GIS Techniques for Flood Map Modernization and Hazard Mitigation Plans

Dr. Shane Parson, PE, CFM, Dr. Randel Dymond, PE, and Rachael Heltz Herman

Abstract

This paper will detail the GIS techniques utilized for flood map modernization and hazard mitigation plans by the Virginia Tech Center for Geospatial Information Technology (CGIT) in support of several Federal Emergency Management Agency (FEMA) funded projects for Virginia. FEMA has recently begun several initiatives focused on updating floodplain mapping and developing local and state hazard mitigation plans. The main goal for flood map modernization is development of up-to-date flood hazard data nationwide in a digital format. CGIT assisted the Virginia Department of Conservation and Recreation with development of a map modernization business plan, employing different automated hydrology and hydraulics GIS techniques. CGIT also worked with the Virginia Department of Emergency Management to develop the Hazard Mitigation Plan for Virginia, which covered all natural and man-made hazards that impact the state. CGIT developed a number of hazard-specific GIS techniques to assess and mitigate hazards for sites statewide.

Introduction

This paper highlights some of the different GIS techniques used in support of projects concerned with floodplain mapping updates and natural hazards mitigation planning. After providing some background on the FEMA flood map modernization efforts and hazard mitigation planning, the paper discusses the prominent role of GIS in providing new information for decision making and the importance of scale considerations for data gathering and analysis.

Background

CGIT

Founded in January 2003, the Virginia Tech Center for Geospatial Information Technology (CGIT) is comprised of fulltime research staff, affiliated faculty and students at facilities in Blacksburg and Alexandria, VA who are focused on using geospatial technologies to solve today's problems in new ways. These researchers provide technical expertise in GIS and Global Positioning Systems (GPS), with application areas from natural resource management to wireless communication networks, from environmental monitoring to homeland security, and from public health to smart development. The Center seeks to implement partnerships bringing researchers and partners together, utilizing the newest and most applicable geospatial information technology tools for solving critical research questions in Virginia and the nation.

Flood Map Modernization

One area where CGIT has played a prominent role in Virginia has been in statewide floodplain management planning. Working with the Virginia Department of Conservation and Recreations (DCR), CGIT assisted the Virginia National Flood Insurance Program (NFIP) Coordinator in assessing the current status of floodplain mapping within Virginia. These efforts originated from efforts by the Federal Emergency Management Agency (FEMA), recently integrated into the Department of Homeland Security (DHS), to update all NFIP maps nationwide. The floodplain maps developed by FEMA over the last 30 years, commonly called Flood Insurance Rate Maps (FIRMs), have not been consistently updated and maintained. Many communities have FIRMs with differing creation or revision dates as well as differing levels of mapping detail. To address this issue, FEMA developed a plan in 1997 to modernize the FEMA flood mapping program, called Map Modernization. The plan outlined the steps necessary to update FEMA's flood maps for the nation to digital format and streamline FEMA's operations in raising public awareness of the importance of the maps and responding to requests to revise them. Since that time, the plan has continually evolved as new products, processes, and technical specifications have been developed and implemented within present funding levels, which have not approached the levels necessary to fully update the national map inventory (FEMA 2003b).

FEMA required states to develop Map Modernization Business Plans, which prioritizes communities' flood map update needs and the administrative details that will be implemented by each state to assist in floodplain mapping. One part of the development of the Business Plan was documenting the flood map update needs for the highest priority communities in Virginia. These needs were then entered in the FEMA Mapping Needs Update Support System (MNUSS). During this process, CGIT developed a number of different GIS processes for gathering flood map update needs, as well as a procedure to "cluster" counties and cities into more manageable groups for floodplain map updates.

All-Hazards Mitigation Planning

While FEMA traditionally has focused on floods and several other natural hazards, such as wildfires and earthquakes, there has been a recent emphasis to develop more comprehensive short-term response and long-term mitigation planning for all hazards. Congress passed the Disaster Mitigation Act of 2000 (DMA 2000) to provide the foundation for this new approach of multi-hazard planning. One major requirement of DMA 2000 was the development of local and state all hazards mitigation plans by November 1, 2004. If communities do not have approved plans by the deadline, then future mitigation and post-disaster assistance from FEMA for their community will be greatly reduced. For example, FEMA provides assistance to the general public and communities following a Federally Declared Disaster. If a state does not have an approved All-Hazards Mitigation Plan then no funds will be provided by FEMA for things like debris removal and local and state government employee overtime (FEMA 2004).

State and local all-hazards mitigation plans are developed by first forming a planning committee to oversee the process. This committee gathers stakeholders for the region to provide information and guidance for the plan. The committee then conducts a hazard identification and risk assessment (HIRA) to determine the highest priority hazards for the region and what is at risk from the hazard. Often a consultant or university may be used to develop the HIRA and facilitate the plan development. The HIRA results are used to develop mitigation goals and strategies to address the mitigation needs. The final plan includes the HIRA, mitigation goals and strategies, and information about how the plan will be implemented and maintained.

