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Virginia ConservationVision: Development Vulnerability Model 2015 Interim Edition

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Virginia ConservationVision:
Development Vulnerability Model
2015 Interim Edition

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Abstract

The Virginia Development Vulnerability Model quantifies the predicted relative risk of conversion from “natural”, rural, or other open space lands to urbanized or other built-up land uses. It is presented as a raster data set and associated maps, in which the relative vulnerability of lands ranges from 0 (least vulnerable) to 100 (most vulnerable). Cells in which development has already occurred are coded as 101.

This model is based on travel times to three development “attractors”: urban areas, metropolitan areas (a subset of urban areas), and impervious growth hotspots. It also incorporates the legal protection status and biological management intent of conservation lands in the state. The model is based in part on the most recent imperviousness data available from the National Land Cover Database (NLCD), and thus represents conditions circa 2011. The model will be updated periodically as new data representing more recent conditions become available. A future, more complex version of the model is currently under development. It will incorporate a wider array of predictor variables representing various driving forces of development, and will employ a rigorous statistical analysis and/or machine-learning techniques to derive the relative probability of development.

The Virginia Development Vulnerability Model is one of several in a suite of conservation planning and prioritization models developed by the Virginia Natural Heritage Program and partners, known collectively as Virginia ConservationVision. The vulnerability model can be used in conjunction with other data to help prioritize lands for immediate protection. The model can also serve as an input for simulating future land cover change and its consequences under different planning scenarios.

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Introduction

As human populations and demand for resources expand, natural areas and rural lands are increasingly threatened by encroaching development. The Virginia Department of Conservation and Recreation (DCR), Division of Natural Heritage (DNH), has a mission to protect Virginia's native plant and animal life and the ecosystems upon which they depend, with a focus on globally and state rare species and natural communities. As part of its work, DNH develops and maintains a suite of geospatial models intended to guide strategic land conservation and management decisions. This suite of models is known as Virginia ConservationVision. The models under the ConservationVision umbrella address a variety of conservation issues and priorities, and include a Natural Landscape Assessment Model, a Cultural Model, a Recreation Model, an Agricultural Model, a Watershed Integrity Model, a Forest Economics Model, and a Development Vulnerability Model.

The Virginia Land Conservation Foundation (VLCF) provides state funding to purchase or establish conservation easements on various lands of conservation concern. Given limited funds, it is essential to have a means of prioritizing lands worthy of preservation. The purpose of the Virginia Development Vulnerability Model is to quantify the relative risk of conversion from "natural", rural, or other open space lands to urbanized or other built-up uses. It provides some of the information needed for prioritizing lands to be placed under conservation easements in the interest of maintaining green infrastructure across the state. The model is similar to the Chesapeake Bay Program's Vulnerability Model produced as part of their 2008 Resource Lands Assessment (CBP 2008). They define vulnerability as a function of suitability for development and proximity to growth "hot spots". However, the CBP map is restricted to the Chesapeake Bay watershed, and does not cover the state of Virginia in its entirety.

An earlier edition of the Virginia Vulnerability Model was produced by DNH in 2008 (VADNH 2008). Since then, the Multi-Resolution Land Characteristics Consortium (MRLC) released the 2011 edition of the National Land Cover Database (NLCD; Homer et al. 2015). The update to the Development Vulnerability Model, described in this report, takes advantage of the 2011 NLCD data, roads data from 2015, and data derived from DNH's Conservation Lands Database. The current model was developed from a variety of spatial data sets using a suite of

Geographic Information Systems (GIS) tools. It is presented as a raster data set and associated maps, in which the relative vulnerability of lands to development pressure ranges from 0 (least vulnerable) to 100 (most vulnerable). Lands where development has already occurred are coded as 101. The relative vulnerability of lands is assessed primarily based on travel times to several development "attractors", while also accounting for land protection and current development status.

Methods

The Development Vulnerability Model is derived from three primary components: a "Raw Vulnerability Score", a "Protection Multiplier", and development status based on NLCD 2011 impervious cover data (Figure 1). The Raw Vulnerability Score, which ranges from 0 (least vulnerable) to 100 (most vulnerable), is based on travel times to three major development attractors. The Protection Multiplier, which ranges from 0 (greatest level of protection) to 1 (no protection), is derived from information on legal protection status and biodiversity management intent of protected lands, obtained from the DNH Conservation Lands Database. Details of the methodology used to produce the model components and final model are presented in the following sections.

Spatial Data Processing

ArcGIS software (versions 10.2-10.3; ESRI 2015) was used for all spatial data processing. In addition to using standard ArcGIS tools, we developed a set of custom ModelBuilder tools and Python script tools to carry out the necessary procedures. Input datasets are listed in Table 1, and created datasets are listed in Table 2. To avoid boundary effects when producing travel time rasters, a 50-mile buffer was applied to the state border of Virginia to set the processing extent. For this reason, data from states bordering Virginia had to be included.

As needed, all input datasets were subset to the relevant study area, and reprojected to the Albers Equal Area coordinate system to match the NLCD data prior to processing. Where applicable, an NLCD raster was used as a snap raster to set cell size and alignment for all raster processing and vector-to-raster transformations. Unless otherwise stated, a 30-m cell size was used. Once all processing was complete, deliverable products were reprojected to the Virginia

Lambert coordinate system to match other state spatial data, and clipped to the Virginia state border.

Raw Vulnerability Score

In this model, vulnerability to development is assumed to be a function of travel times to three development attractors: urban areas, metropolitan areas (a subset of urban areas), and hotspots of impervious growth. To create the travel time rasters, a travel time cost surface and rasters representing the targets of interest were needed. These are described in the next subsections, followed by an explanation of how travel times were transformed and rescaled to derive the Raw Vulnerability Score.

Development Attractors

We created three rasters representing locations attractive to development. These are the Urban Areas, Metro Areas, and Impervious Growth Hotspots rasters (Table 2). Each of these has cell values coded 1 for the target of interest, and no data in all other cells.

The Urban and Metro rasters were derived from the U.S. Urban Areas polygon shapefile (Table 1), provided by the U.S. Census Bureau. The shapefile represents areas of relatively high population density and urban land use. Two polygons types are identified: "Urban Clusters" representing smaller towns such as Culpeper, VA, and "Urbanized Areas" representing larger metropolitan areas such as Richmond, VA and its surrounding cities (Urban Area Criteria for the 2010 Census). The Urban Areas raster was created by converting all input polygons to raster cells. The Metro Areas raster was created by converting only the subset of polygons identified as "Urbanized Areas".

The Impervious Growth Hotspots raster was derived from the 2006 and 2011 NLCD Percent Impervious Cover datasets (Table 1; Figure 3). First, the 2006 raster was subtracted from the 2011 raster to produce a difference raster. The difference raster was smoothed with a low-pass filter. Any raster cells in which the smoothed difference value was at least 20% were identified as potential hotspots. Potential hotspot cells were grouped into contiguous regions, and any regions less than 2 hectares in size were eliminated from the final output.

Travel Time Cost Surface

To determine the travel time between any raster cell and a target of interest, a travel time cost surface is required. A travel time cost surface is a raster representing the amount of time it takes to traverse a unit distance through each cell. The time required to travel a unit distance is determined by road speed. Thus, a necessary first step in producing the cost surface was the collection and processing of roads data. Two sets of roads data from 2015 were used (Table 1). For roads within the state of Virginia, we used the Virginia Roads Centerlines (RCL) data provided by the Virginia Geographic Information Network (VGIN). For the roads in the 50-mile buffer area around Virginia, we used TIGER roads datasets provided by the U.S. Census Bureau.

The Virginia RCL data include a *Speed* attribute, indicating the posted travel speed limit in miles per hour. For most records, we assumed the speed value to be correct. However, we flagged records where the value was either 0 (zero) or not divisible by 5, since we considered these to be suspect values. For the flagged records, we updated the speed value as indicated in Table 3. The lowest allowable speed for walkways and other non-roads included in the data was set to 3 mph, on the assumption that this is a reasonable walking pace. We added a new attribute field, *Travel Time*, which was derived from *Speed* using Equation 1. Based on this equation, travel time is the amount of time, in minutes, needed to travel a distance of 1 meter (Table 4).

Equation 1

$$\boldsymbol{Travel\,Time}\ (\boldsymbol{min/m}) = \frac{\mathbf{0.037}}{\boldsymbol{Speed\ Limit}\ (\boldsymbol{miles/hr})}$$

The TIGER roads data are delivered by county, so the required datasets were downloaded in bulk and then merged to produce a seamless dataset for the boundary area. These data did not include a *Speed* attribute, so we added a new *Speed* attribute field and assigned values based on Table 3. We also added the field *Travel Time* and calculated it as with the Virginia RCL data. Finally, the TIGER data were merged with the Virginia RCL data to produce a Regional Roads dataset covering the state and border area (Table 2). A *Unique ID* field was populated with unique road segment identifiers from the original datasets.

Once the Regional Roads dataset had been produced, the road features were converted to two rasters (Table 2). The Road Travel Time raster was populated with continuous values from the *Travel Time* field, and the Road Zones raster was populated with integer values representing zones based on the *Unique ID* field. We set an output cell size of 5-m cell size to ensure more faithful representation of lines in the output rasters. The 2011 NLCD Percent Impervious Cover raster was also resampled from 30-m to 5-m cell size.

The Resampled Impervious Cover, Road Zones, and Road Travel Time rasters were used to create the Travel Time Cost Surface (Figure 2). First, a zonal statistics operation was performed, with the Road Zones raster defining the zones, and the resampled Impervious Cover raster defining the values to assign to each zone. This step identified the maximum imperviousness value within each road segment zone, and assigned that value to all cells within that zone.

All cells where the zonal maximum imperviousness was greater than 0 (and therefore at least partially developed) were assigned to the values of the Road Travel Time raster. Cells in zones with no imperviousness (i.e., zonal maximum = 0) were assigned the value 0.01233, which is the time, in minutes, needed to traverse 1 meter when travelling at 3 mph (walking speed; Table 4). This effectively backdated the Road Travel Time raster to conditions circa 2011, matching the NLCD data (Figure 4).

Next, the backdated raster was aggregated from 5-m cells back up to 30-m cells. The minimum value of each block of input cells was used to determine the aggregated output cell values. This means that faster roads (shorter travel times) took precedence over slower roads in the final output. For cells without any roads, the value was set to 0.01233, so that no hard barriers were imposed by null values in the final Travel Time Cost Surface raster.

Travel Times and the Raw Vulnerability Score

The ArcGIS Cost Distance tool can be used to calculate the least accumulative cost over a cost surface, from each raster cell to the nearest target of interest. For this model, we used the Travel Time Cost Surface raster as the cost surface for this tool, so that "cost" represents travel time in minutes. The Urban Areas, Metro Areas, and Impervious Growth Hotspots rasters were used in turn as the targets to create corresponding Travel Time rasters (Table 2).

For each of the Travel Time rasters, a logarithmic transformation was applied according to Equation 2, yielding values theoretically ranging from 0 to $-\infty$. The transformed values were truncated so that the minimum value was set to -5 (i.e., the value derived from approximately 2.5 hours travel time). Using Equation 3, the truncated, transformed values were rescaled to range from 0 (longest travel time, least vulnerable) to 100 (shortest travel time, most vulnerable;). This yielded the Urban, Metro, and Hotspot Score rasters, which were then averaged (Equation

4) to obtain the Raw Vulnerability Score raster. The relationship between selected travel times and vulnerability scores is shown in Table 5.

Equation 2

$$\boldsymbol{Transformed\ Travel\ Time = -ln(Travel\ Time + 1)}$$

Equation 3

$$\boldsymbol{Score = 100 \times (Truncated\ Transform + 5)/5}$$

Equation 4

$$\boldsymbol{Raw\ Vulnerability\ Score = \frac{1}{3} \times (Urban\ Score + Metro\ Score + Hotspot\ Score)}$$

Protection Multiplier

Because the Raw Vulnerability Score raster does not account for conservation status, we needed a means of reducing vulnerability values in the final model as a function of the level of land protection. Lands that are essentially off-limits to development are assigned the value 0, because this nullifies vulnerability values by multiplication. Unprotected lands are assigned the value of 1, since this leaves vulnerability values unchanged by multiplication. Lands with intermediate levels of protection should accordingly fall somewhere along the continuum between 0 and 1.

The Virginia Conservation Lands Database is developed and maintained by DCR-DNH, and was used as the primary data source for the Protection Multiplier (Table 1). To match the NLCD data, we used a dataset that was backdated to reflect conditions in 2011 (D. Boyd, pers. comm.). The polygon dataset contains the boundaries for lands of conservation and recreational interest in Virginia, such as parks, national forests, natural area preserves, and conservation easements. It also includes two important quantitative attributes: biological management intent (BMI; Table 6) and legal protection status (LPS; Table 7).

The Conservation Lands dataset was used to create two rasters: one with the BMI status as the cell values and one with the LPS value as the cell values (Table 2). BMI values range from 1 to 5 in the original feature class, with "U" signifying "unknown" (Table 6). LPS values range from 1 to 4 in the original feature class, again with "U" signifying "unknown" (Table 7). Prior to rasterization, “U” values were set to the lowest protection rank, which is the highest numeric value: 5 for BMI and 4 for LPS. In addition, we added priority fields for BMI and LPS, with values in the opposite rank order to BMI and LPS, respectively. In cases of polygon overlap, the priority fields were employed in the rasterization process to ensure that the higher-ranked (lower integer value) BMI or LPS value prevailed. Raster cells not covered by a conservation lands polygon were set to the value 6 for the BMI raster and to the value 5 for the LPS raster.

Values in the LPS and BMI rasters were rescaled, then averaged together to derive the values for the final Protection Multiplier raster (Equation 5). This raster has values ranging from 0 (complete protection; undevelopable) to 1 (unprotected). The 2011 NLCD Land Cover was used to set open water bodies to the value 0, under the assumption that these would not be developed.

Equation 5

$$\boldsymbol{Protection\ Multiplier} = \frac{\mathbf{1}}{\mathbf{2}} \times \left(\frac{\boldsymbol{BMI} - \mathbf{1}}{\mathbf{5}} + \frac{\boldsymbol{LPS} - \mathbf{1}}{\mathbf{4}}\right)$$

Final Development Vulnerability Model

In the final model, the 2011 NLCD Imperviousness Raster was used to set all cells that are already developed (imperviousness > 0) to 101. For undeveloped cells, The Raw Vulnerability Score and Protection Multiplier were combined according to Equation 6 to generate Development Vulnerability values ranging from 0 (undevelopable) to 100 (highest risk of development).

Equation 6

$$\boldsymbol{Development\ Vulnerability} = \boldsymbol{Raw\ Vulnerability\ Score} \times \boldsymbol{Protection\ Multiplier}$$

After all processing was complete, the final Development Vulnerability raster was converted to an integer raster, projected to the Virginia Lambert coordinate system using nearest-neighbor resampling, and clipped to the state border. A field was appended to the raster attribute table to contain class values representing ranges of vulnerability scores, as shown in Maps 1-22.

Results

The final output of the modeling process described above is a raster dataset covering the state of Virginia, with cell values representing the vulnerability score. Model values range from 0 (least vulnerable) to 100 (most vulnerable), with cells in which there was already development coded as 101. At the planning district level, mean vulnerability values ranged from 14.8 for the

Accomack – Northampton planning district to 50.1 for the Northern Virginia planning district (Table 8). The spatial distribution of vulnerability values across the state is represented in Map 1, with values shown by planning district in Maps 2-22.

Discussion

Model comparison with previous edition

The current and previous (VADNH 2008) editions of the Virginia Vulnerability Model are both based on travel times to targets deemed attractive to development, similar in concept to a model developed by Westervelt et al. (2011). However, data inputs and methodology differ between models. Thus, it is important to understand that the numeric values of outputs are not directly comparable between models, although they are roughly correlated.

In the previous edition (VADNH 2008), three sub-models were developed for urban, suburban, and rural zones on the basis of the rural-urban commuting area (RUCA) codes; these were then averaged to produce the final composite model. In the current edition, there are no equivalent sub-models. The previous model output, represented in vector (polygon) format, consisted of categorical ranks, with vulnerability represented as a discrete value ranging from 1 (low threat of development) to 8 (hotspot or high threat). The sub-model values ranged from 1 to 5. The current model output is in raster format, with continuous values ranging from 0 (least vulnerable) to 100 (most vulnerable). Rough equivalents of vulnerability values based on travel times are presented in Table 5. The previous edition did not explicitly code areas in which development had already occurred; many of the "high-threat" areas were actually already developed. The current model codes developed areas as 101 to distinguish them from high-risk areas.

