Development and Land Use Change in the Central Potomac River Watershed

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Introduction and Motivation

The Potomac River Watershed drains 14,760 square miles across parts of West Virginia, Maryland, Virginia, Pennsylvania, and Washington DC (ICPRB, 2012). The population of the region was 6.9 million in 2010, with an estimated 2.3 million additional residents estimated to move to the region by 2040 (Potomac Conservancy, 2014). According to the latest report from the Potomac Watershed Conservancy, rural and suburban areas are projected to see a 44% population increase by 2040, while urban areas are expected to grow 24% in the same timeframe.

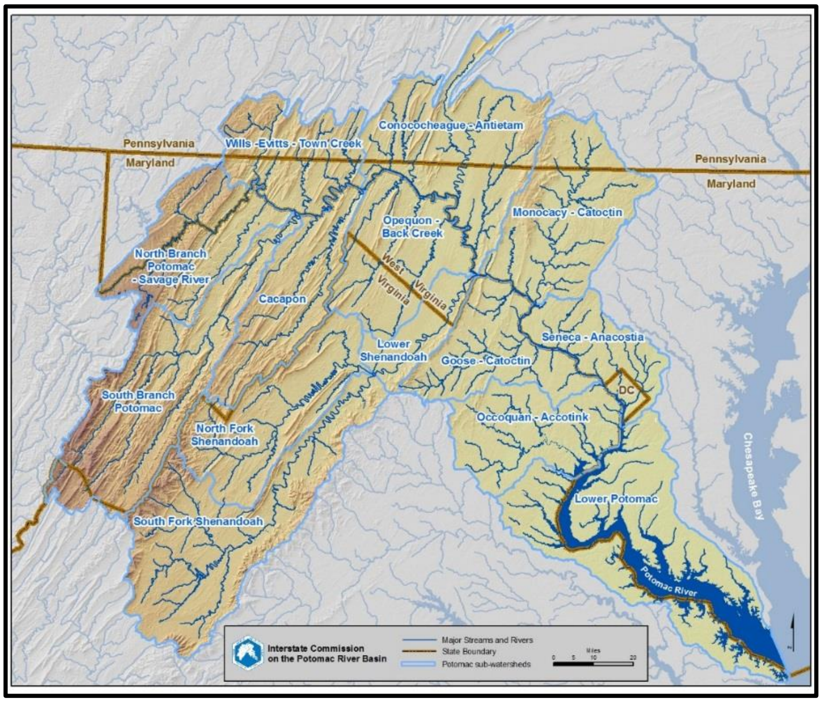
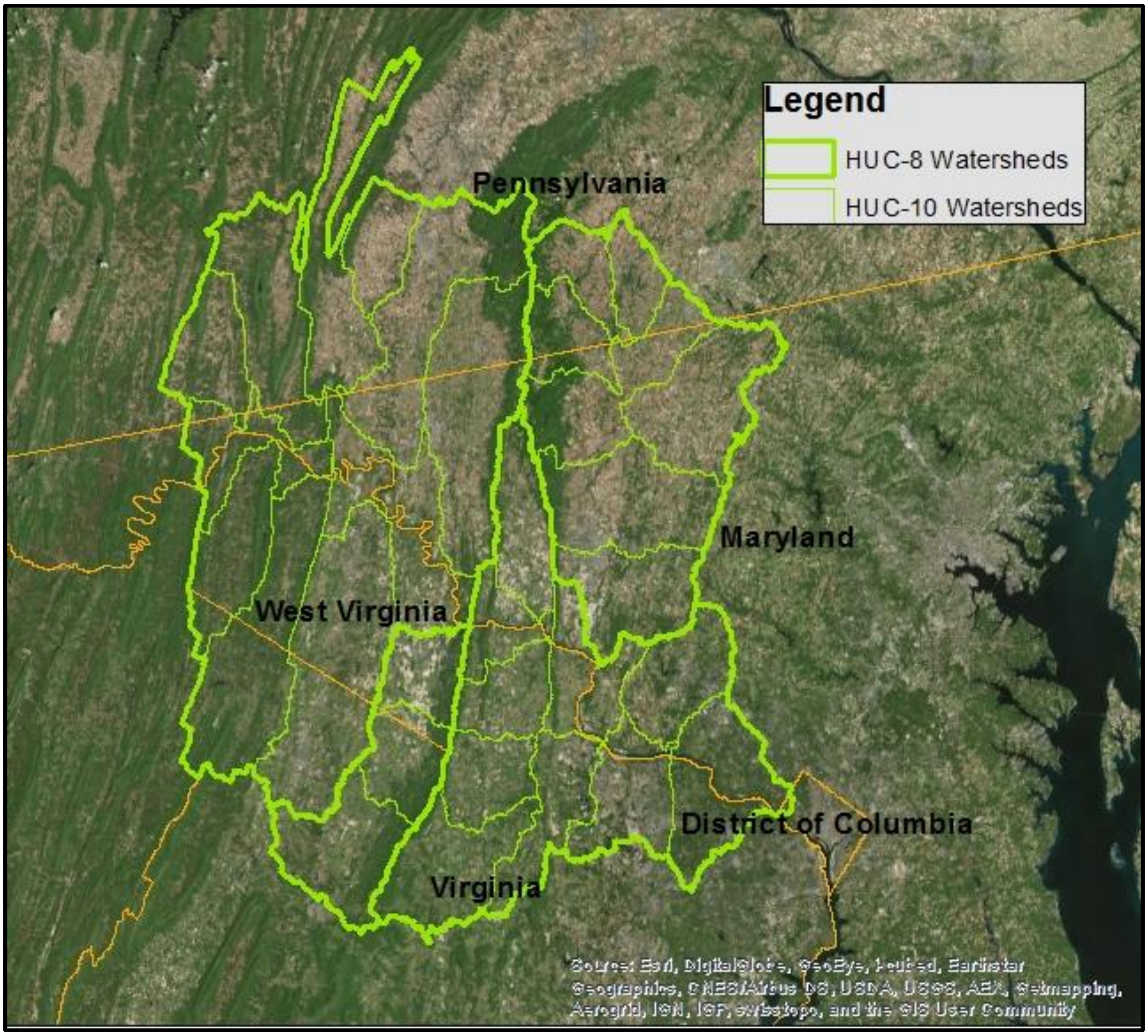


Figure 1. Entire Potomac River Basin Watershed (Image: ICPRB)

For this project I will consider in detail one subsection of the Potomac River Watershed that is covered by four HUC-8 regions, shown in Figure 2. This region covers 4,837 square miles (about 1/3 of the total watershed area). This area has historically been primarily forested and agricultural land but development has increased over the past few decades as a result of population outgrowth from the Washington DC metro area.

