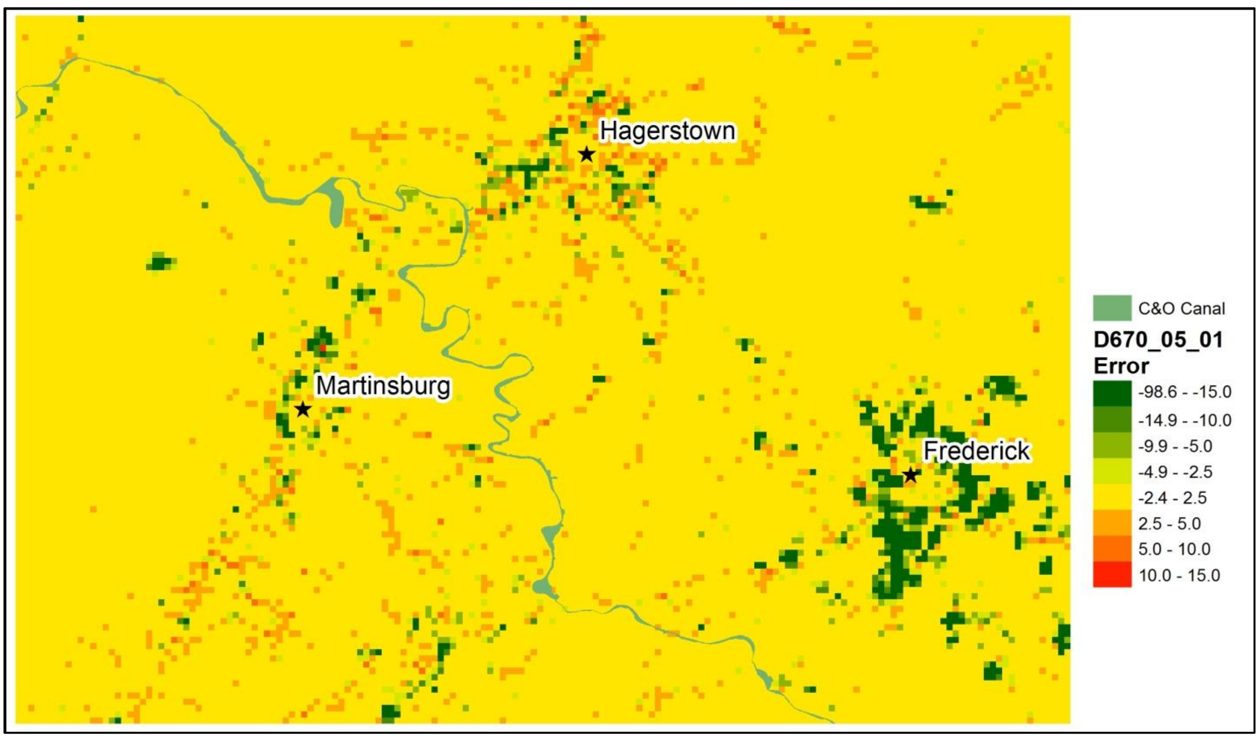

Figure 5. Output for model calibration run # 670_05

Validation

The results of the validation were quite satisfactory. The model's validation to the 2006 dataset predicted the urban area within the study area was only a 0.51 % overestimation (Table 3) (Figure 6). As with the calibration model runs, the area with the largest underestimation of urban land covers was Fredrick, Maryland. However, the validation did not have any areas of overestimation over 2.5%. Fredrick had the most area of underestimation, in both the calibration and the validation model runs. However, the results from the validation show that there was less underestimation around Fredrick than was calculated in the calibration runs, further adding to the validity of our result.

Table 3. Actual and predicted urbanization within the C&O Canal study area.

Year	Urban Area (Sq. km)	Total Area (Sq. km)	Overall developed Land (% of study area)
2006 (Actual)	384.4701	4475.0016	8.591507543
2006 (Modeled)	384.9804	4475.0016	8.602911094