Targets in the previous model include growth hotspots based on change in imperviousness between 1990 and 2000, population growth, and rate of residential land conversion. Hotspots were identified separately for urban, suburban, and rural zones. In contrast, targets in the current version are impervious growth hotspots based on changes between 2006 and 2011, as well as urban areas and metropolitan areas as delineated by the U.S. Census.

Travel times to targets in both models were based on speeds along the road network. The previous edition used roads data from 2000 provided by the U.S. Census. The current version uses 2015 data, backdated to 2011 to match land cover and imperviousness data. Road centerlines provided by VGIN were used within the Virginia border, and roads data from the U.S Census were used to cover the area in a 50- mile buffer around the state to avoid boundary effects in the travel time analysis.

The Virginia Conservation Lands Database (backdated to 2011) was used in the current edition of the model to create a protection multiplier, accounting for both biological management intent and legal protection status. The multiplier has the effect of reducing the final vulnerability score where applicable, to reflect the mitigating impact of conservation on development risk. This mitigating factor was not considered in the previous model.

Model limitations

This model, like any other model, is limited by the data inputs as well as by the assumptions made and processes used in combining these inputs. For example, the input land cover data has a 30-m pixel size, and the raster output was generated to match. This may be unsatisfactory for detailed planning at local scales. Each user must decide whether this model meets their particular purpose. The model has not been formally validated at this time.

We realized after the model was completed that the travel time analyses did not account for the fact that travel cannot proceed directly onto and off of limited access highways except at specific interchanges (Westervelt et al. 2011). As a result, the threat of development is exaggerated adjacent to highways where direct access is not actually possible. This shortcoming will be addressed in a future edition.

The maps presented in this report, and the underlying raster model used to produce them, should be considered as a snapshot in time, reflecting ground conditions in the year 2011 and current assumptions about vulnerability pressures. Ground conditions as well as development pressures are constantly changing over time, so frequent updates to this model are recommended. We expect that the vulnerability assumptions and modeling processes will evolve as well. We encourage users to send us their constructive feedback so that we can take that into consideration in future editions of the model.

Model applications

The Virginia Development Vulnerability Model is intended as a guide to the relative risk of development across the state. We expect the model to be helpful to state and local governments, planning districts, environmental consultants, land trusts, and others involved in land use planning and conservation prioritization. In many, if not most cases, this model should be used in conjunction with other pertinent information and data models, including other ConservationVision models. The model can also serve as an input for simulating future land cover change and its consequences under different planning scenarios.

We have made our modeling approach as transparent as possible, both to allow for quick updates in the future, and to allow users to produce customized versions of the model as desired. Most of the GIS processes used to produce the Development Vulnerability Model are available on request in the form of a customized ArcGIS toolbox containing a suite of tools organized logically into toolsets. Users may employ these tools to produce a customized model for their particular area of interest. Examples of customizations that could be made include:

- Using higher-resolution imperviousness data as an input
- Using alternate equations to combine input datasets into indicators of vulnerability and conservation status
- Using data from different years
- Using a different set of development attractors for the travel time analyses
- Using additional transportation systems (e.g. rail) to develop the travel time cost surface

Future model improvements

The next update of this model will incorporate the same components as the current edition: travel times to development attractors, along with conservation status. However, we intend to also include a number of additional geophysical and socio-political input datasets such as slope of the land, type of land cover, employment opportunities, public road access, school district quality, and proximity to attractive bodies of water. Moreover, instead of combining the input data according to the equations used here, we will use the inputs as explanatory variables in a statistical and/or machine-learning analysis to more rigorously explore the relative importance of different development pressures. We will be guided by similar work that has been completed by others to produce development probability surfaces used in urban growth simulations (e.g., Westervelt et al. 2011; Meentemeyer 2013; Terrando et al. 2014; P. Claggett, pers. comm.)

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Tables

Table 1: Data sources used to produce the Virginia Vulnerability Model

Dataset	Data Use[1]	Data Type	Data Source	Data Files
NLCD Percent Impervious Cover (2006, 2011)	UAS, MAS, IHS, TTCS, PM	Raster	Multi-Resolution Land Characteristics (MRLC) Consortium. Retrieved April 2015 from www.mrlc.gov/index.php.	nlcd_2011_impervious_2011_edition_2014_10_10.img; nlcd_2006_impervious_2011_edition_2014_10_10.img
NLCD Land Cover (2011)	PM	Raster	Multi-Resolution Land Characteristics (MRLC) Consortium. Retrieved April 2015 from www.mrlc.gov/index.php.	nlcd_2011_landcover_2011_edition_2014_10_10.img;
Virginia Conservation Lands Database (2011)	PM	Polygon feature class	Virginia Dept. of Conservation and Recreation, Division of Natural Heritage. Obtained in-house.	Conslands_2011.shp
U.S. Urban Areas (2010)	UAS, MAS	Polygon shapefile	U.S. Census Bureau's Master Address File / Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) Database (MTDB). Retrieved September 2015 from http://www2.census.gov/geo/tiger/TIGER2010/UA/2010	tl_2010_us_uac10.shp
Virginia Road Centerlines (RCL; 2015 quarter 2)	UAS, MAS, IHS, TTCS	Geodatabase line feature class	Virginia Geographic Information Network: VA GIS Clearinghouse. Retrieved August 2014 from tinyurl.com/vgin-rcl	VBMP_RCL_FGDB.gdb\RCL (2015Q2 version)
TIGER Roads (2015)	UAS, MAS, IHS, TTCS	Line shapefile	United States Census Bureau: Roads data. Retrieved August 2015 from ftp2.census.gov/geo/tiger/TIGER2015/ROADS	tl_2015_nnnnn_roads.shp, where '*nnnnn*' is a 5-digit code representing the state and county.

[1] Used to produce Urban Score (UAS), Metropolitan Area Score (MAS), Impervious Surface Hotspot Score (IHS), Backdated Travel Time Cost Surface (TTCS), and/or the Protection Multiplier (PM)

Table 2: Datasets created in developing the Vulnerability Model

Dataset Title	Dataset Description	Dataset Type	Data Filename	Data Inputs Used
Urban Areas	This raster dataset identifies the locations of urban areas as delineated by the 2010 U.S. Census.	Raster	vm_Products.gdb\ ysn_tlUrban_2011	tl_2010_us_uac10.shp
Metro Areas	Raster dataset identifiying the locations of metropolitan areas, defined as "Urbanized Areas" in the 2010 U.S. Census. Metropolitan areas are a subset of the more general "Urban Areas".	Raster	vm_Products.gdb\ ysn_tlMetro_2011	tl_2010_us_uac10.shp
Impervious Growth Hotspots	Raster dataset identifying the locations of hotspots of growth in impervious surfaces between the years 2006 and 2011.	Raster	vm_Products.gdb\ ysn_ImpHot_2011	nlcd_2006_imperviousness_2011_edition_2014_10_10.img; nlcd_2011_imperviousness_2011_edition_2014_10_10.img
Regional Roads	Line feature class representing roads within VA and bordering states within a 50-mile buffer around the state border.	Vector	vm_Products.gdb\Roads2015	VBMP_RCL_FGDB.gdb\RCL (2015Q2 version); tl_2015_nnnnn_roads.shp
Road Travel Time	Rasterized road centerlines dataset with values representing road segments' travel times.	Raster	vm_Archive.gdb\ rd_RoadTrvTm_2015	vm_Products.gdb\Roads2015
Road Zones	Rasterized road centerlines dataset with values representing road segments' unique IDs	Raster	vm_Archive.gdb\ rd_RoadZones_2015	vm_Products.gdb\Roads2015
Resampled Impervious Cover	NLCD Imperviousness Raster resampled to 5 meter cells	Raster	nlcdVA_albers.gdb\ nlcd2011_imp5	nlcd_2011_impervious_2011_edition_2014_10_10.img
Travel Time Cost Surface	Raster dataset representing travel time (minutes per meter) required to traverse a cell based on the status of roads in the year 2011.	Raster	vm_Products.gdb\ cs_TrvTm_2011	nlcdVA_albers.gdb\nlcd2011_imp5; vm_Archive.gdb\rd_RoadTrvTm_2015; vm_Archive.gdb\rd_RoadZones_2015

Dataset Title	Dataset Description	Dataset Type	Data Filename	Data Inputs Used
Travel Time to Urban	Raster dataset representing the travel time, in minutes, to urban areas, as defined by the 2010 U.S. Census and based on roads ca. 2011.	Raster	vm_PredVars2011.gdb\tt_Urban_2011	vm_Products.gdb\cs_TrvTm_2011; vm_Products.gdb\ysn_tlUrban_2010
Travel Time to Metro	Raster dataset representing the travel time, in minutes, to metropolitan areas, defined as “Urbanized Areas” in the 2010 U.S. Census and based on roads ca. 2011.	Raster	vm_PredVars2011.gdb\tt_Metro_2011	vm_Products.gdb\cs_TrvTm_2011; vm_Products.gdb\ysn_tlMetro_2010
Travel Time to Hotspots	Raster dataset representing travel times, in minutes, to hotspots of impervious growth, defined by differences in impervious cover between 2006 and 2011 and based on roads ca. 2011.	Raster	vm_PredVars2011.gdb\tt_ImpHot_2011	vm_Products.gdb\cs_TrvTm_2011; vm_Products.gdb\ysn_ImpHot_2011
Hotspot Score	Raster dataset derived from the Travel Time to Hotspots raster that rescales the travel time to a vulnerability model score between 0 – 100.	Raster	VulnMod_Dec2015_Albers.gdb\Score_Hotspot	vm_PredVars2011.gdb\ tt_ImpHot_2011
Urban Score	Raster dataset derived from the Travel Time to Urban raster that rescales the travel time to a vulnerability model score between 0 – 100.	Raster	VulnMod_Dec2015_Albers.gdb\Score_Urban	vm_PredVars2011.gdb\ tt_Urban_2011
Metro Score	Raster dataset derived from the Travel Time to Metro raster that rescales the travel time to a vulnerability model score between 0 – 100.	Raster	VulnMod_Dec2015_Albers.gdb\Score_Metro	vm_PredVars2011.gdb\ tt_Metro_2011
Raw Vulnerability Score	Raster dataset with scores, from 0 to 100, representing vulnerability to development based on component rasters: a Hotspot Score, an Urban Score, and a Metro Score.	Raster	VulnMod_Dec2015_Albers.gdb\Score_RawVuln	VulnMod_Dec2015_Albers.gdb\Score_Hotspot; VulnMod_Dec2015_Albers.gdb\Score_Urban; VulnMod_Dec2015_Albers.gdb\Score_Metro

Dataset Title	Dataset Description	Dataset Type	Data Filename	Data Inputs Used
Biological Management Intent (BMI)	Raster dataset derived from the Biological Management Intent field from the VA Cons Lands Database. It has values ranging from 1 to 6.	Raster	vm_PredVars2011.gdb\ rd_ConsBMI_2011	conslands_2011.shp
Legal Protection Status (LPS)	Raster dataset derived from the Legal Protection Status field from the VA Cons Lands Database. It has values ranging from 1 to 5.	Raster	vm_PredVars2011.gdb\ rd_ConsLPS_2011	conslands_Raster2011.shp
Protection Multiplier	Raster dataset representing the relative level of land protection in Virginia, ca. 2011. Raster values range from 0 (highest level of protection) to 1 (no protection).	Raster	VulnMod_Dec2015_Albers. gdb\Mult_Protection	vm_PredVars2011.gdb\rd_ConsBMI_2011; vm_PredVars2011.gdb\rd_ConsLPS_2011; nlcdVA_albers.gdb\nlcd2011_lc
Development Vulnerability Model	Raster dataset representing vulnerability to development, based on travel times to three development "attractors", mitigated by land conservation status, and accounting for existing development.	Raster	VulnMod_Dec2015_Albers. gdb\VulnerabilityModel	VulnMod_Dec2015_Albers.gdb\Score_RawVuln ; VulnMod_Dec2015_Albers.gdb\mult_Protection; nlcdVA_albers.gdb\nlcd2011_imp

Table 3: Road speed assignments[1]

MTFCC Code	MTFCC Code Definition	Road Speed (miles/hour)
S1100	Primary Road	65 55[2]
S1200	Secondary Road	45
S1300	Collector/Arterial Road	45
S1640	Service Drive usually along a limited access highway	45
S1630	Ramp	30
C3061	Cul-de-sac	25
C3062	Traffic Circle	25
S1400	Local Neighborhood Road, Rural Road, City Street	25
S1740	Private Road for service vehicles (logging, oil fields, ranches, etc.)	25
S1500	Vehicular Trail (4WD)	15
S1730	Alley	15
S1780	Parking Lot Road	15
S1820	Bike Path or Trail	10

[1] Speed assignments were primarily used for out-of-state TIGER roads. Virginia roads data included speed, which was only overridden with tabulated values above in specific circumstances as described in the Methods section.
[2] All Virginia primary roads without valid speed values (rare) were assigned a speed of 55. TIGER roads were assigned 65 if designated as an interstate, and 55 otherwise.

Table 4: Speed and travel time equivalents

Speed (mi/hr)	Travel Time (sf·min/m)[1]
3[2]	1233
15	247
25	148
30	123
35	106
40	93
45	82
50	74
55	67
60	62
65	57
70	53

[1] Travel time represents the amount of time (in minutes) required to traverse a distance of 1 meter; values here are multiplied by a scale factor (sf) of 100,000 for readability.
[2] For roadless areas, we assumed travel could proceed at a walking speed of 3 miles per hour.

Table 5: Relationship between travel time and vulnerability values[1]

Travel Time (min)	2015 Vulnerability Score[2]	2015 Vulnerability Class[3]	2008 Composite Model Rank	2008 Sub-Model Rank
0	100	5	8	5
1	86	5	8	4
5	64	4	8	4
10	52	3	8	4
15	45	3	7	4
20	39	2	7	3
30	31	2	6	3
40	26	2	5	2
50	21	2	4	2
60	18	1	3	2
70	15	1	2	1
80	12	1	2	1
90	10	1	2	1
100	8	1	1	1
120	4	1	1	1

[1] Ranks from the 2008 composite and sub-models are included for comparison with the current model, highlighting the fact that model rank/class values are not equivalent between years and should not be treated as such.
[2] Vulnerability values of 0 (undevelopable) or 101 (already developed) are not shown in this table but do exist in the raster dataset.
[3] Vulnerability classes 0 (undevelopable) or 6 (already developed) are not shown in this table but do exist in the raster dataset. There is no equivalent for these extremes in the 2008 datasets.

Table 6: Biological Management Intent (BMI) Codes

BMI Code	Code Explanation
1	Specifically managed for the protection of plant and animal communities
2	Managed for the conservation of plant and animal communities with limited impacts permitted
3	Managed for general natural resource conservation
4	General open space conservation
5	No designation or management for conservation of natural conditions
U	Unknown status

Table 7: Legal Protection Status (LPS) Codes

LPS Code	Code Explanation
1	Permanent Protection
2	Long Term Protection
3	Voluntary Protection
4	No Protection
U	Unknown

Table 8: Zonal statistics for the Virginia Development Vulnerability Model output values[1]

Geographic Area	Maximum	Mean	Std. Dev.
Accomack - Northampton	53.5	14.8	14.9
Central Shenandoah	100.0	24.5	22.8
Commonwealth Regional Council	75.6	30.0	8.8
Crater	100.0	35.8	14.2
Cumberland Plateau	62.8	25.9	10.4
George Washington	100.0	40.4	21.3
Hampton Roads	100.0	35.5	25.1
LENOWISCO	88.2	31.8	14.3
Middle Peninsula	99.7	30.5	16.0
Mount Rogers	100.0	31.0	17.6
New River Valley	100.0	35.7	19.1
Northern Neck	75.8	23.8	12.6
Northern Shenandoah Valley	100.0	36.5	20.8
Northern Virginia	100.0	50.1	29.1
Rappahannock - Rapidan	100.0	34.3	17.0
Region 2000	100.0	38.2	16.8
Richmond Regional	100.0	46.2	20.5
Roanoke Valley - Alleghany	100.0	25.2	22.5
Southside	72.4	30.1	10.3
Thomas Jefferson	100.0	33.9	15.6
West Piedmont	78.3	34.6	10.3

[1] Statistics were calculated by PDC zones, while ignoring the already developed (101) cells.