While development in the Potomac River Watershed is an important water quality issue in its own right, it is also closely monitored because it drains directly to the Chesapeake Bay, seen in Figures 1 and 2. Development (and the accompanying increase in impervious surface cover) increases water runoff from the land That water carries with it higher loads of pollutants because the pollutants do not have as much of a chance to be filtered out in plants and soil as they move across the landscape. The pollutant increases have contributed to the declining health of the Chesapeake Bay in recent decades. In recent years, much attention has been paid to contributing areas of the Chesapeake Bay Watershed in order to try and understand land use change and how the effects on the Bay can be mitigated.

The purposes of this project is to examine the link between land cover change, precipitation, and runoff in a subsection of the Potomac River Watershed. Land use and impervious surface datasets derived from aerial photography will be used to analyze change in land cover over time. Then, precipitation data and stream gage flow data for the region will be obtained, and runoff coefficients (flow/total precipitation) will be analyzed in subwatersheds. I plan to investigate whether it is possible to see correlations between increasing land development and increasing water runoff using readily available data products.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2. Study Area showing HUC-8 and HUC-10 watersheds. The study area drains parts of WV, MD, PA, VA, and DC. A wide variety of topography in the area can be seen from the background imagery.

Data Sources

Three main data sources were utilized for this project: land cover grids from the National Land Cover Database, precipitation data from NOAA (National Oceanic and Atmospheric Administration), and stream flow data from the US Geological Survey. The information obtained from each of these datasets is detailed below.

Stream Flow

Stream flow data was obtained from the US Geological Survey (USGS) interactive map. Once a bounding area was selected, all the stream gages in the area were selected and exported to a new file. Of the 70+ total gages, 49 had annual stream flow data, which was the data of interest. The data for these 49 gages were exported to Excel. However, many of the stream gages only had a few years of data, and the purpose of using stream gage data in this project was to show change over time. Therefore, any stream gage that had fewer than ten years of data from 1990-2013 was discarded. 26 gages remained to be used in analysis.

Land Cover

The National Land Cover Database (NLCD) provides raster datasets with categorical variables about how the land is used (ie. developed-low intensity, open water, shrub/scrub, etc.). Datasets are available for 1992, 2001, 2006, and 2011. The 1992 dataset is available at 200-meter resolution, while the others are available at 30-meter resolution. Data on land cover and percent imperviousness (a derived product from land cover) for the study area, including a buffer area, were downloaded from the National Map (nationalmap.gov).

Precipitation Stations

Precipitation data was obtained from the NOAA National Climatic Data Center (ncdc.noaa.gov). Stations were located by putting in the relevant states and then selecting the stations that are within the study area. Annual summaries of total precipitation (rainfall + snowfall) from 1990-2013 were extracted, however these files (when in .csv format) still only give monthly totals. The 12 months were added to give an annual total; however in many cases, a station would be missing one or more months of data for a given year. In that case, the data for that year had to be discarded because the annual total would be invalid. There were a total of 29 precipitation stations that had annual data for the time period of interest. The average year had data at 16 of the 29 stations. The year with the poorest data coverage was 2012 (12 stations), and the years with the best data coverage were 1996-1998 (each with 20 stations).

Methods

Once the data sources were downloaded, they were imported to ArcGIS for analysis. First, the rivers from NHD Plus were used to find the mouth of the study area. The gage closest to the mouth was identified, and the entire watershed upstream of this gage was delineated. This drainage area included almost all of the area in the four HUC-8 regions, and it was this area that was used for the rest of the analysis.

First, the stream gage data were used to delineate upstream watersheds using the Watershed tool in the ArcGIS Hydro online services. The tool delineates the unique watershed that drains to each region, so there were several overlapping regions. These regions were converted to polygons from rasters, and then a variety of spatial proximity tools were used to eliminate the overlapping areas and to fill in the slivers between the polygons. This resulted in 25 delineated watershed areas, each draining to a particular gage, as shown in Figure 3. These watersheds, as opposed to the HUC-10 regions, were used for the remainder of the analysis because that allows building relationships directly between land use and the draining area.