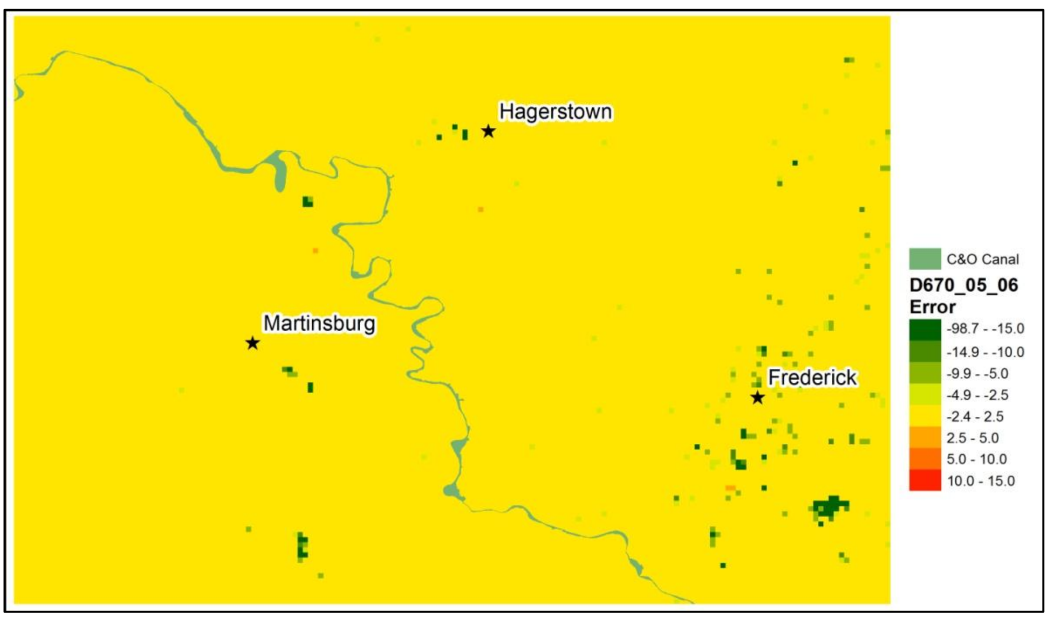

Figure 6. The model's validation to the 2006 dataset predicted the urban area within the study area was only a 0.51 % overestimation.

DISCUSSION

Historical patterns of urban growth around the C&O Canal, 1984 -2001

In 1984, the total amount of the C&O Canal study area that was classified as developed was more than 7%. By 2001, this number had grown to nearly 8.5% (Table 4). This shows a trend of increasing urbanization through time; this trend is concerning to officials working for organizations like the C&O Canal and other protected areas.

Table 4. Historic patterns of urban growth around the C&O Canal, 1984-2001

Year	Urban Area (Sq. km)	Total Area (Sq. km)	Overall developed Land (% of study area)
1984	328.5729	4475.0016	7.342408548
1992	364.5648	4475.0016	8.146696529
2001	378.8127	4475.0016	8.465085242

Model Validity Assessment

The results of the model calibration and validation showed consistently underestimated predicted values for development in the area of Frederick, Maryland. The SLEUTH model, in this study, does not incorporate population forecasts; however, a known 30% increase in population occurred in Frederick between 1990 and 2000 (National Park Conservation Association, 2004). Self-modification rules, which modify the growth efficient, would be utilized in order to compensate for the high growth rate.

Implications of projected urban growth for the C&O Canal

Parks and protected areas are attractive to populations; people want to live and work near scenic, beautiful places. The problem, then, is that park boundaries become increasingly threatened by burgeoning development. Growing populations demand ever-increasing residential areas, hotels, retail complexes, roads, and other infrastructure to make these amenities more convenient to access (Giesser, 1993). As a result, the beautiful parks that the populations were drawn to suffer damage. Buildings block scenic views; new transportation networks mean increased traffic congestion and impervious surfaces. Air quality is diminished as noise and pollution levels increase, and water quality suffers as stormwater runoff increases due to added impervious surfaces (Giesser, 1993).

In Frederick County, Maryland population grew by 30% between 1990 and 2000 (National Park Conservation Association, 2004). With this population increase came an increase in impervious surfaces, which resulted in significant flooding well-above historic levels in the park, damaging habitats, eroding historic waterways, and washing sediment and invasive species into the park from surrounding lands (National Parks Conservation Association, 2004).

Another consequence of urban development surrounding park lands is habitat fragmentation. Growing populations require more utilities, such as electricity, water, and sewage. The C&O Canal Park is legislatively mandated to provide utility rights of way. The utility lines go through park lands resulting in increasing edge effects (National Parks Conservation Association, 2004). The Potomac Gorge region of the C&O Canal National Historic Park is considered one of the most biologically diverse in the United States (National Parks Conservation Association, 2004). It is home to more than 200 rare species and communities, 16 of which are considered globally rare (National Parks Conservation Association, 2004). Fragmentation of habitat puts these species in peril and threatens the livelihood of the park, as their inherent value attracts park visitors.

Pollution, both from utilities and otherwise, is also a major issue facing the C&O Canal. The Potomac Sewage Interceptor, which services the highly-populated Loudoun and Fairfax Counties in Virginia, Montgomery County in Maryland, and Washington, D.C., runs under the park and discharges into the nearby Potomac River, often overflowing into the park during times of high stream flow such as storm events (District of Columbia Water and Sewer Authority, 2011). All of the issues described above are consequences of urban development around protected natural areas.

CONCLUSION

Urban development poses real threats for protected natural areas, from the habitats that comprise them to the organisms – human and animal – that live in and around them. Although areas like the C&O Canal National Historic Park *are* protected, they are not guaranteed safety from the pressures of development surrounding their borders. Expansion of impervious surface increases overland flow and associated flooding and pollution and sedimentation of waterways. Habitat fragmentation often occurs as infrastructure is built through existing park boundaries, or near its edges, in order to support the surrounding populations. Protected areas are often home to threatened or endangered plant and animal species, and the loss of habitat impacts their abilities for survival.

Policies that support resource protection are crucial for ensuring the future preservation of natural resource lands. "Limiting the footprint" of developed land should be a priority for limiting sprawl and protecting vulnerable environments such as the C&O Canal (Jantz & Morlock, 2011).

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