Figures

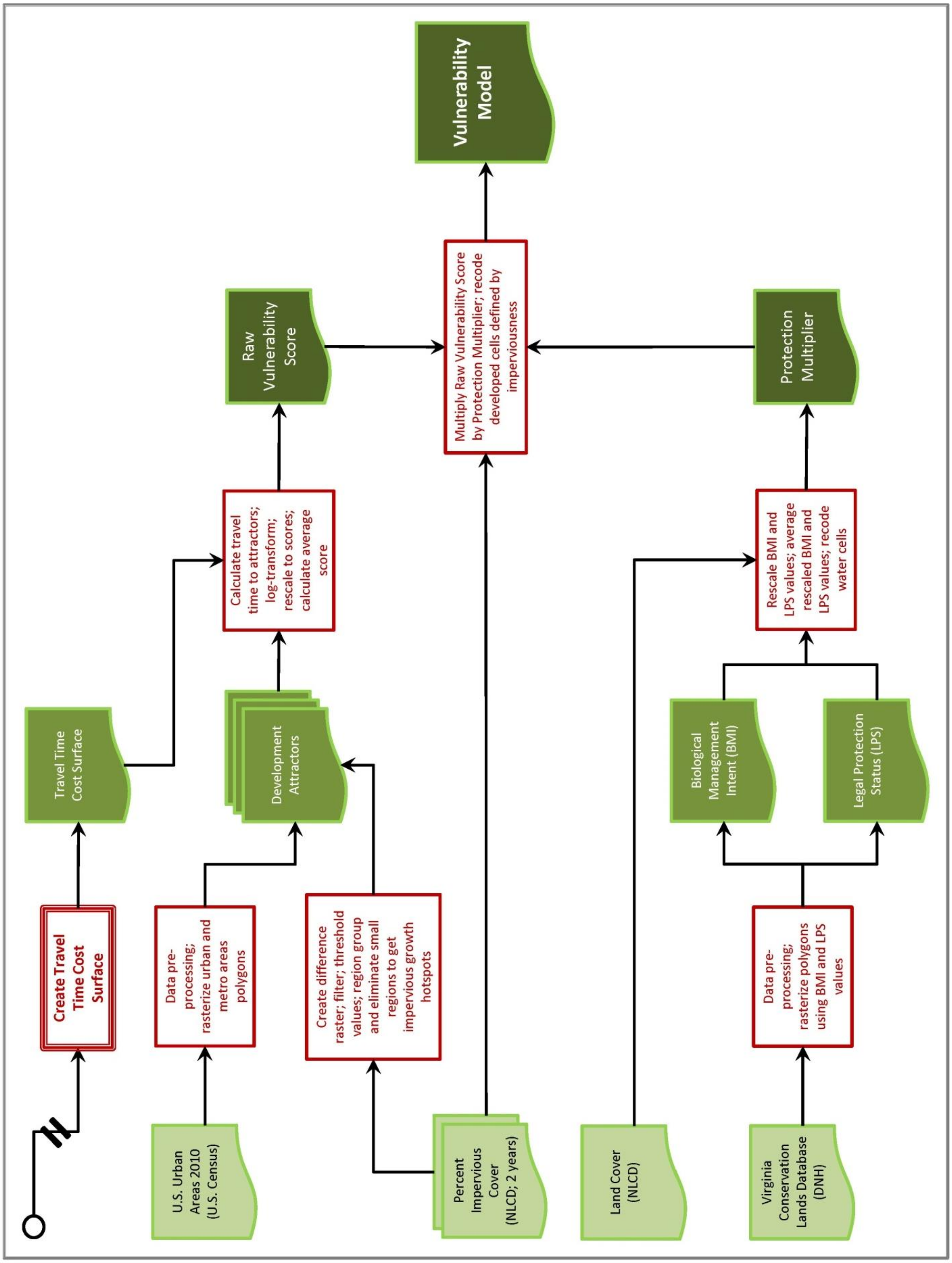


Figure 1: Flow diagram illustrating the sequence of geoprocessing steps leading to the Vulnerability Model. Input data sources are represented in the lightest shade of green, with the source indicated in parentheses. Intermediate products are shown in a medium shade of green, and final products are shown in the darkest shade of green. A stack is used to represent a set of similar data sources or products. The arrow starting from the circle in the top left corner connects this flow diagram to another sub-process used to create the Travel Time Cost Surface (Figure 2), which was run before the steps in this diagram. Refer to the Methods section for more details on geoprocessing.

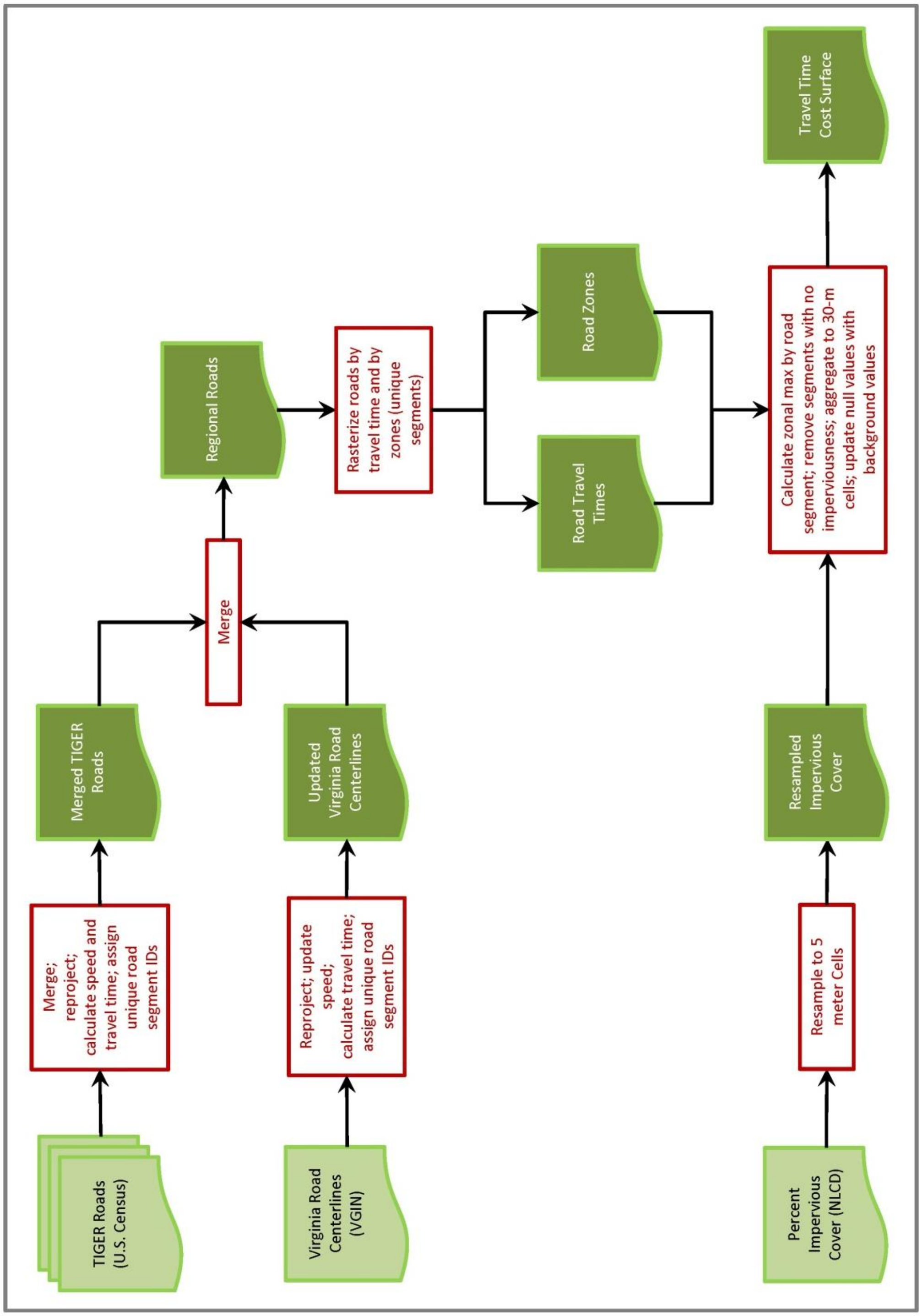


Figure 2: Flow diagram illustrating the sequence of geoprocessing steps leading to the Travel Time Cost Surface raster. Input data sources are represented in the lightest shade of green with the source indicated in parentheses, and intermediate products are shown in a darker shade of green. A stack is used to represent a set of similar data sources or products. Roads data from 2015 were used as the primary source, but the imperviousness raster was used to backdate the cost surface to conditions in 2011. The output Travel Time Cost Surface is an intermediate product, needed as an input to determine travel times to various development attractors, as shown in Figure 1.

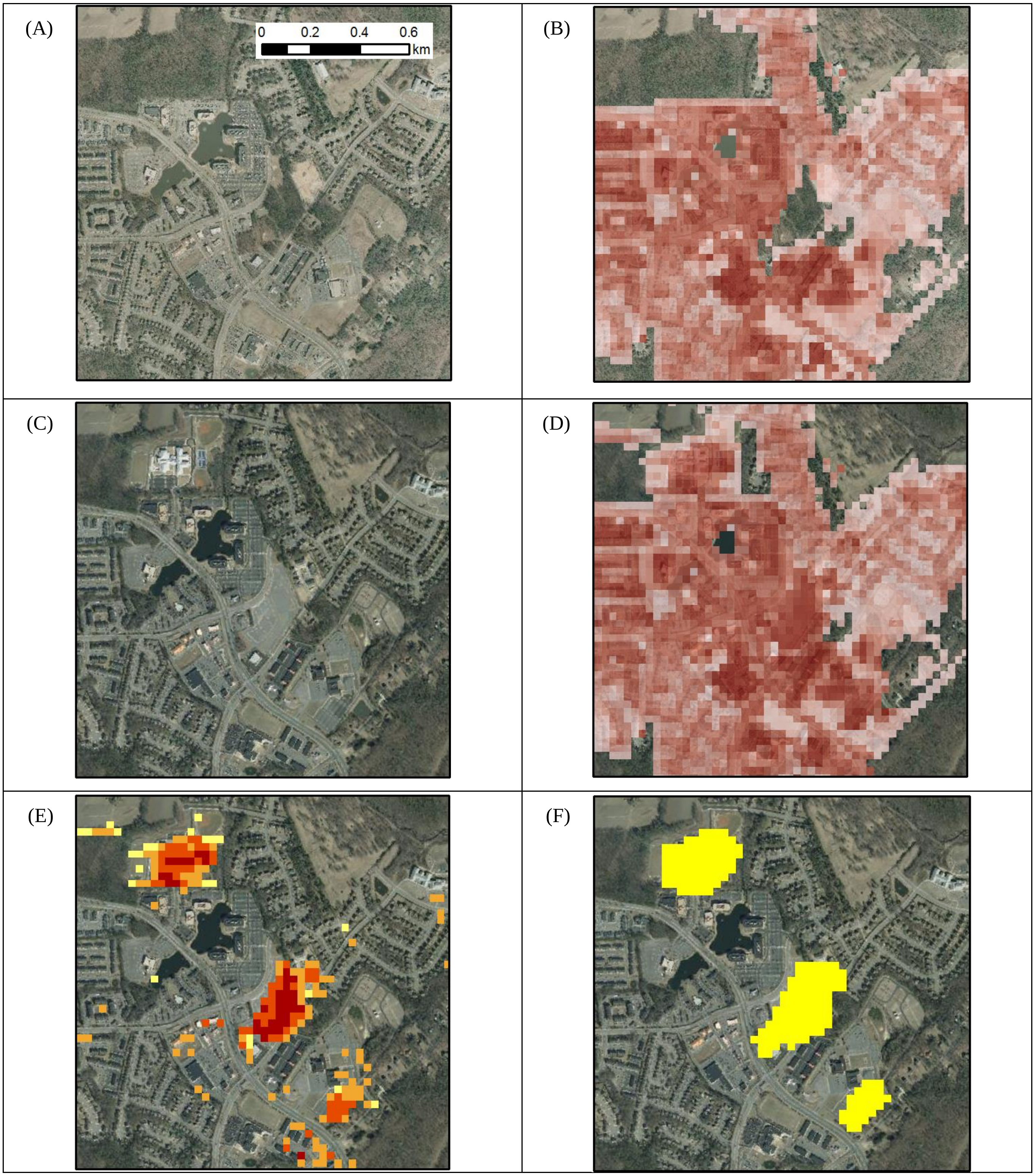


Figure 3: Identification of impervious growth hotspots.
Identification of impervious growth hotspots is based on differences in imperviousness between two years. (A) High-resolution aerial photography of a sample area in 2006. (B) Raster representing impervious cover of the same area in 2006. Darker shades of red represent higher percentage of imperviousness (development). (C) High-resolution aerial photography of the same area in 2011. (D) Raster representing impervious cover of the same area in 2011. (E) Difference raster representing the increase in imperviousness between 2006 and 2011, overlaid on 2011 imagery. Darkest shades correspond to areas with the greatest increase in the amount of imperviousness. Areas where impervious cover did not increase by at least 20% are not shown. (F) Final impervious growth hotspot regions, after filtering, removing cells with values under the 20% cutoff, region-grouping, and removing regions under 2 ha in size. Note that the speckling seen in frame (E) has been eliminated.