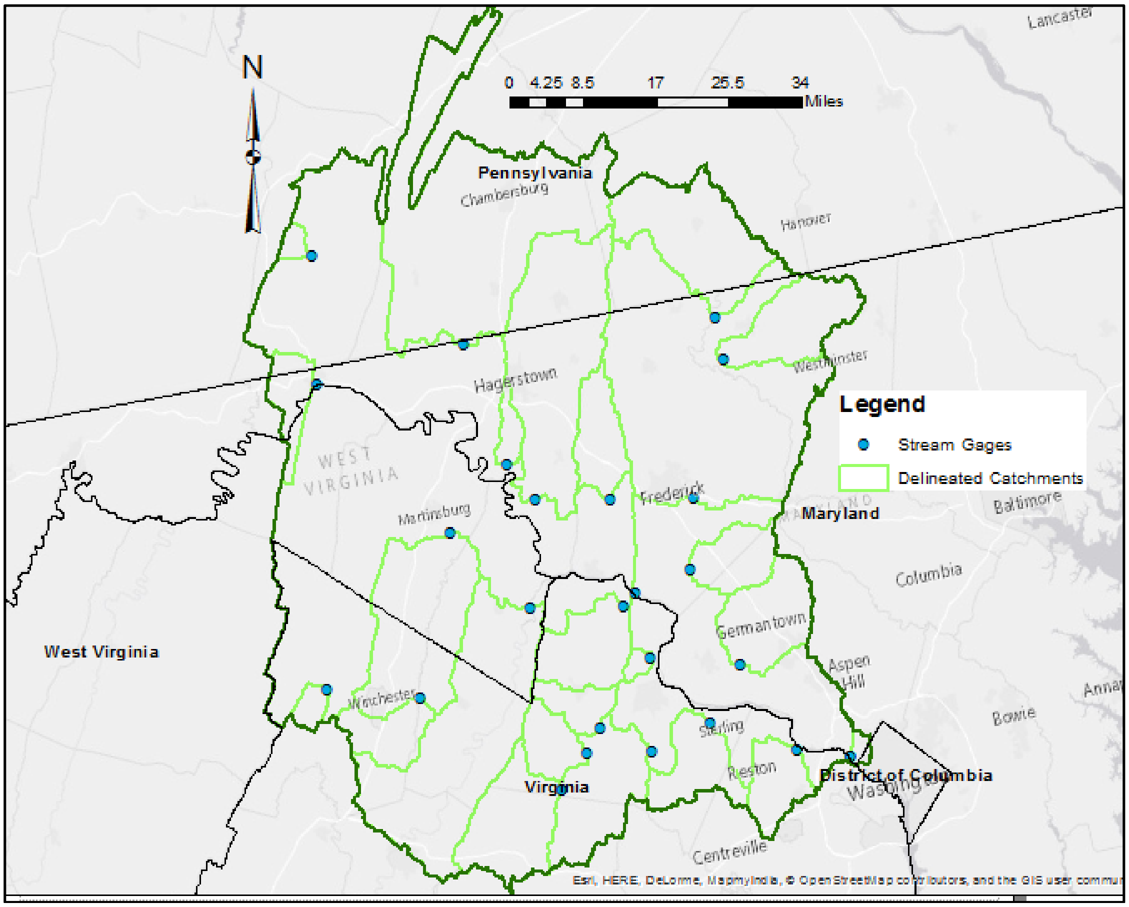


Figure 3. USGS Stream Gages (with at least 10 years of data) and their delineated catchments

Next, the NLCD data were imported into ArcMap. The NLCD categories for the 2001, 2006, and 2011 datasets are show in Figure 4a. These were recategorized using the Reclassify tool into a more generalized set of categories, shown in Figure 4b. For the remainder of analyses, the generalized categories were used, except for analysis that analyzed the change in the type of development. Each generalized category was extracted into its own raster using the Raster

Calculator to make a series of rasters that have, for example, cropland in 2001, developed land in 2001, and so on.

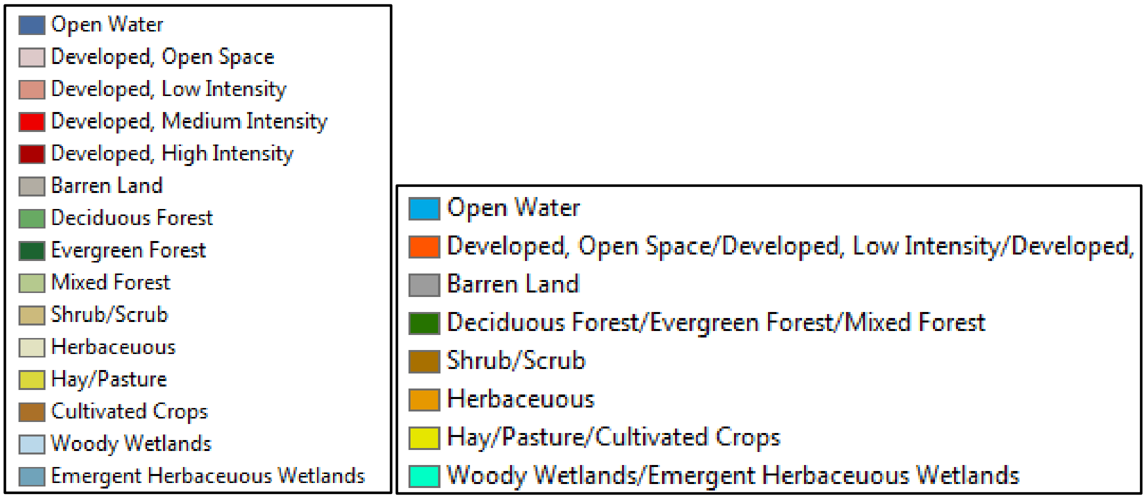


Figure 4. Categories of land use in the 2001, 2006, and 2011 National Land Cover Datasets (left); reclassified categories for ease of analysis (right)

For the NLCD, changes in the following variables were performed for each time frame (2001/06, 2006/11, 2001/11): forested land, agricultural land, developed land, impervious surface, development intensity, and impervious cover. These were performed with the Raster Calculator. One raster (always the older one) was multiplied by 10, so the values in the raster were 10 and 0. Then, the rasters were subtracted, for example:

$$2001\ Cropland\ (10\ or\ 0) - 2006\ Cropland\ (1\ or\ 0) = Change\ in\ Cropland$$

This equation handles each case of cropland change over time uniquely. In this example, 10: forest loss, 9: forested area, no change, -1: forest gain, 0: not forested, no change. Then, this resulting raster is can be analyzed using Zonal Statistics as Table with the 25 unique watersheds delineated previously to determine land use change in each watershed. For all area-based calculations (which were much of the calculation work done in this project) North America Albers Equal Area projection was used to make sure area calculations could be interpreted properly. On a few occasions, points that were given in geographic coordinates had to be converted to projected coordinates to be displayed properly; ArcGIS has a tool to accomplish this, so the task is pretty simple.

Precipitation data was imported into ArcGIS and the points were plotted. A variety of interpolation methods including Spline, IDW, and Thiessen Polygon were tried to see which would best represent the data without adding or eliminating significant trends. None fo the interpolation methods seemed to provide particularly convincing estimates of trends, and the general trends observed from one year to the next changed because of the precipitation stations that had available data for that year. Because of the lack of convincing, high-resolution data, the data was examined only visually. It was determined that the data did not have high enough resolution to merit doing zonal statistics to see how a region's precipitation and streamflow over time. The trends that would be observed would more likely be an artifact of errors in interpolation then actually showing something about changes in the hydrology of the landscape.