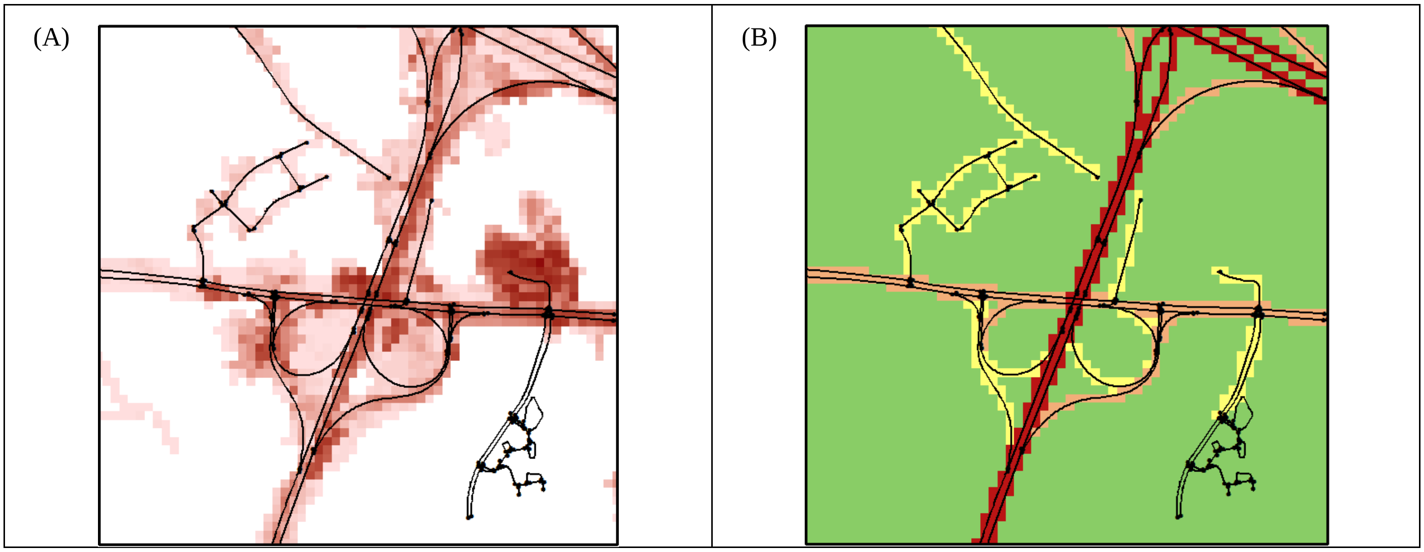
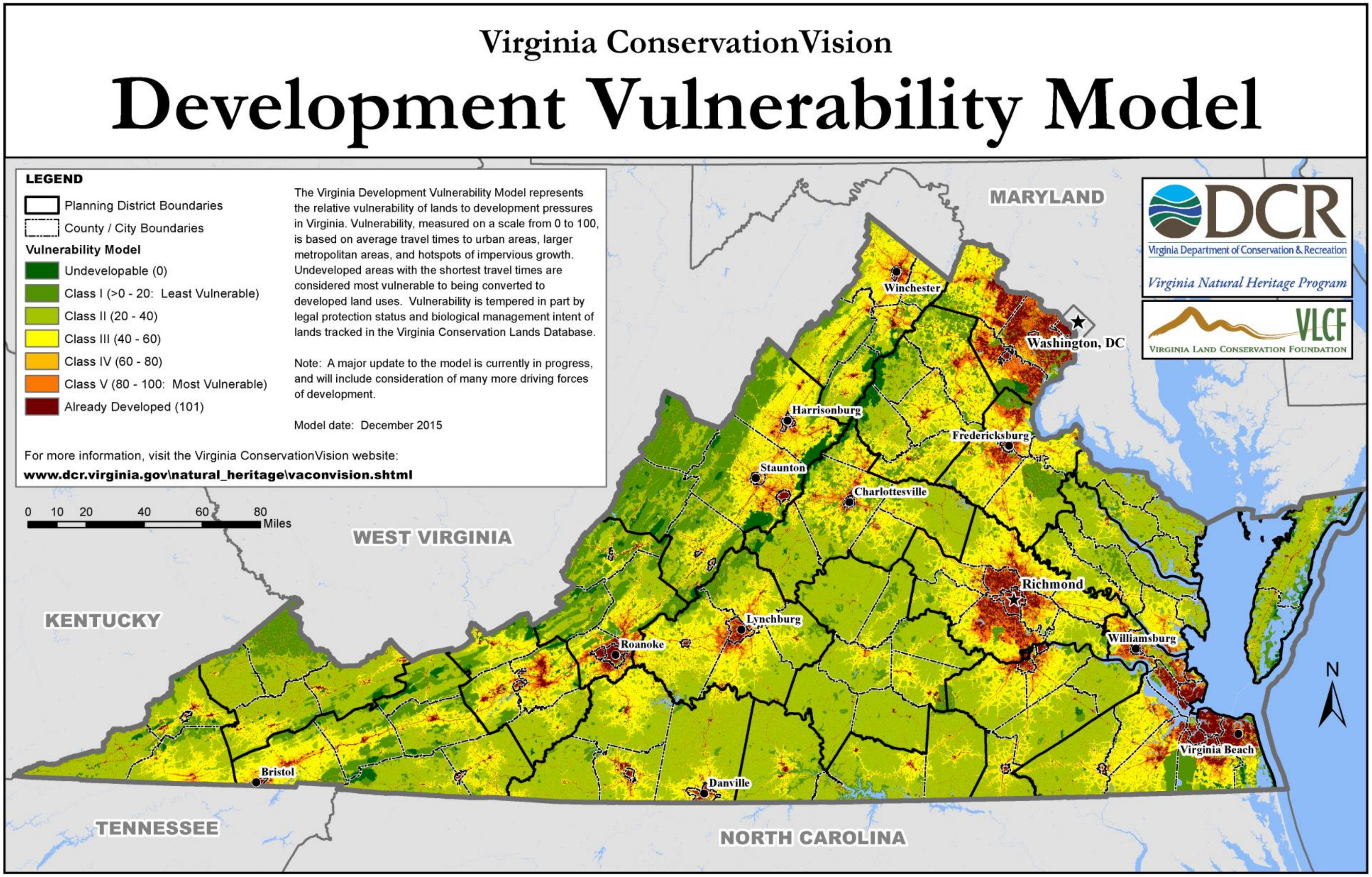


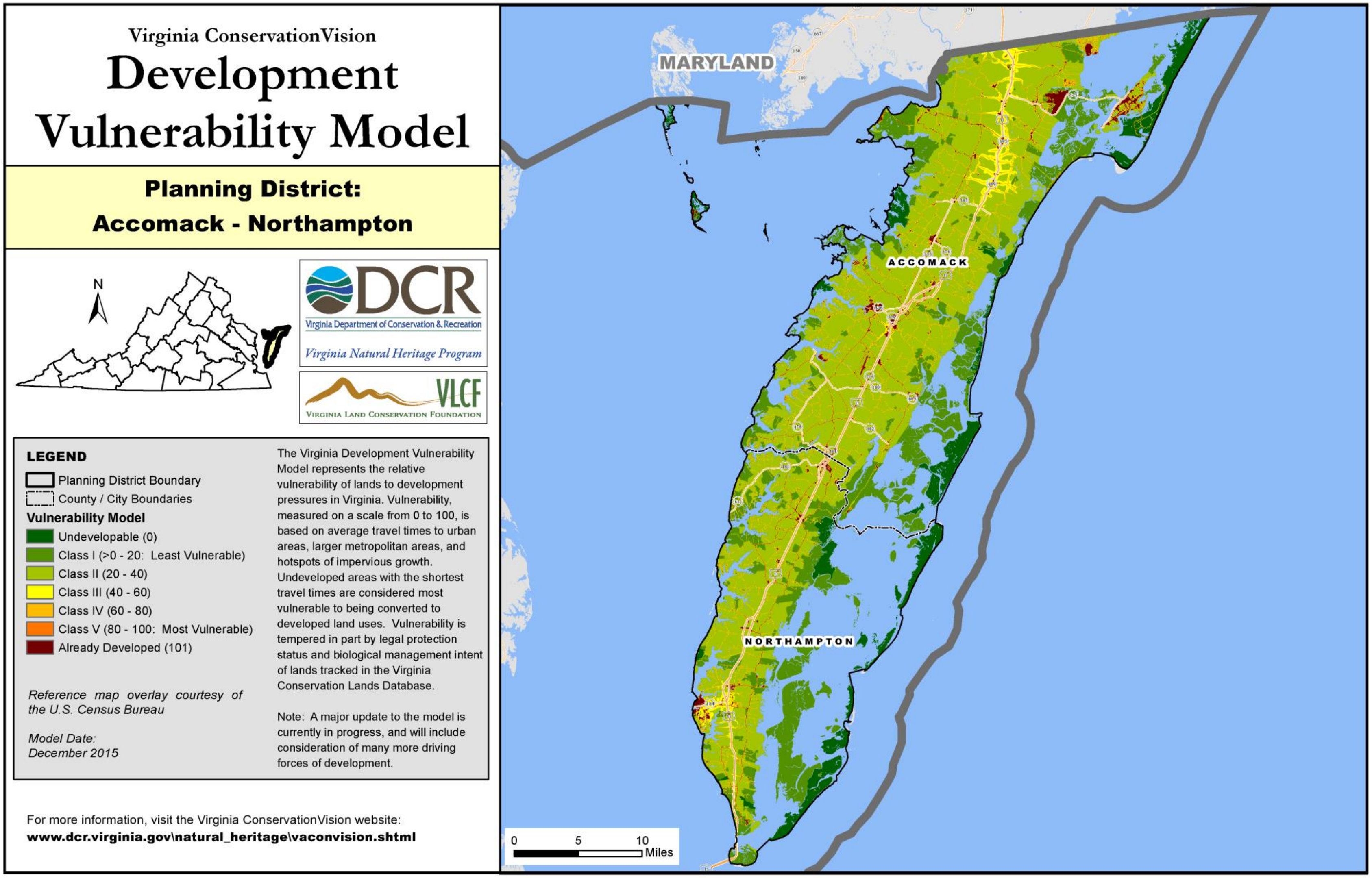
Figure 4: Development of the back-dated Travel Time Cost Surface.
The Travel Time Cost Surface raster represents the time, in minutes, required to traverse one meter. It is developed from vector data representing the roads network and raster data representing percent impervious cover. Refer to Table 4, which shows conversions from speed (mi/hr) to travel time in (min/m). (A) Impervious surface cover (2011 data; shown in shades of red) overlaid with the road network (2015 data; shown as black line segments). Darker shades of red represent higher percentage of imperviousness (development), and white corresponds to areas of no imperviousness (no development). (B) Travel Time Cost Surface raster (2011) overlaid with the road network (2015 data). Red represents roads with the highest travel speeds (interstates) and thus the lowest travel times in the travel time cost surface. Orange represents major roads with intermediate speeds, and yellow represents local roads and ramps with the lowest speeds. Green represents roadless areas in which a background walking speed of 3 mi/hr is assumed, and travel time values are the highest. Note how the road segments in the bottom right are not included as roads in the raster, because they were likely not yet present in 2011 based on the imperviousness data. Road segments not intersecting any imperviousness are eliminated in the back-dating process.

Maps

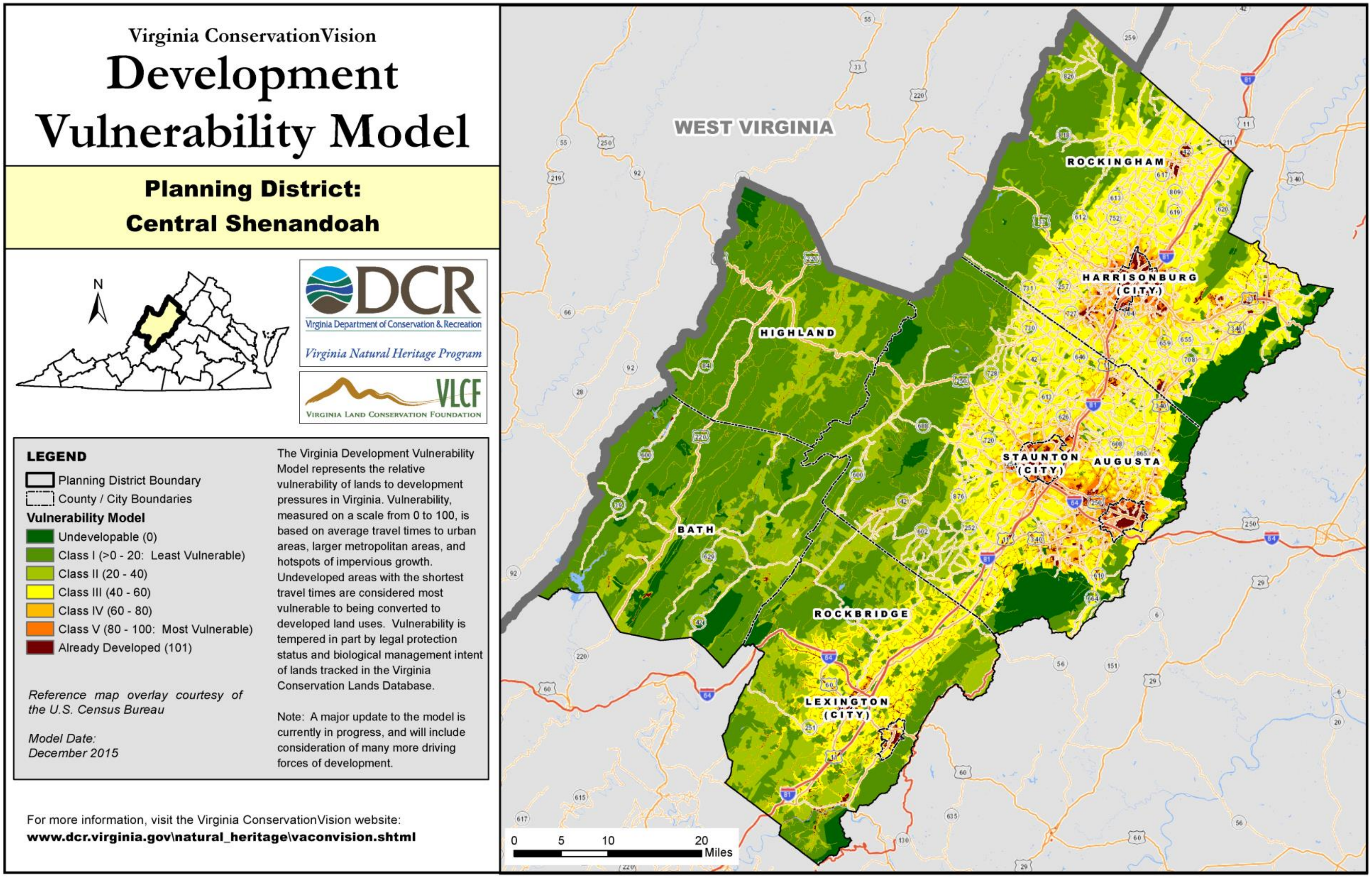
Map 1: Statewide Vulnerability Model



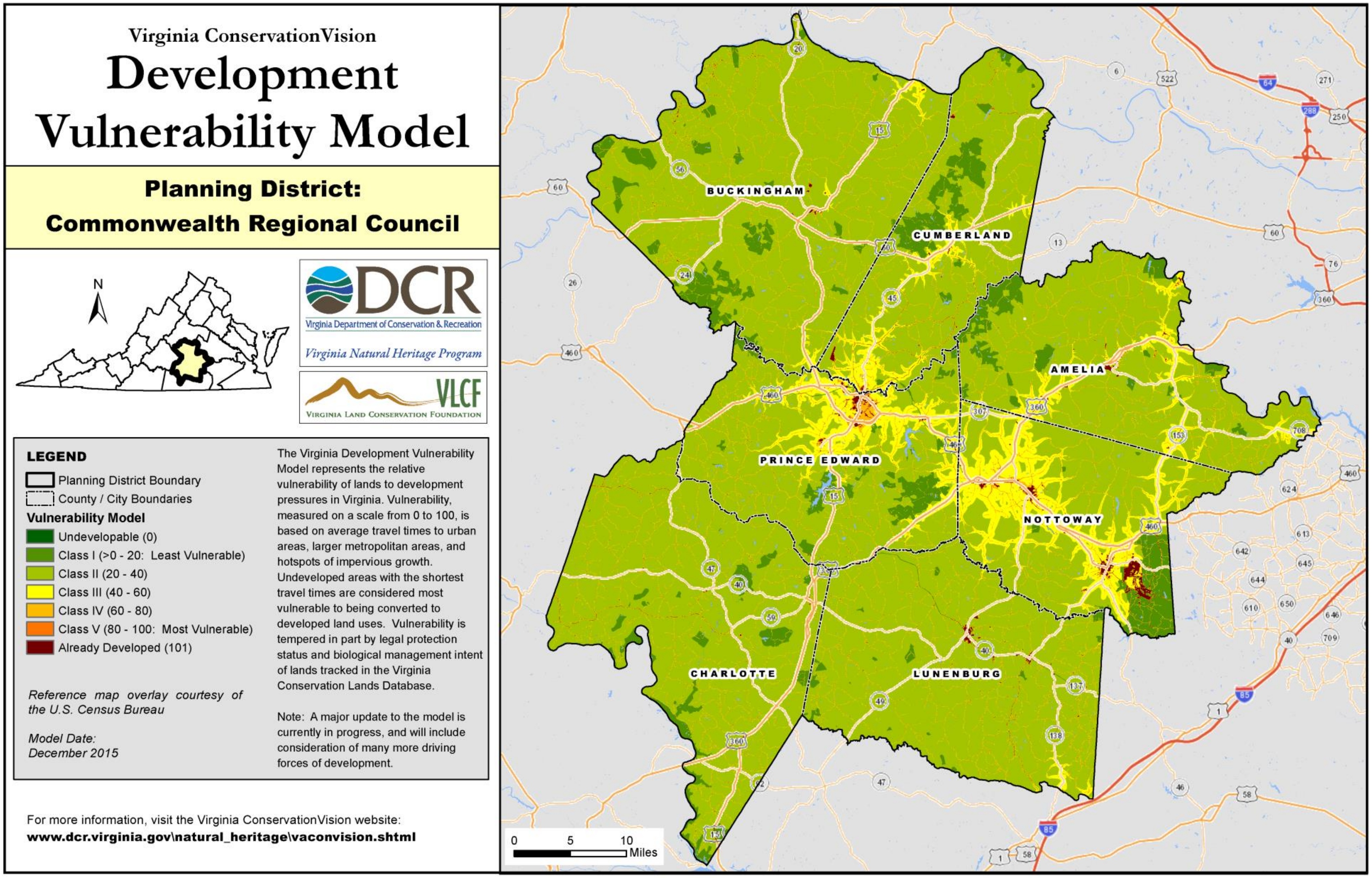
Map 2: Accomack-Northampton Planning District



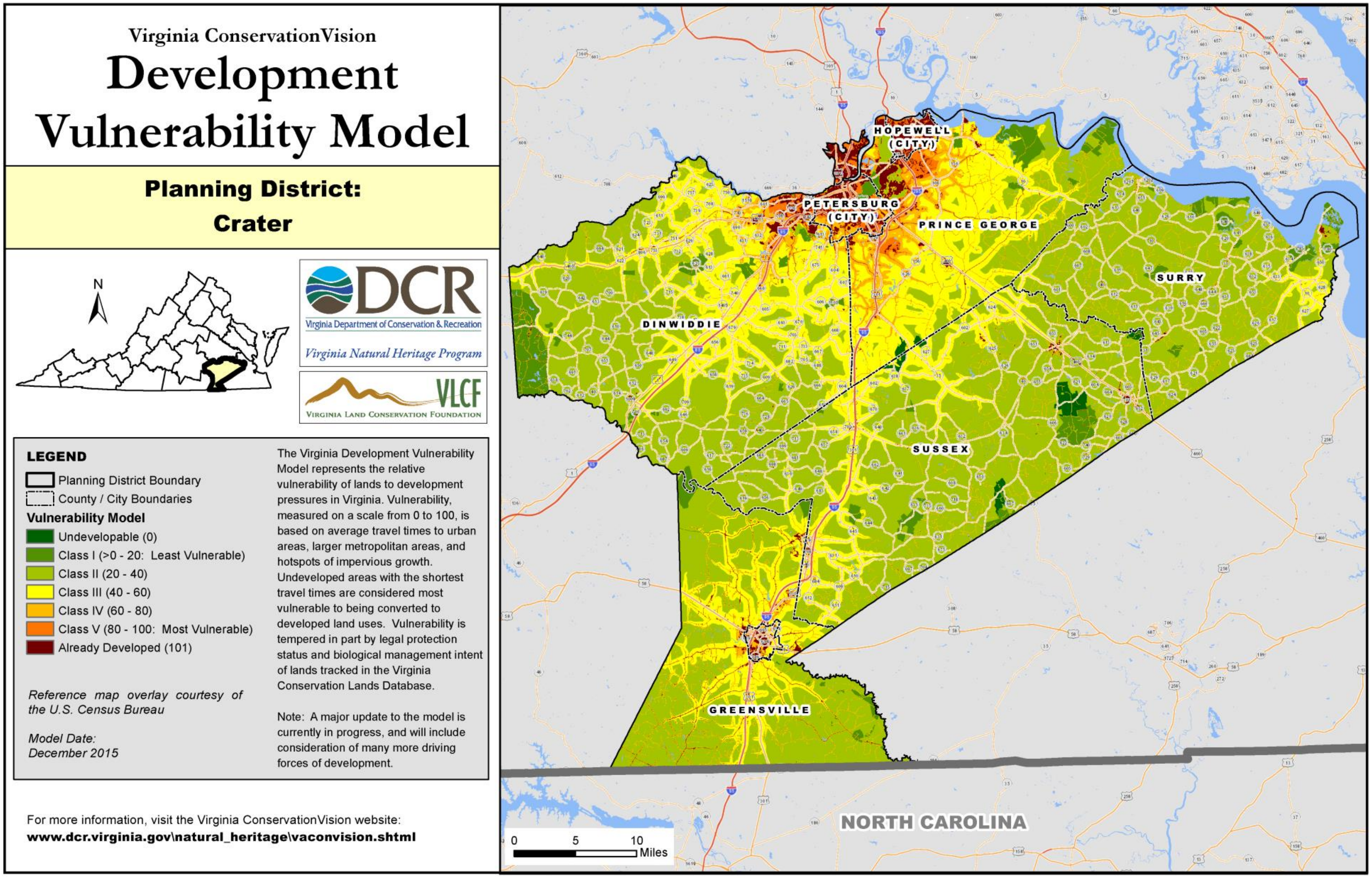
Map 3: Central Shenandoah Planning District



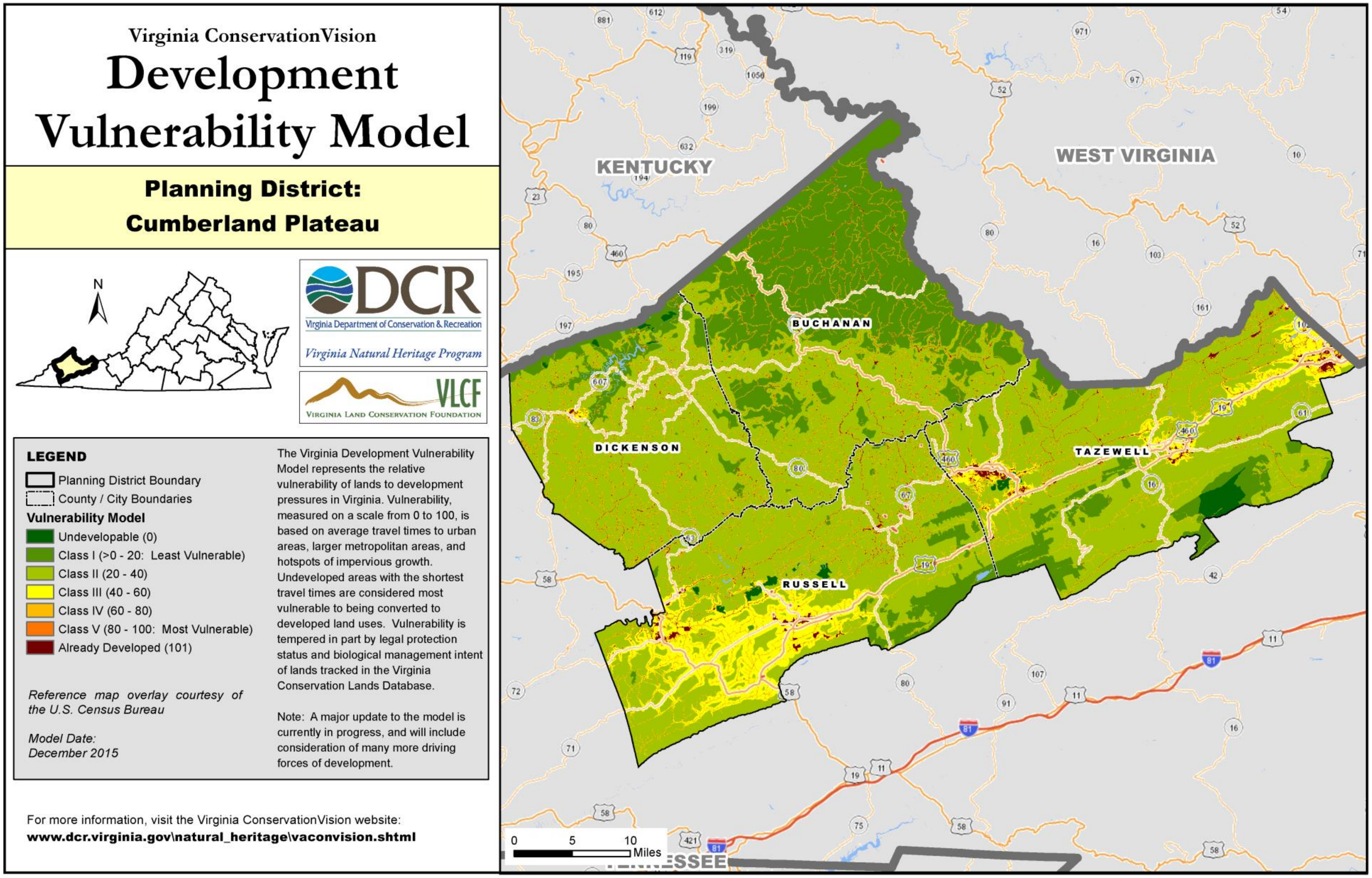
Map 4: Commonwealth Regional Council Planning District



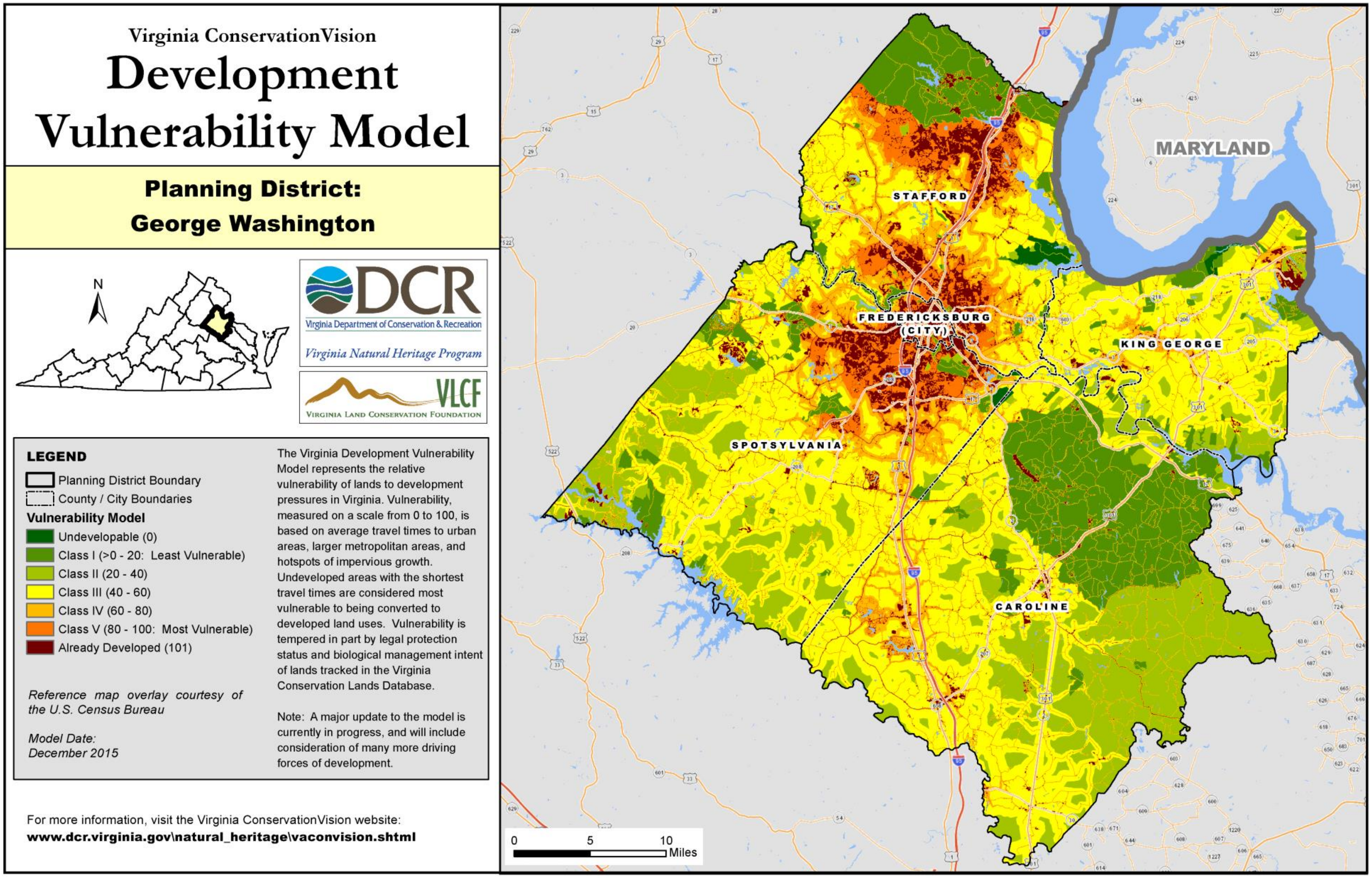
Map 5: Crater Planning District



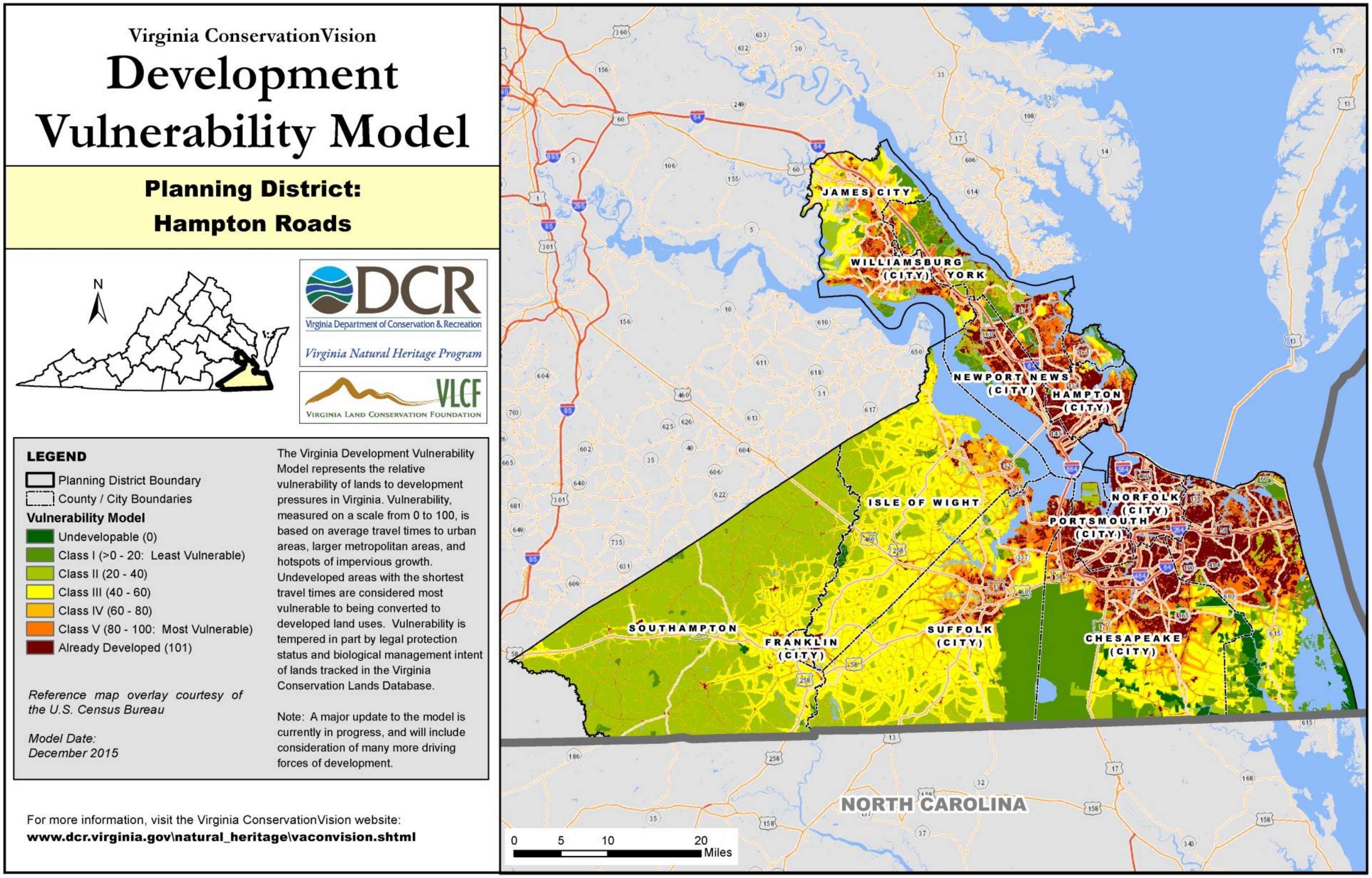
Map 6: Cumberland Plateau Planning District