Results

As will be discussed at the end of this section, the precipitation source data did not prove very useful for obtaining the type of information that was desired. Nevertheless, even without direct comparisons to hydrologic changes, land use changes over time tell something fundamental about how a region is changing. Different ways of examining how land use has changed have been listed earlier in the paper. Many analysis methods were tried; a few of the most telling and interesting results from various ArcGIS analyses are outlined below.

Forest and Cropland Change

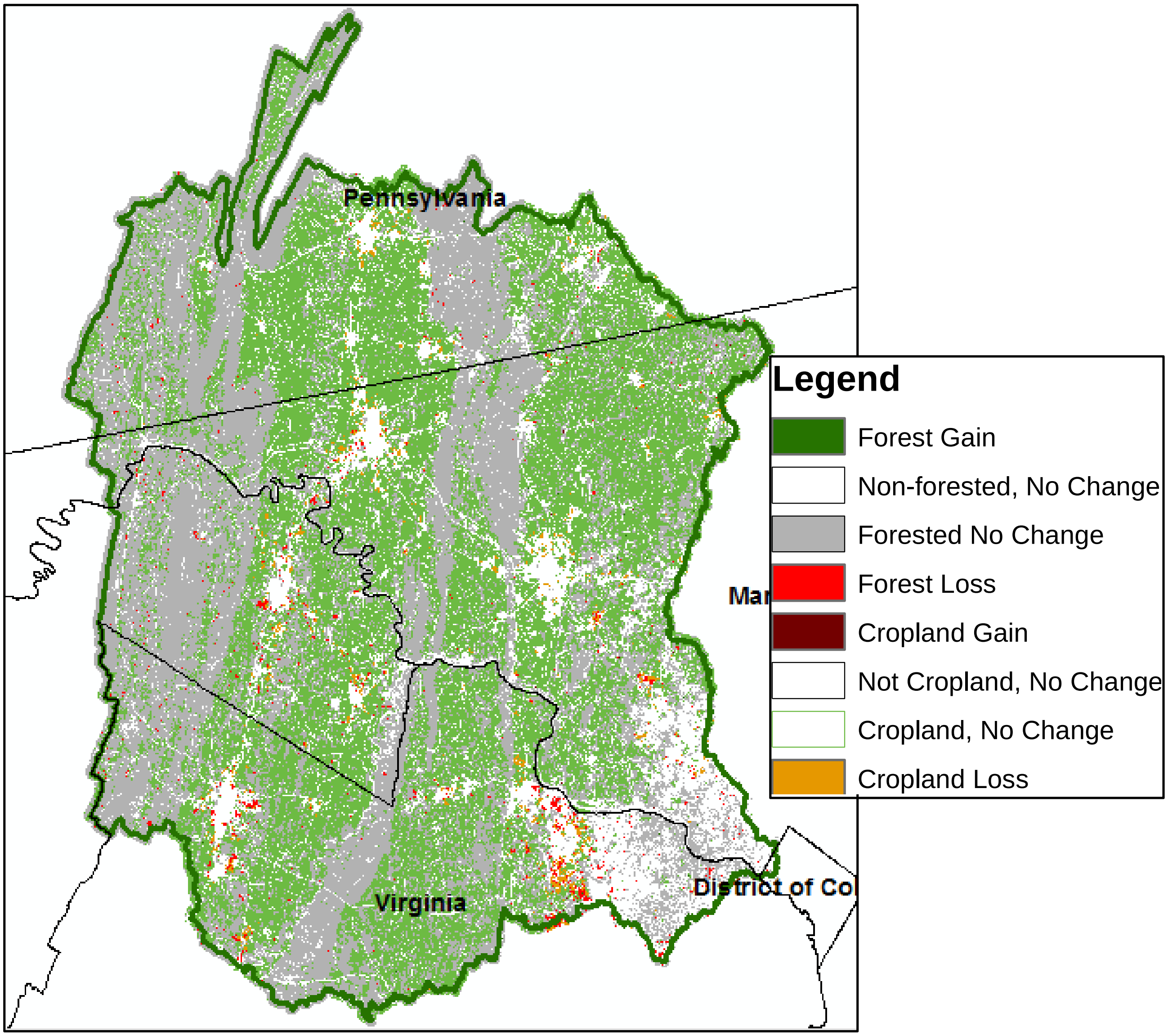


Figure 5. Change in crop land and forest land from 2001 to 2001

In a predominantly rural area on the East Coast that has experienced substantial development, much of the land use change is going to be in the form of agricultural and forested land being converted to other forms. The map in Figure 5 illustrates these changes. Loss in cropland and forest land is shown in yellow and red, respectively. Areas that remained forested are shown in gray, and areas that remained cropland are shown in light green. This means that much of the developed area is shown in white. From this map, it is easy to see that forest and crop land loss has occurred most on the outskirts of Washington DC, but land loss to other types can also be seen on the fringes of other towns in the region. While this is an unsurprising result, the map provides a valuable way to look at this information spatially for a relatively small geographic area. The results of the land cover change as presented in Figure 5 are also summarized in Table 1, below.

Table 1. Forest and Crop Land Use Change from 2001-2011

Land Use Change Category	Acres
Forest Gain	769
Forested, Remained Constant	131,436
Forest Loss	21,373
Cropland Gain	1,809
Cropland, Remained Constant	132,117
Cropland Loss	26,404

Table 1 also elucidates some interesting trends about land use change over the decade considered. The amount of cropland and forest land is roughly equal. Cropland is being lost at a faster rate, but it is also being added (in different locations from where it is lost) at a faster rate. This table suggests that, when looking at the effects development plays on rural landscapes in the region, understanding changes to forests and agricultural land are equally important.