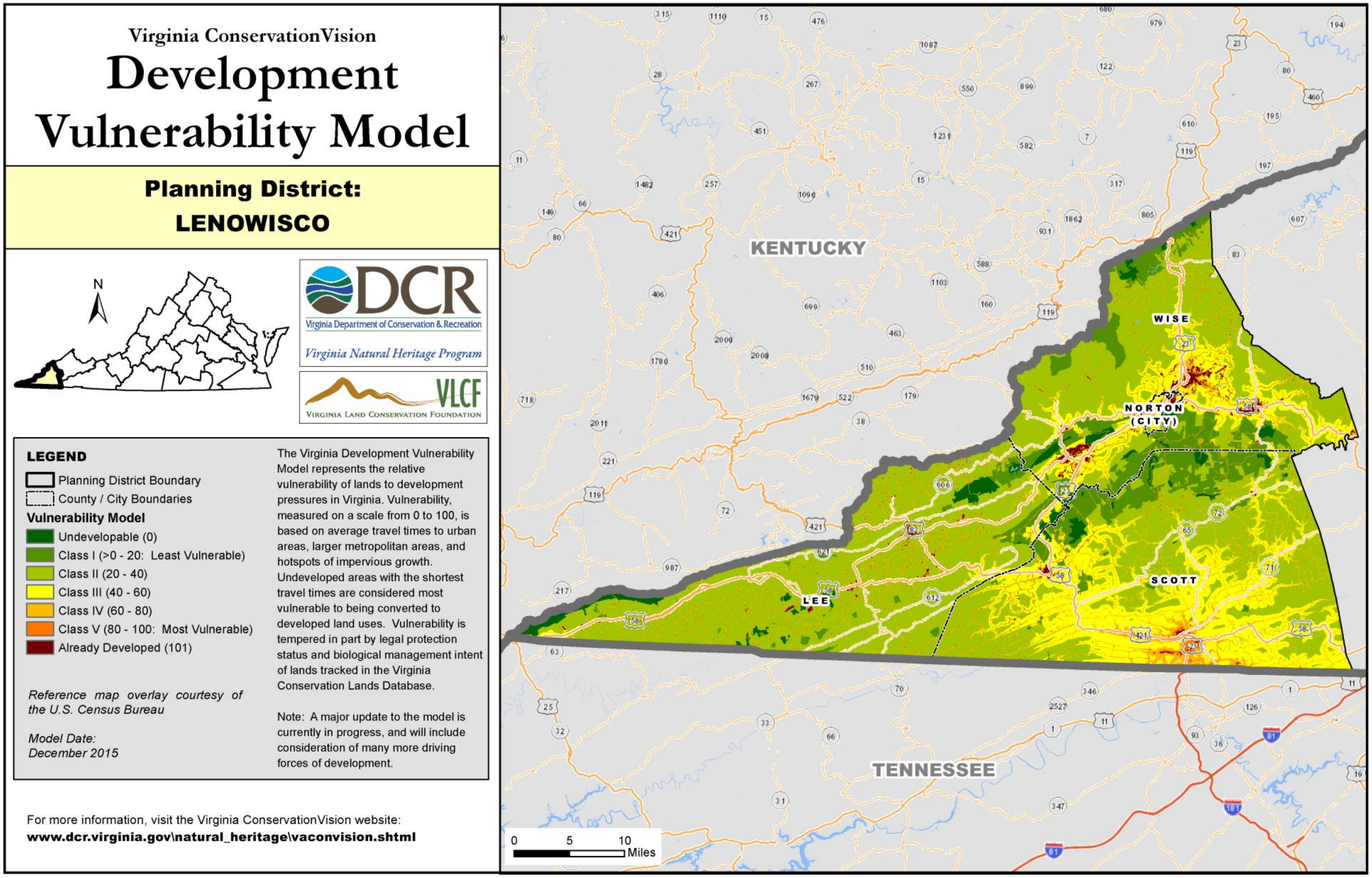
Map 7: George Washington Planning District



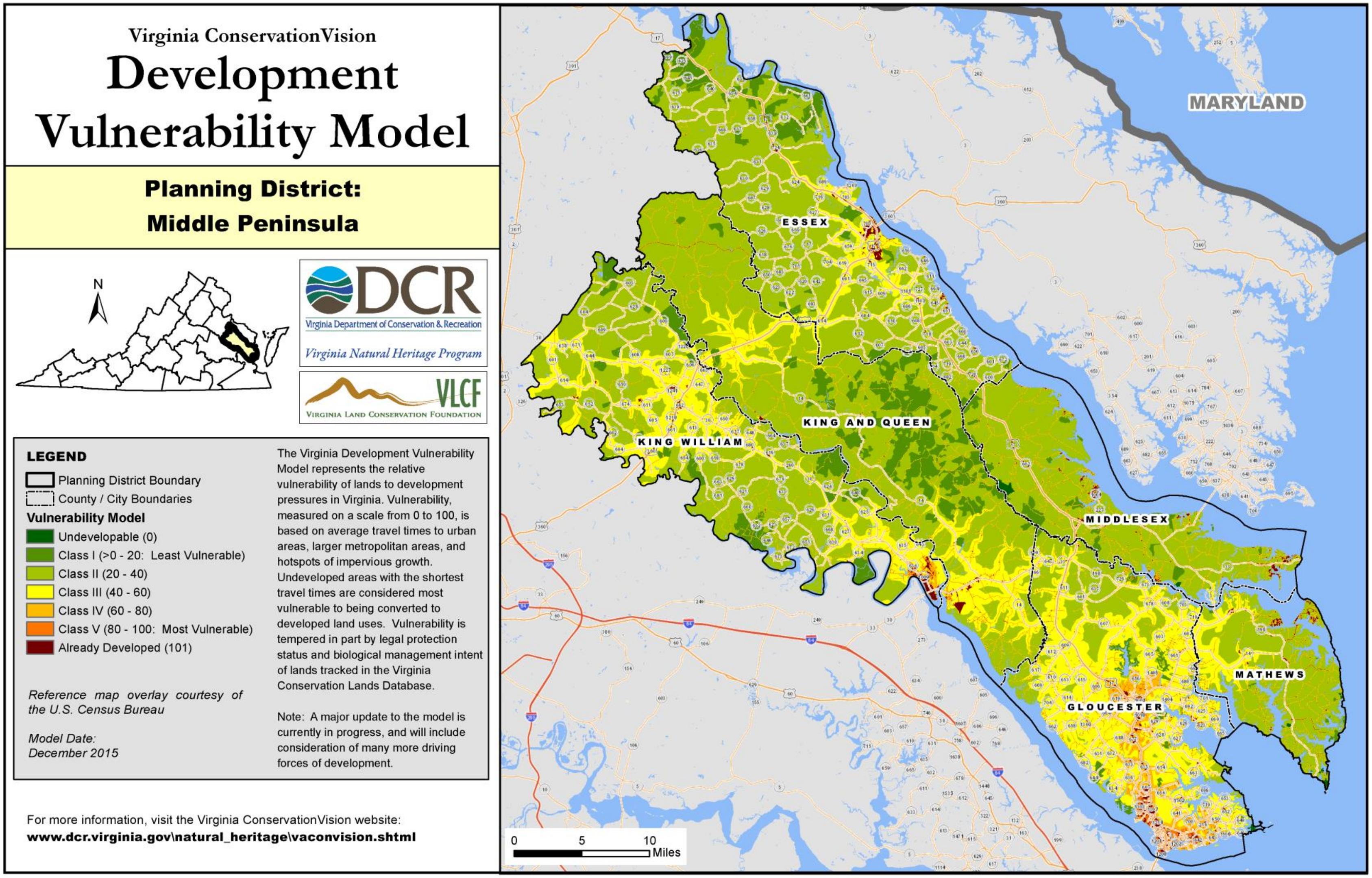
Map 8: Hampton Roads Planning District



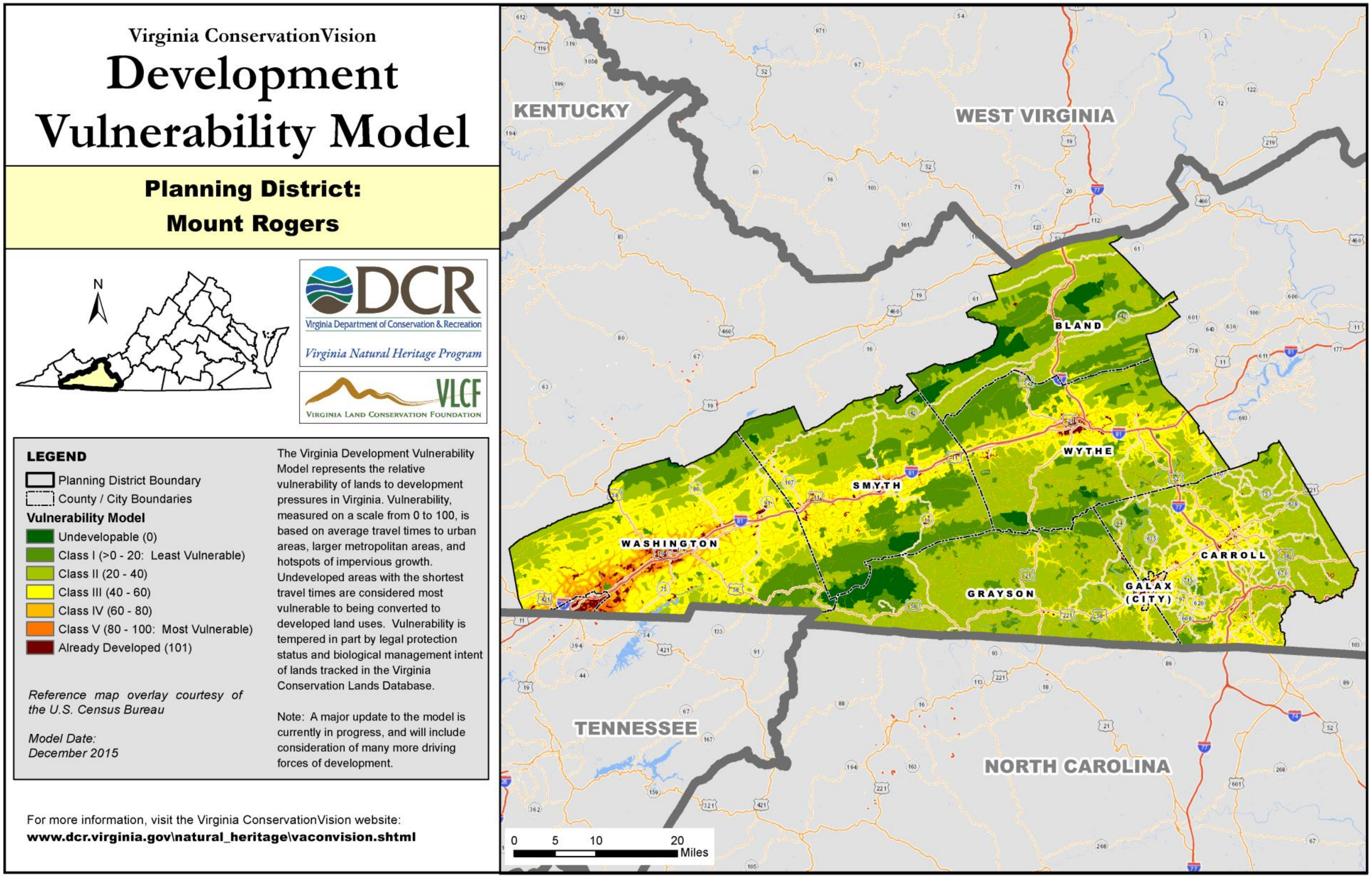
Map 9: LENOWISCO Planning District



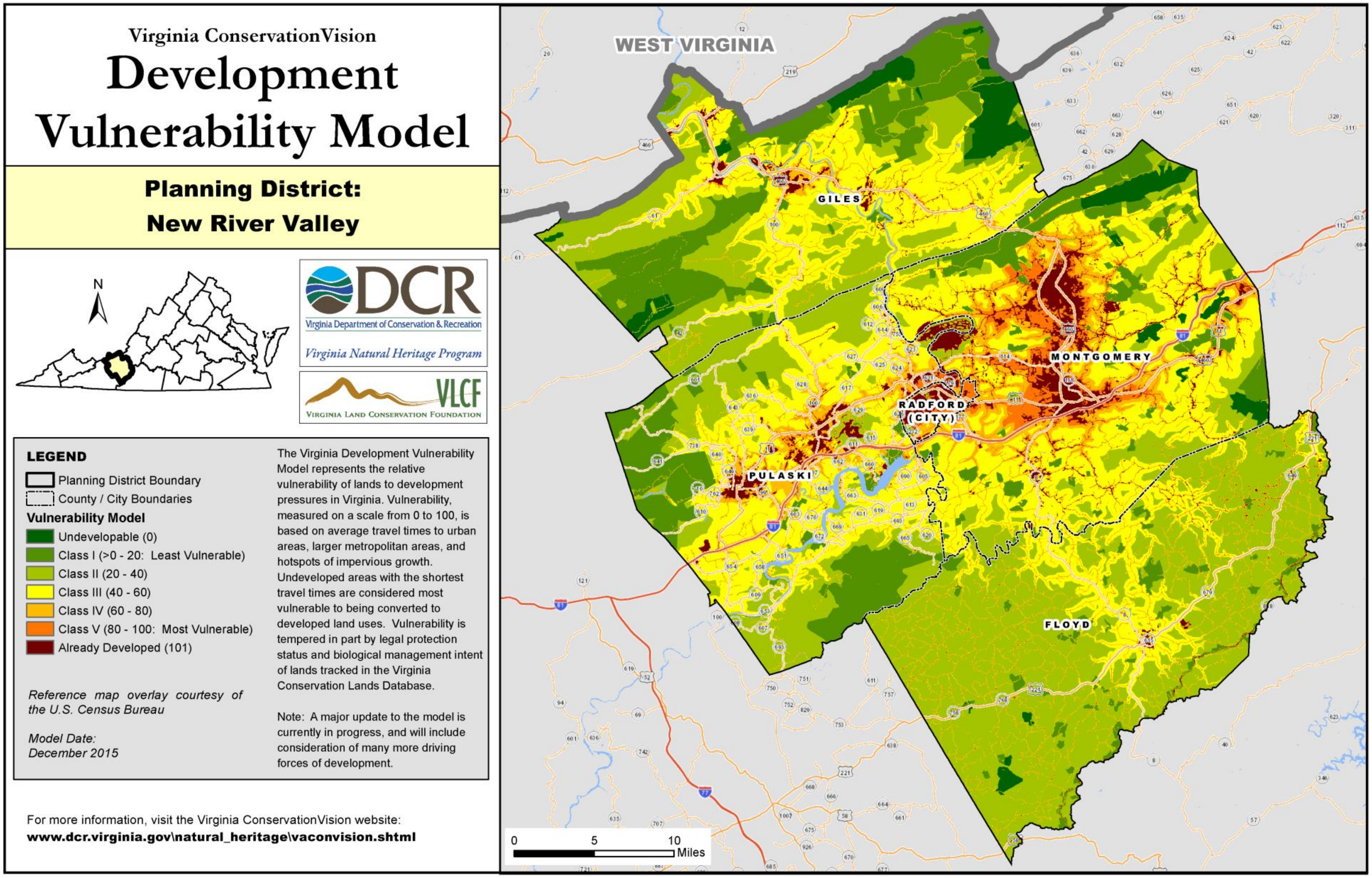
Map 10: Middle Peninsula Planning District