It is also possible to visualize using ArcGIS these land use changes over defined subregions. For the purposes of this project, the catchments delineated with USGS stream gages were chosen, but any other subregion of choice including a HUC boundary could work just as well. The results of forest acreage lost in these catchments are shown in Figure 6, below. Acreage of forest lost in a particular catchment varies from 0 to 4881 acres. While these areas vary widely in size, it is still useful to see forest loss attributed to an area that has hydrologic meaning. Then, smaller areas that have higher acreage losses can be flagged, for example, for increased water quality monitoring.

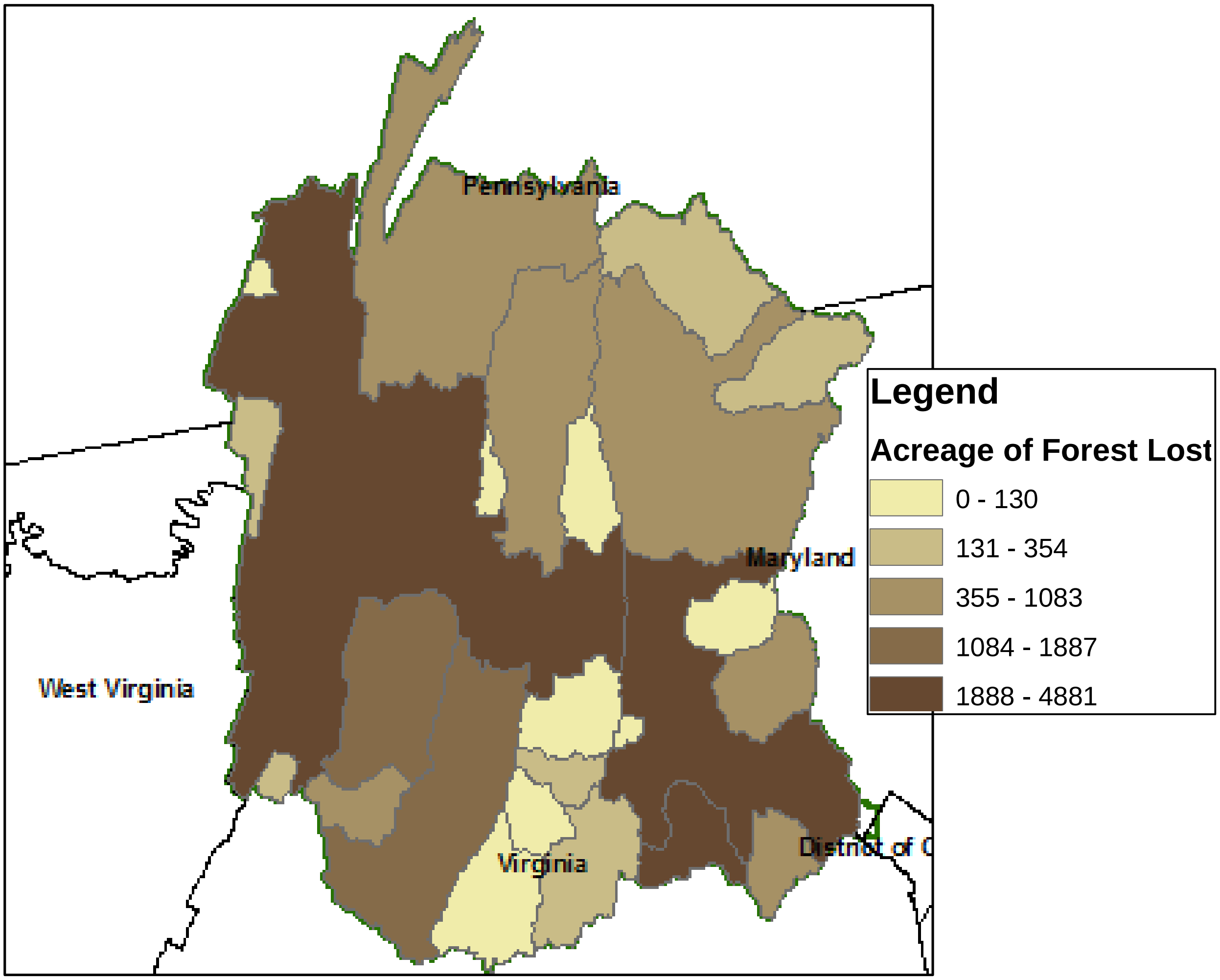


Figure 6. Acres of forest lost per catchment from 2001 to 2011. Note that catchments vary widely in size, but this could be still used as an indicator of stress on a particular waterway

Increase in Development Intensity

Another way of looking at land use change from the NLCD is at the change in development intensity. Referring back to Figure 4, the NLCD classifies developed land as either open or low, medium, or high development intensity. In contrast to forest and cropland loss, which tells something about how much land has been lost presumably to development, development intensity provides a look at if already developed land is being used in a more stressful way. While the reasons for the increasing development intensity cannot be determined from the NLCD, it does tell something about what people in concentrated areas are doing with the environment around them.

Figure 7 shows the change in development intensity of areas that were classified as "low intensity development" only in 2011. A map of development intensity throws population centers into sharp relief. From the map, it seems that development intensity increases most in the interior of areas that are already built up. Again, this makes intuitive sense, but it is a valuable visual tool to see how a region is changing.

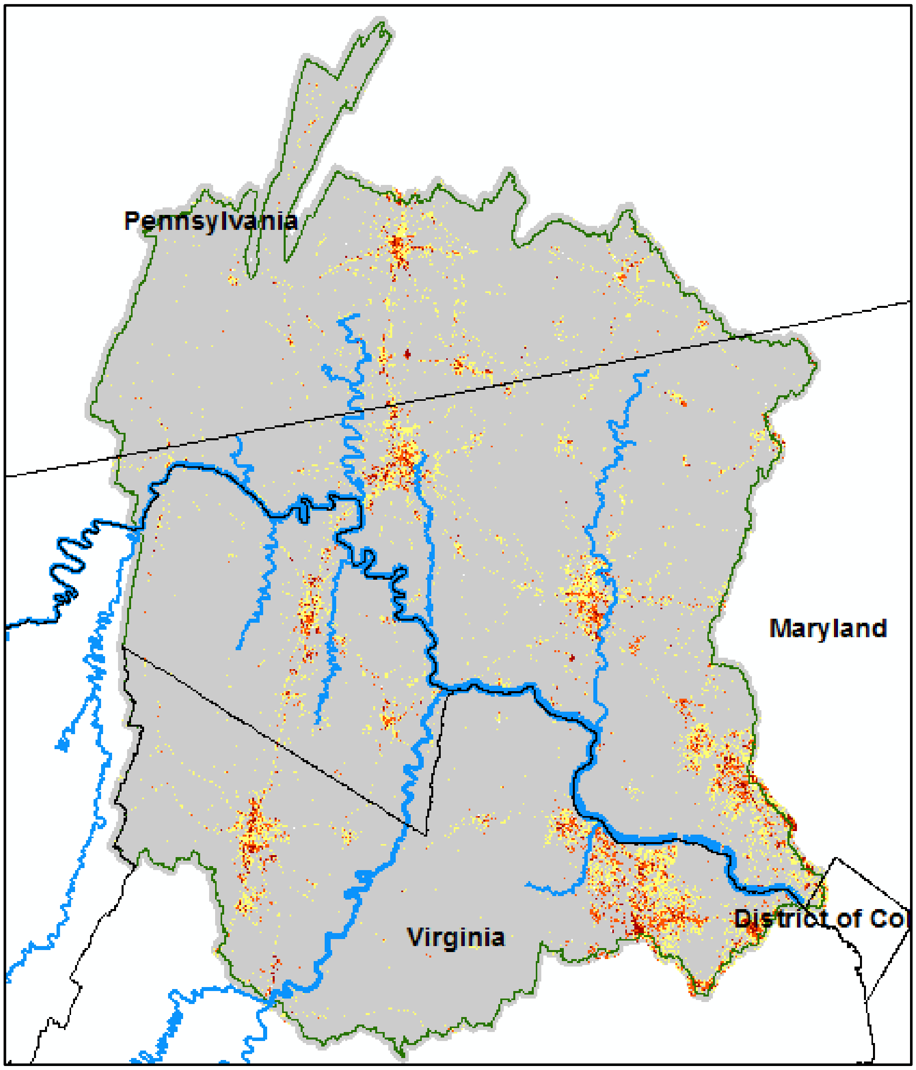


Figure 7. Increase in Development Intensity of low-intensity developed areas from 2001 to 2011. Gray areas were not developed. Yellow areas remained classified as "low development". Orange areas changed from low to medium development, and red areas changed from low to high development.

The results that are presented visually in Figure 7 are presented numerically in Table 2

Table 2. Development Intensity Category Change from 2001 to 2011

Development Intensity Category (2001 to 2011)	**Acreage**
Low to Low	140,907
Low to Medium	57,510
Low to High	15,796

Table 2 shows that most land did not increase in use intensity, but those that did increase were more likely to increase by one category than two. Comparing Table 2 with Table 1 also yields interesting observations. Over the years 2001-2011, increase in land use intensity (73,306 acres) was more common than forest and cropland loss combined (47,777 acres). That means that, while suburbanization is often associated with loss of farms and rural land, changes to land that has already been developed are also an important factor in understanding how the ecosystem changes.

Change in Impervious Cover

A related, although not identical, measure of development is the percent impervious cover on the landscape. This is information that is provided directly from the NLCD. What makes this a valuable tool for assessing land use change is that each raster cell is assigned a value of 0-100, denoting the percent impervious cover in that cell. Thus, when these raster layers are compared for different years, it provides a very quantitative measure of change (as opposed to the categorical “low”, “medium”, and “high” presented in the previous section.