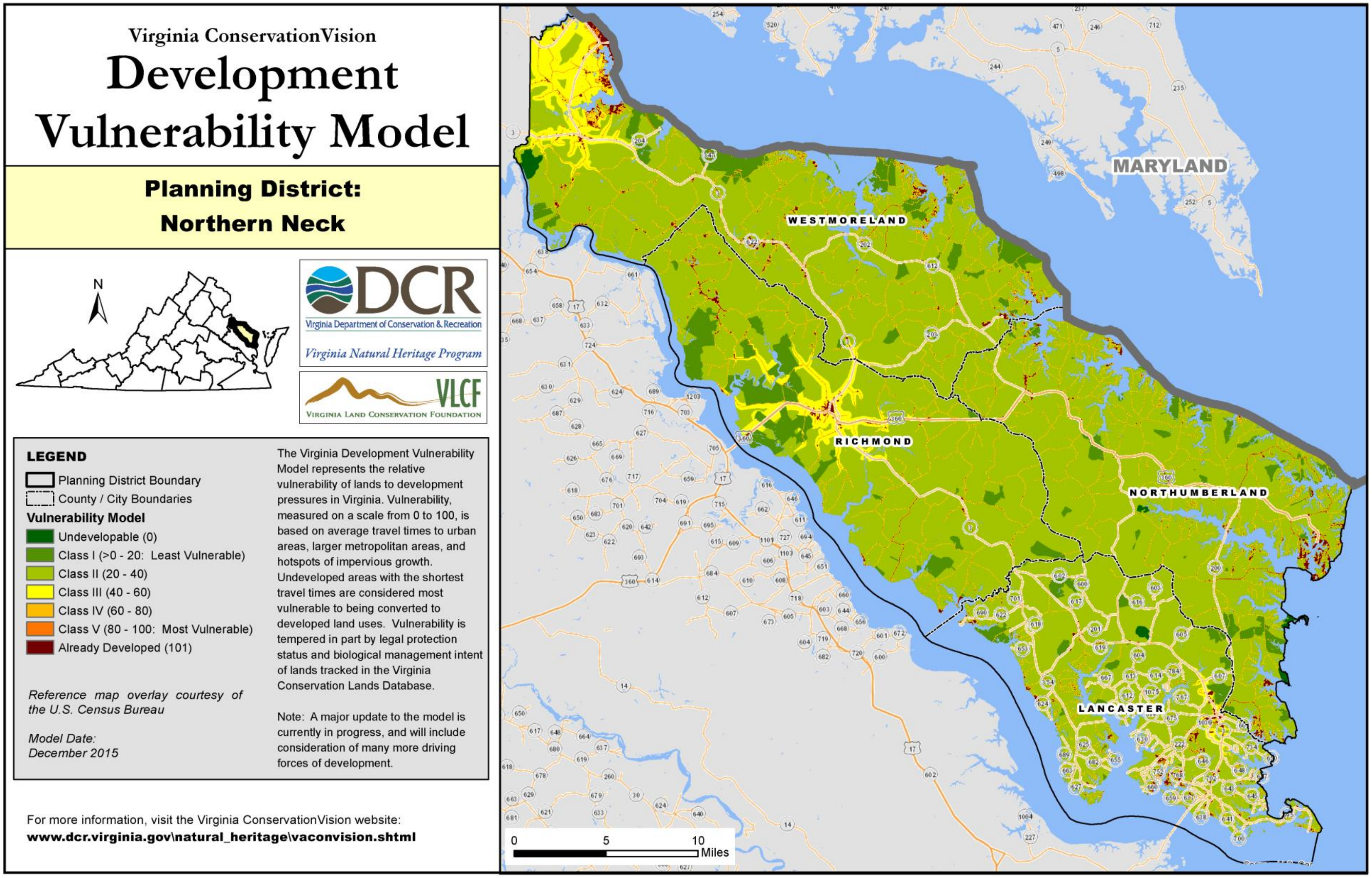
Map 11: Mount Rogers Planning District



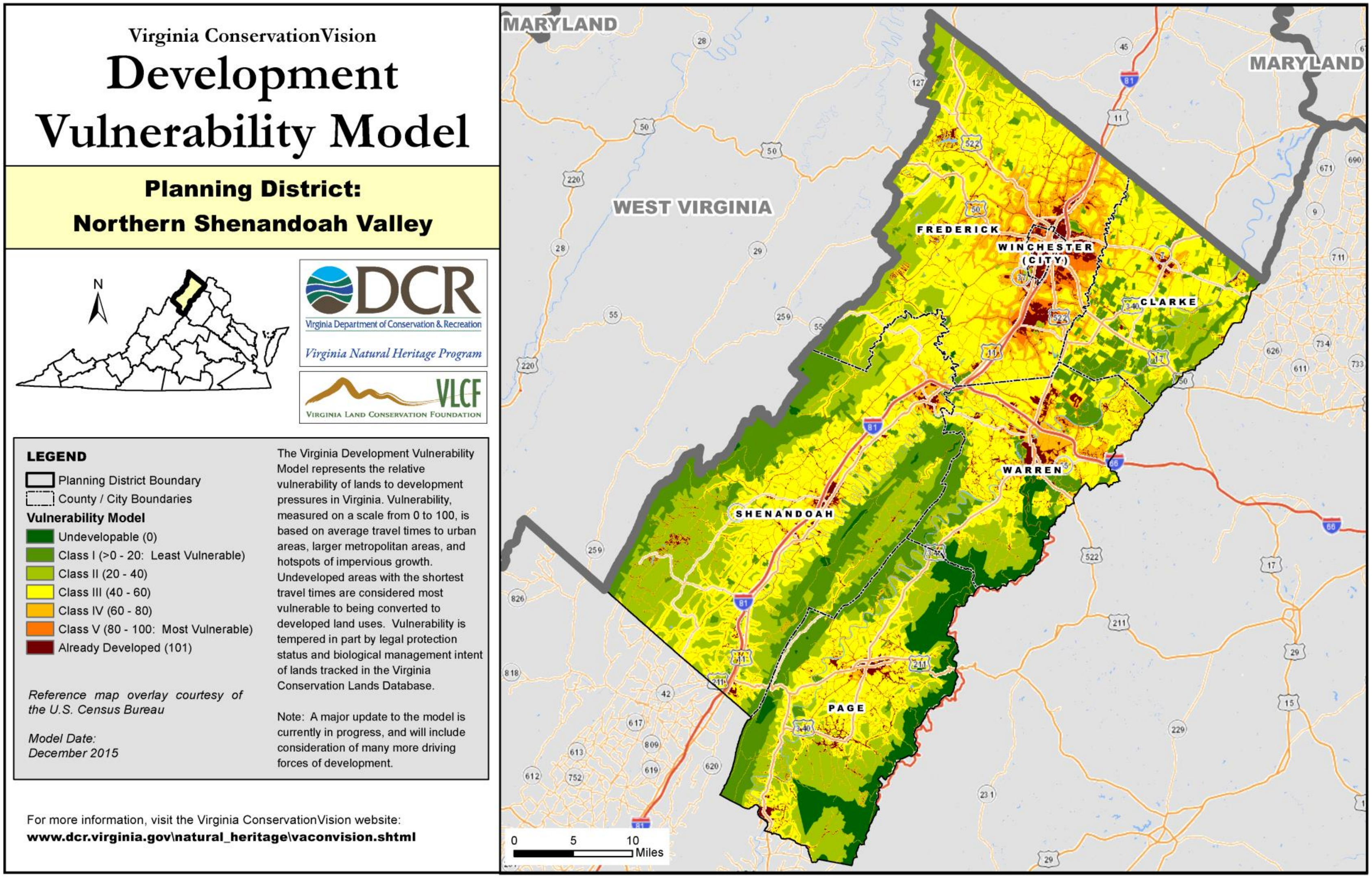
Map 12: New River Valley Planning District



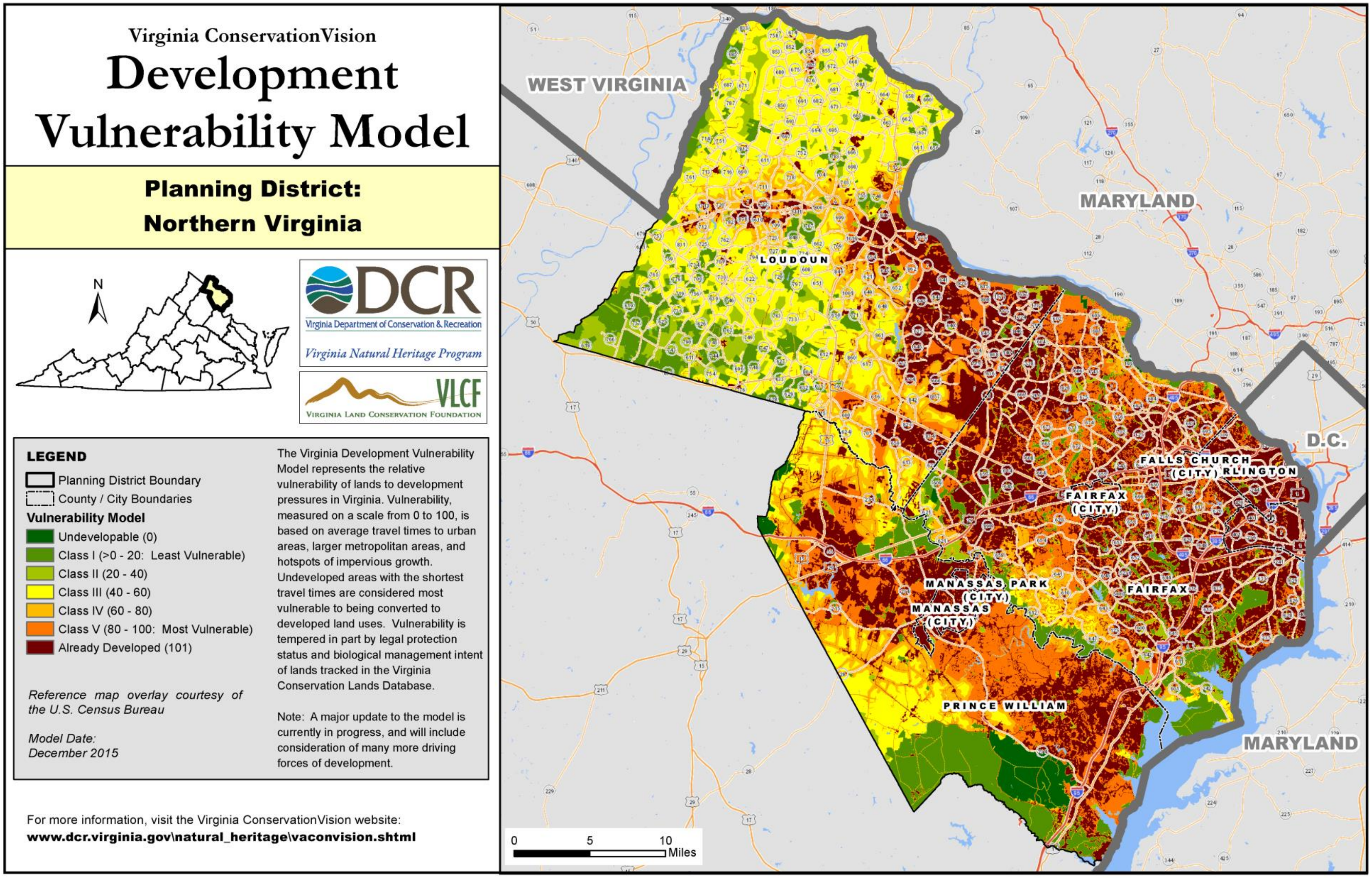
Map 13: Northern Neck Planning District



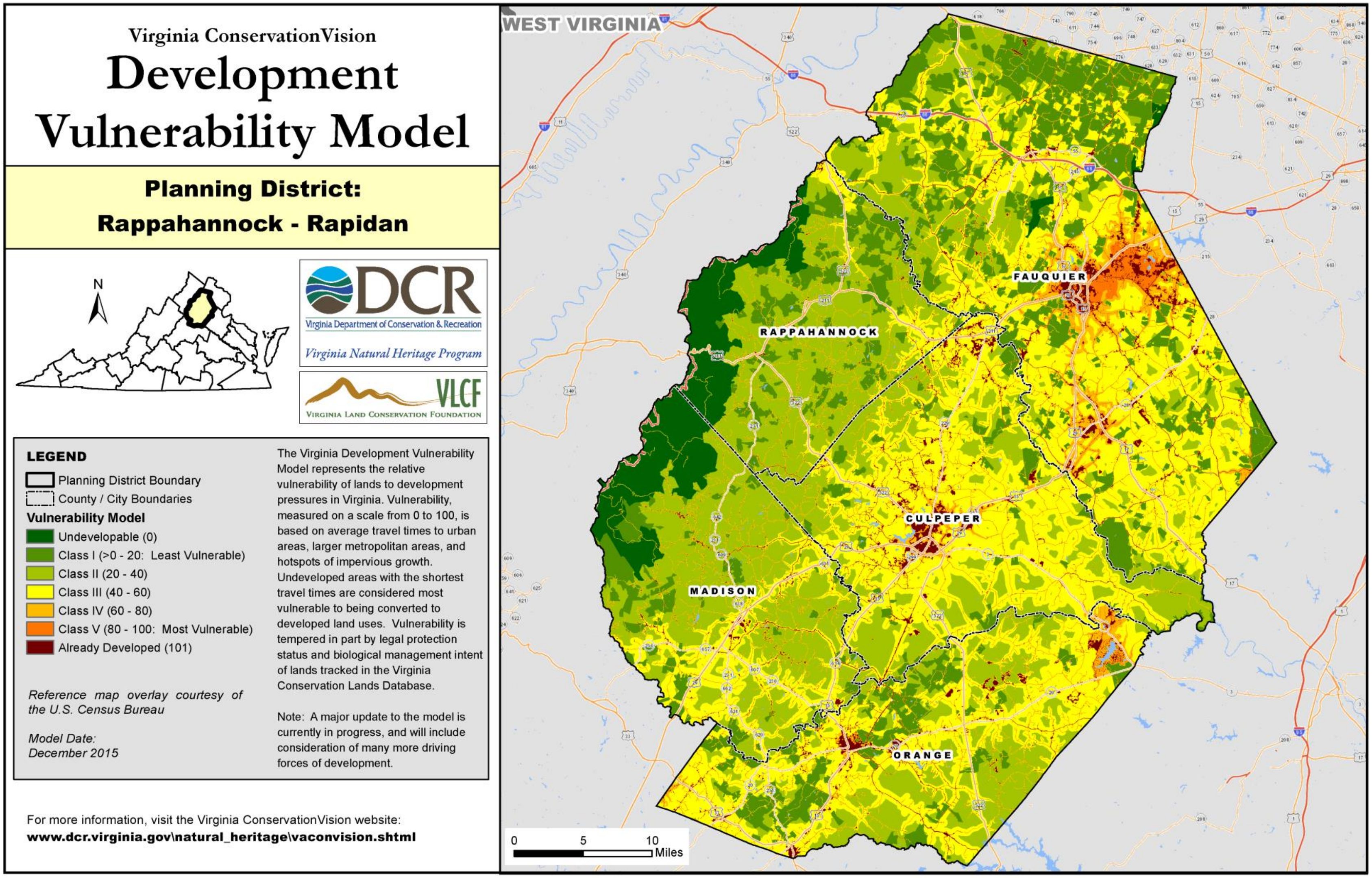
Map 14: Northern Shenandoah Valley Planning District



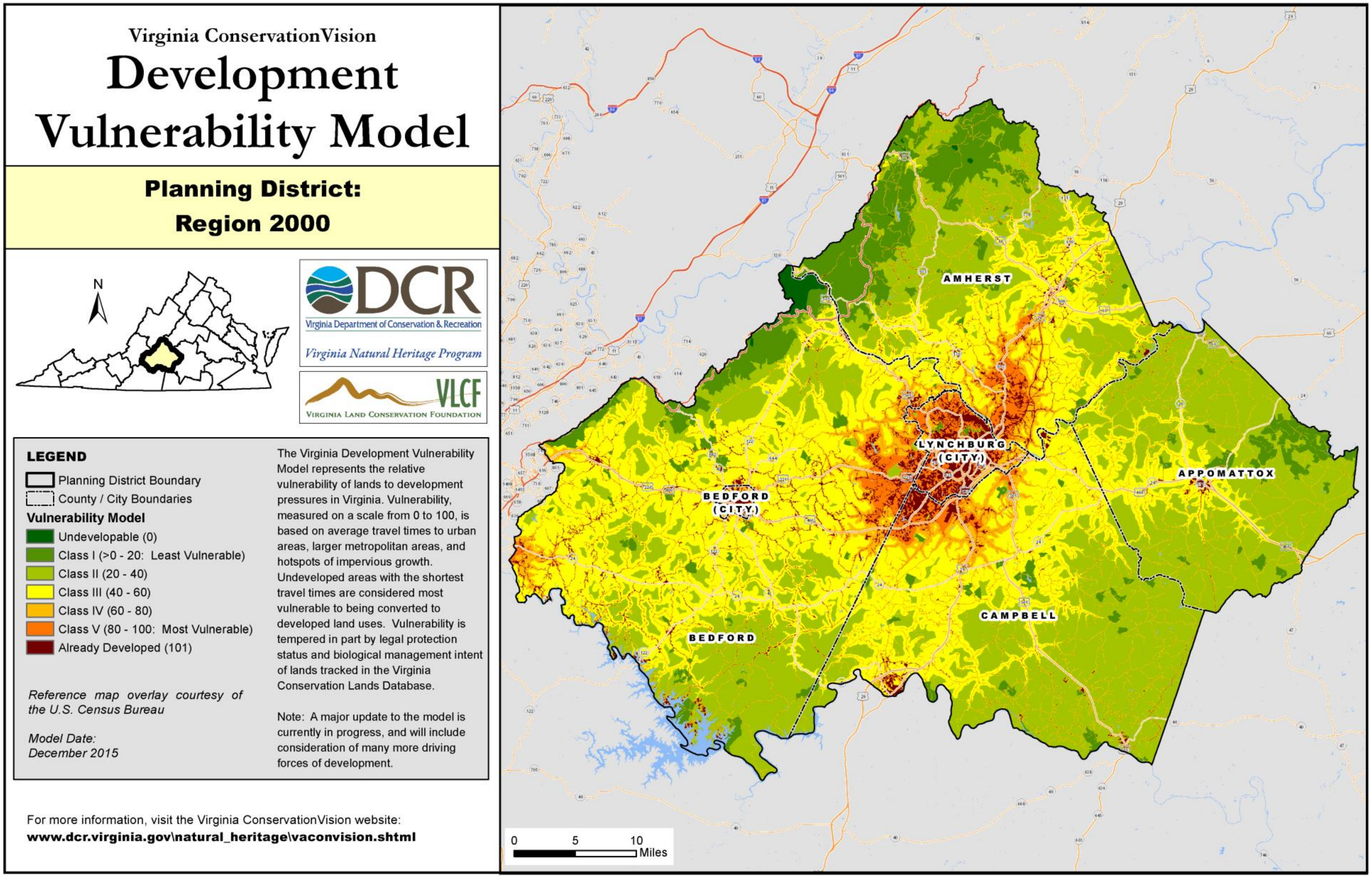
Map 15: Northern Virginia Planning District