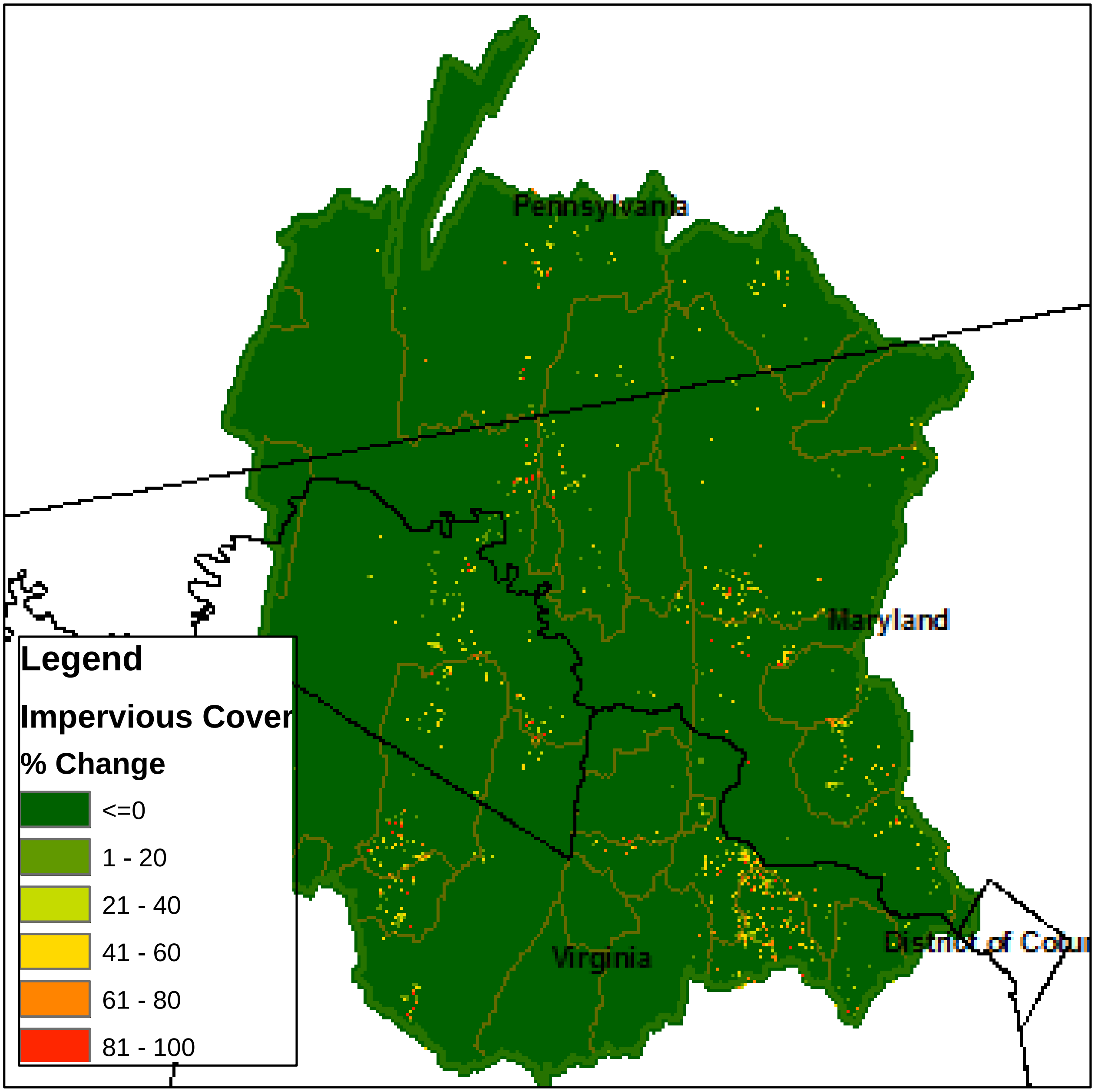


Figure 8. Percent change in impervious cover from 2001 to 2011

Figure 8 (above) shows the percent change in impervious cover over the region from 2001 to 2011. The general trends mirror those presented in the previous sections, which is to be expected. Figure 9 shows a close-up of one area on the above map on the Virginia-West Virginia border. What Figure 9 shows is something more detailed—that impervious cover tends to increase around the edges of an area somewhat, but it increases most in the center of that area. This is seen by the reddest spots with yellow and light green around them in Figure 9.

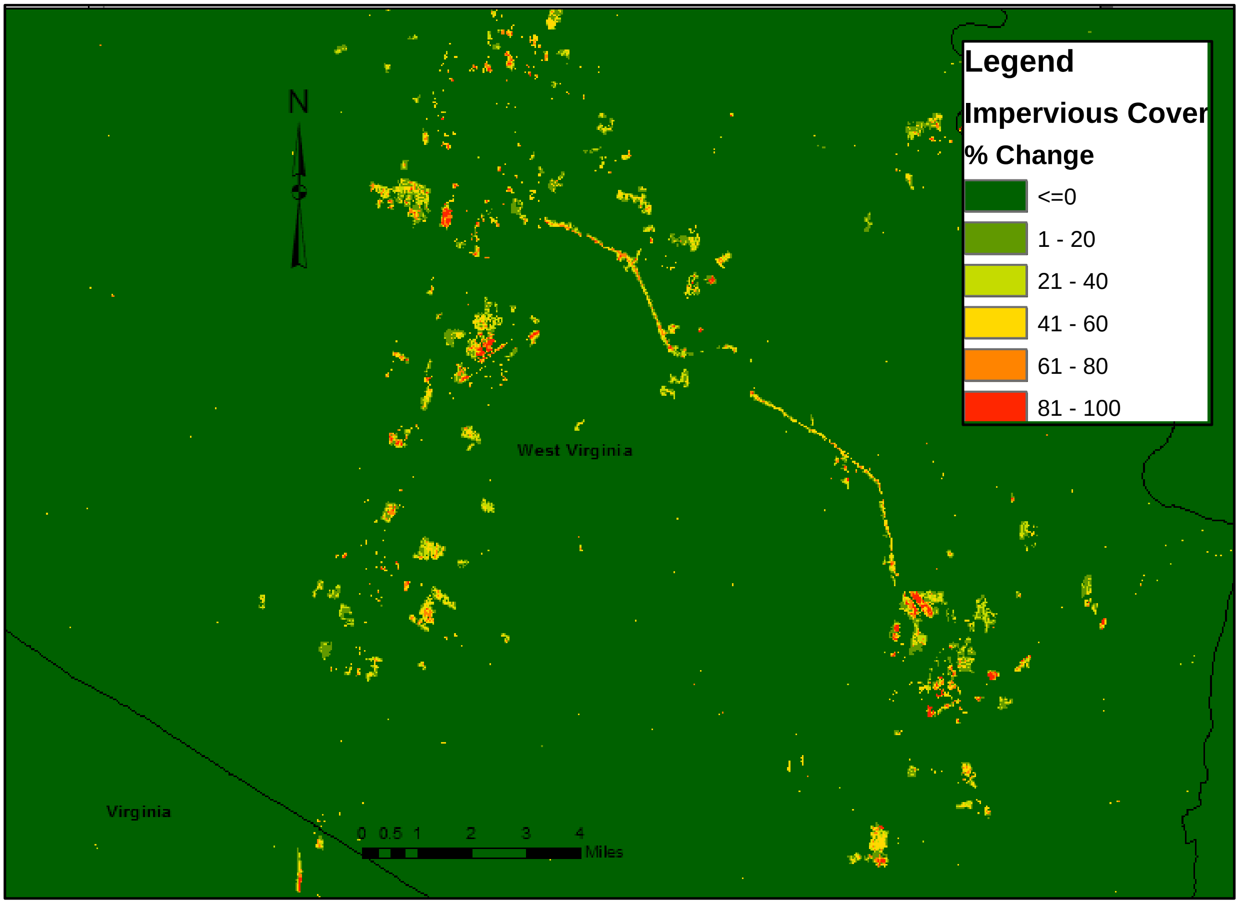


Figure 9. A close-up of one area showing change in impervious cover from 2001 to 2011. This figure suggests that impervious cover increases on the edges of developed areas, and intensity also increases in the "interior" of already developed areas

A statistical analysis of the raster presented in figure 8 showed that 1.55% of the land experienced an increase in impervious cover from 2001 to 2011. Of land that did increase in impervious cover, the median increase was 40%.

Table 3. Acreage per increase in impervious surface category from 2001-2011. Areas may not add to the area of the watershed due to independent rounding.

	0%	1-20%	21-40%	41-60%	61-80%	81-100%
Acreage	3,220,408	17,391	8,381	15,017	7,055	2,764

Hydrologic Data (Streamflow and Rainfall)

The original purpose of this analysis, as discussed previously, was to link the land cover changes to the change in runoff ratio due to increased development. Working with the land cover data was manageable and yielded useful results. However, working with precipitation data in particular did not turn out to be so fruitful.

For the analysis to be valid, time series data for precipitation were needed. Then, for each year, the runoff ratio at each catchment would be computed. However, the time series data obtained from NOAA had many stations with little data, and the stations that did have data varied from year to year. When interpolation methods were attempted with this data, like that in Figure 10, it was noted that precipitation varies widely across the region in general (34 to 57 inches) and that estimates were likely to be quite inaccurate. After noting the data quality, no additional analyses were attempted with time series precipitation data.

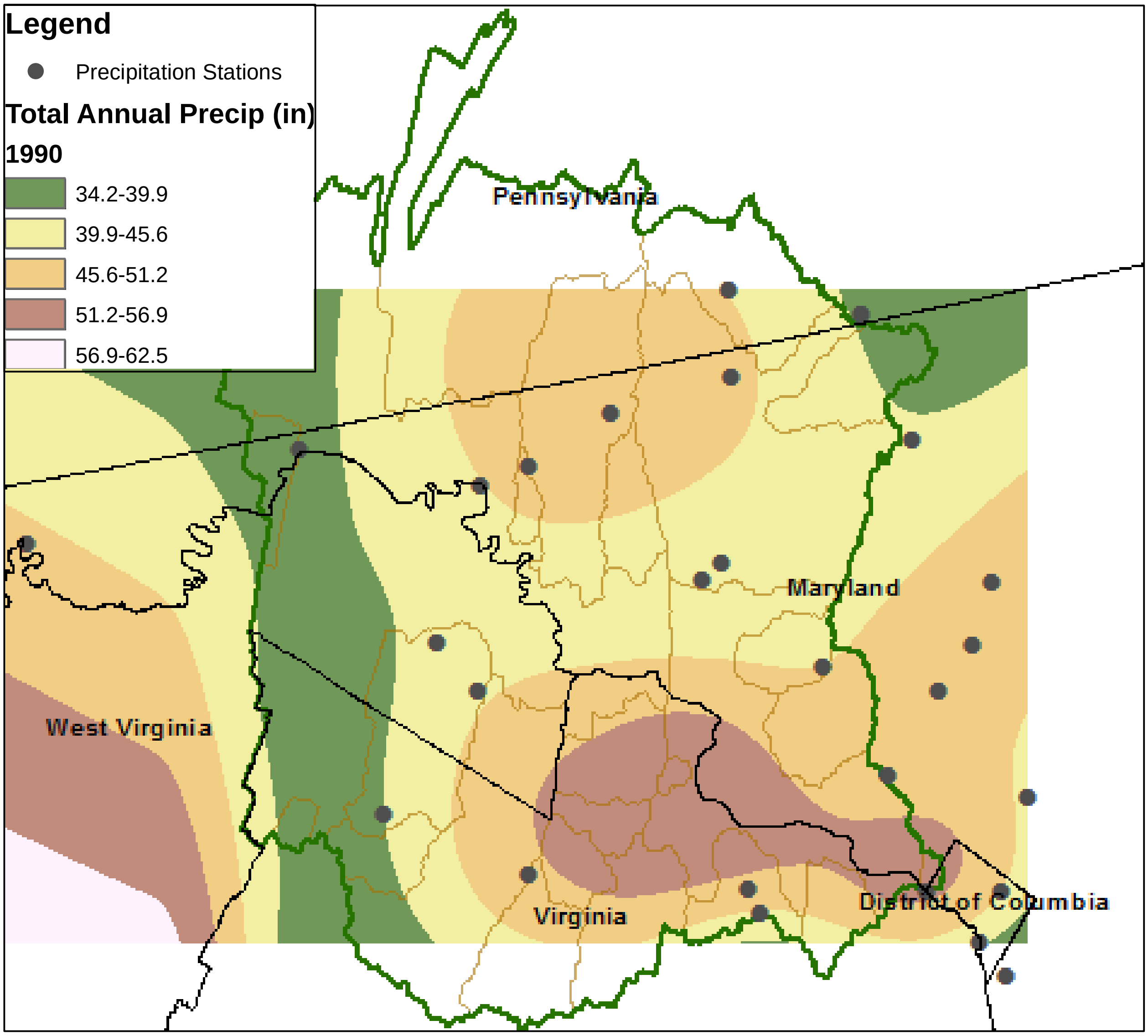


Figure 10. Interpolation using the spline method of precipitation data from NOAA stations for 1990

Conclusions & Discussion

The central Potomac River Basin has experiences significant and quantifiable land use change over the years of 2001 to 2011. Loss of forest, loss of cropland, increase in development intensity and increase in impervious cover can all be seen visually from maps produced in ArcGIS and analyzed numerically. This project has shown that the National Land Cover Dataset can be a valuable tool for showing land use change in a community, even at a fairly small scale.

One main limitation of this analysis that could be addressed with more time is the addition of the 1992 National Land Cover Dataset to allow for an additional decade of comparison with current conditions. It was discovered after all the ArcGIS analysis had been done that there was a format of the 1992 NLCD available that was specifically designed to be compatible with later years.

A data limitation of this project was the availability of precipitation data. However, this limitation is unlikely to be resolved in the near future, so the only thing that can be done is consider the data quality when designing future projects and experiments.

ArcGIS is a powerful tool for visualizing and analyzing changes that take place across a landscape. However, working with many different raster layers and the raster calculator became quite cumbersome. If I were to do more of this work in the future, I would put more work into automating the process so analysis could be done more quickly. There are many additional ways to present information about land cover change beyond those presented here, and additional metrics of change could be examined.

References

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