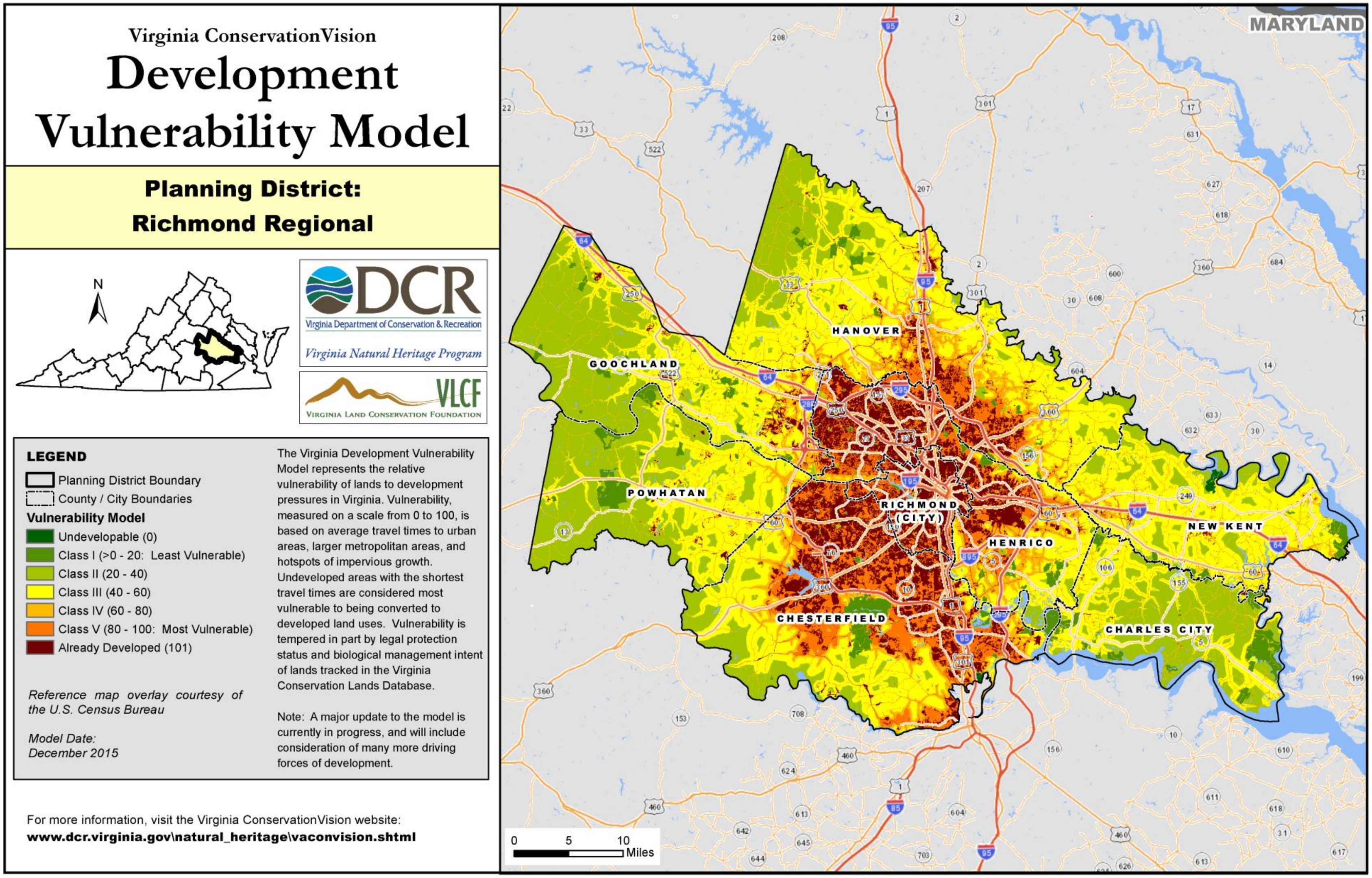
Map 16: Rappahannock - Rapidan Planning District



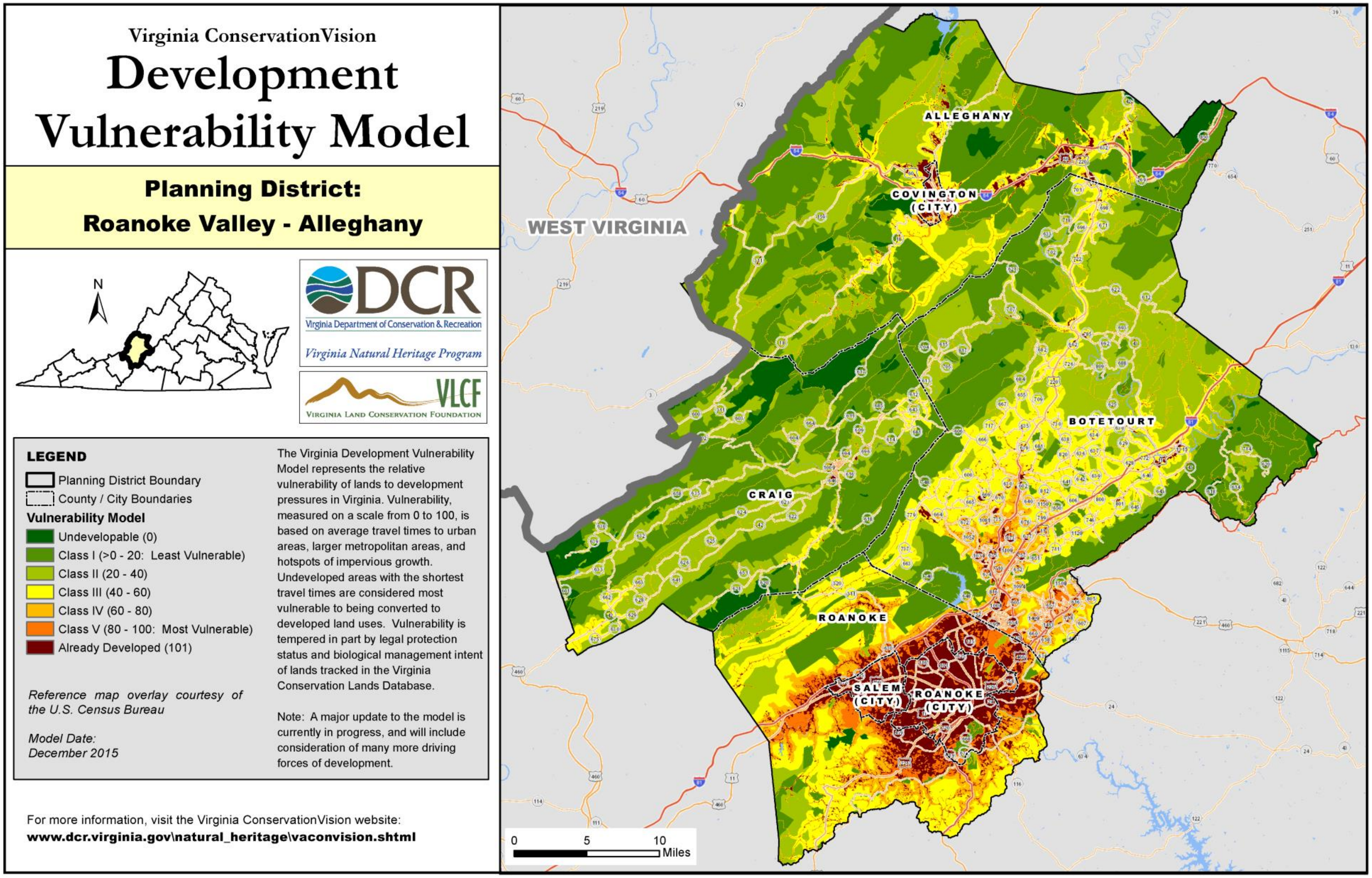
Map 17: Region 2000 Planning District



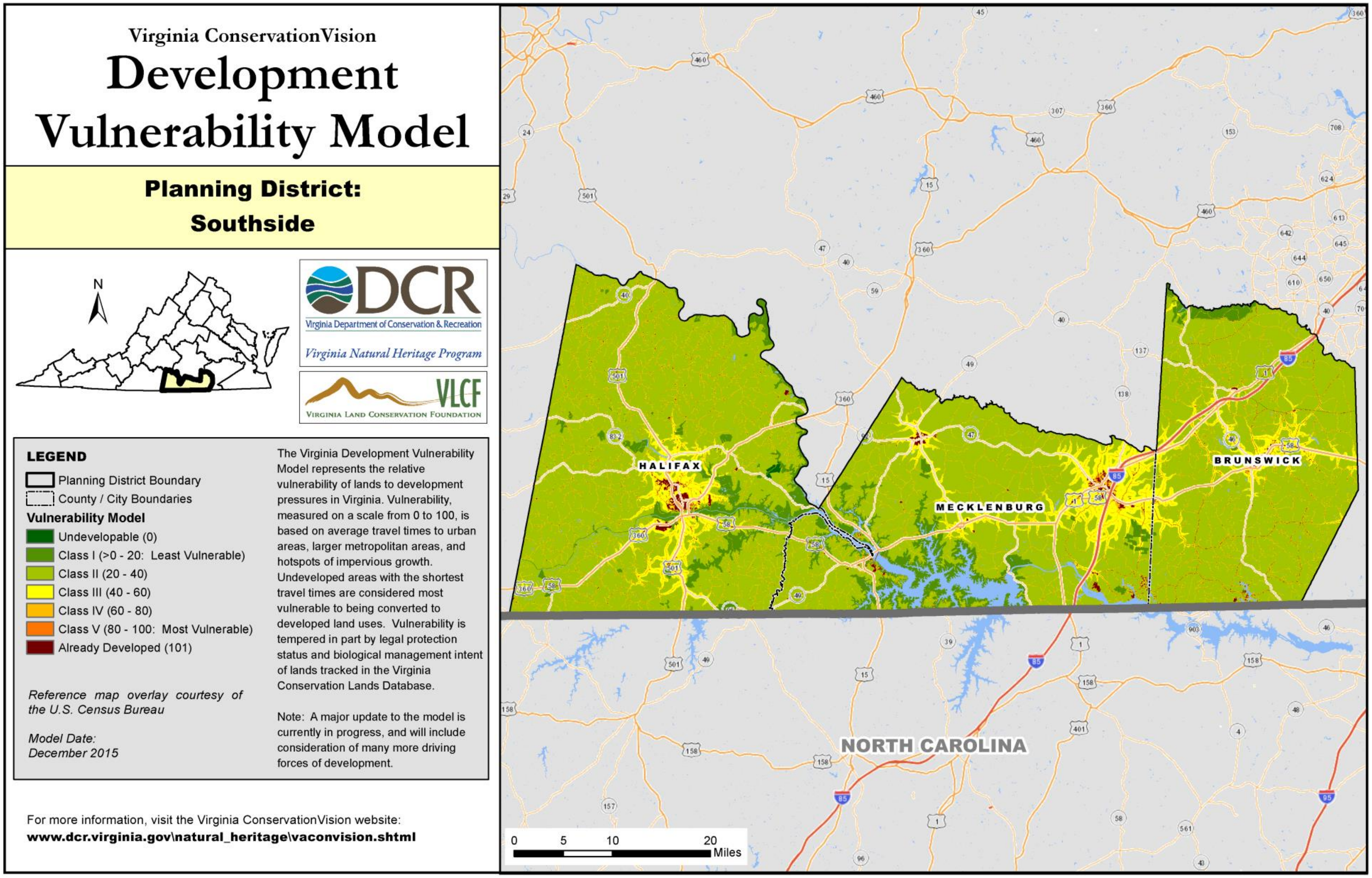
Map 18: Richmond Regional Planning District



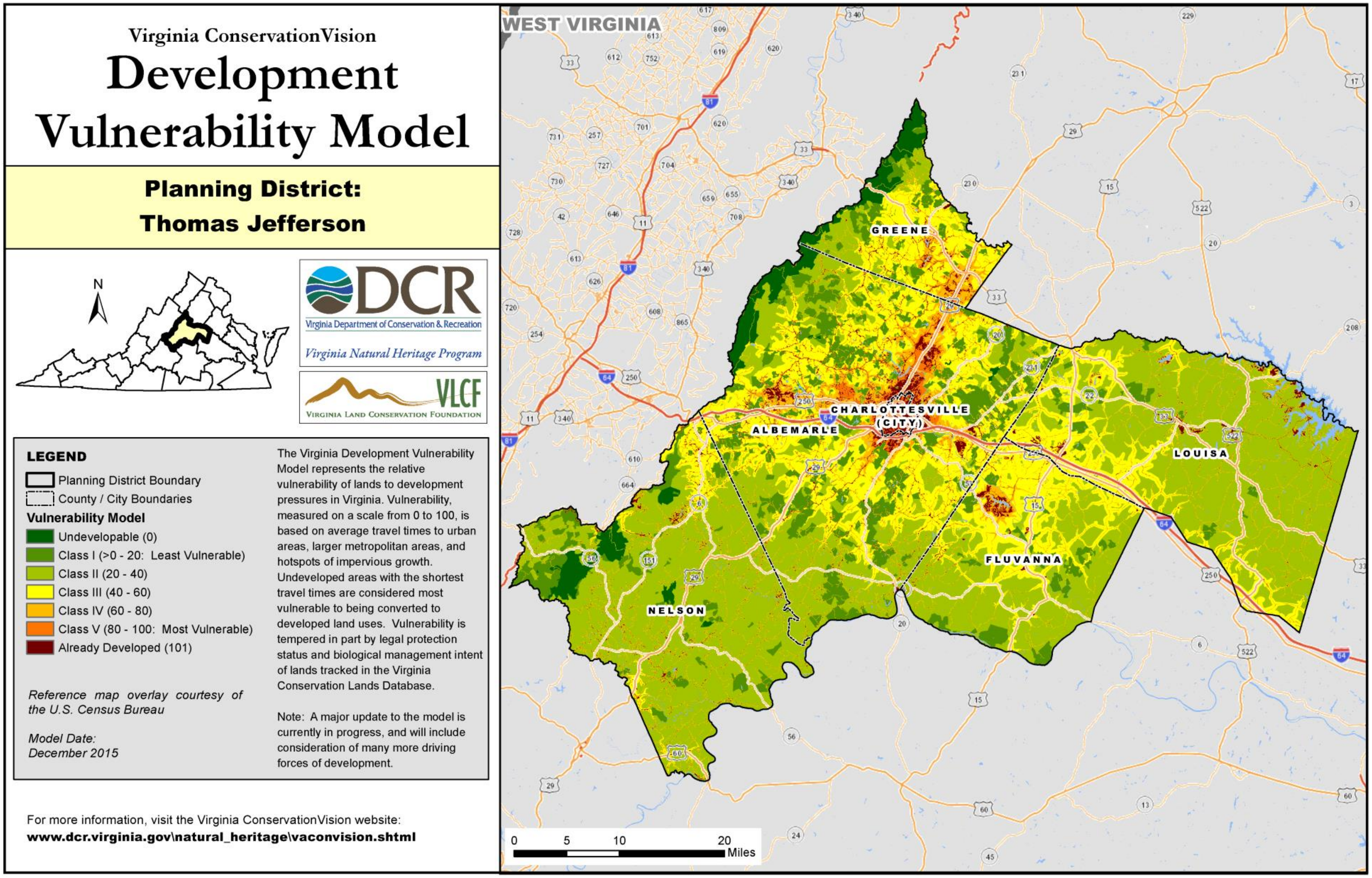
Map 19: Roanoke Valley - Alleghany Planning District



Map 20: Southside Planning District



Map 21: Thomas Jefferson Planning District



Map 22: West Piedmont Planning District