CGIT worked closely with the Virginia Department of Emergency Management (VDEM) to develop the Virginia Hazard Mitigation Plan. While not initially part of the Virginia steering committee, CGIT was brought in to take the lead on the HIRA after Hurricane Isabel hit Virginia in September 2003. CGIT's prior experience with floodplain mapping, as well as an internal library of floodplain mapping data for Virginia, greatly aided the riverine and coastal flooding portions of the HIRA. After completion of the HIRA, CGIT has assisted with the development of the mitigation goals and strategies and the final report.

Role of GIS in Hazard Planning

GIS plays a prominent role in developing both the floodplain update business plan and all-hazards mitigation plans in Virginia and nationwide. The spatial extent of hazards often dictates how mitigation activities are evaluated and conducted. Some hazards, like tornadoes, tend to occur in very small areas for a very limited time, while other hazards like hurricanes and major river flooding can occur over many states for several weeks or months. Hazards such as floods can be mapped very precisely based on accepted models and high detail topographic data nationwide, while other hazards such as landslides have less established mapping methodologies which may be only used in a certain state or geologic region.

This variation in spatial extent and model precision takes on an additional dimension with regards to hazard mitigation planning. The term "mitigation" implies that something is adversely impacted when a hazard occurs. The "target" of this hazard may be a person, building, forest, or an entire state. What can be counted as a hazard target depends on the hazard and the amount of warning time. In most situations, loss of human life is not considered in flood mitigation analysis, because usually most flood events have enough warning time that people can get out of harm's way *if they choose to*. For events with little or no warning time, such earthquakes or tornadoes, loss of human life can be considered part of the mitigation strategy. The severity and probability of the event also impacts what is a target and worthy of mitigation protection. Most flood mitigation strategies focus on structures and contents and either remove them from floodplain areas, elevate them above most floods, or provide some level of waterproofing. Tornado mitigation also focuses on reinforcing a structure, not to preserve the structure or contents, but to provide a "safe room" for the people in the building.

The balance between the hazard extent and what is at risk forms the basis for all analysis and planning strategies. The spatial properties of both items, and their intersection, can greatly limit the resulting analysis, but can also help constrain the resolution needed for a given plan. If wind hazard probability is only known at the county level, then there is no need to have geocoded house locations within 100 feet to assign a wind hazard probability to each house. Likewise, if detailed floodplain information is available at 1:12,000 for only the eastern half of town, then house locations on the eastern side of town need to be at least equivalent to this scale and whereas resolution could be reduced on the western side of town where flood hazard data is unavailable. This balance between hazard and target forms the basis for the analysis.

GIS for Flood Map Modernization Business Plans

The first step in developing the Virginia Flood Map Modernization Business Plan was determining the current status of Virginia's flood maps. Table 1 below describes the different formats of floodplain mapping and Figure 1 shows the extent of the mapping statewide.

Table 1. Virginia Floodplain Map Status

Mapping Format	No. of Communities	Description
Quality Level 1 Digital Flood Insurance Rate Map (*DFIRM*)	21	Most comprehensive floodplain information in GIS format with associated database
Quality Level 3 DFIRM (*Q3*)	44	Only floodplain boundaries in GIS format with no database
Paper Flood Insurance Rate Map (*FIRM*)	71	Scanned paper FIRMs available for communities
Totals	136	

Note: This table only includes counties and cities. Most towns in Virginia are mapped separately from their surrounding counties using the same mapping type.

The goal of FEMA's Map Modernization program is to convert all floodplain mapping to the Quality Level 1 Digital Flood Insurance Rate Map (DFIRM). The DFIRM format has extensive geographic information about floodplain and floodway boundaries, base flood elevations, surveyed cross-sections, and background information on streets and engineering benchmarks. There also is an extensive DFIRM database format that is used to store engineering information used during the hydrologic and hydraulic modeling that produced the maps. However, as Table 1 and Figure 1 show, most of Virginia currently does not have mapping at this detail level. Where GIS-based floodplain maps are available, they are Quality 3 DFIRM (Q3), which only has digitized floodplain boundaries from georectified paper FIRMs. The rest of the state has paper FIRMs, where most of the maps have been scanned into a digital graphic format. Therefore, for almost the entire state, some type of digital floodplain information was available to aid the Business Plan.

The current floodplain mapping format was only one criterion used to develop an initial prioritization for data gathering of remapping needs. Other criteria including map age, population growth, number of Letters of Map Change (LOMC) and Map Amendment (LOMA), and number of FIRM panels. The Virginia NFIP

Coordinator's Office used this information to develop a priority (high, medium, low) for all cities and counties (and their associated towns). CGIT created different GIS methods for determining flood map update needs information for each community.

Initially, CGIT reviewed existing reports and state and federal data sources to determine individual stream and coastal reaches that required updating. When this information was insufficient, CGIT also contacted the local floodplain manager and/or GIS coordinator to gather map update needs. One part of the flood map update needs was determining the existing floodplain map detail, as summarized in Table 2.

Table 2. Floodplain Mapping Detail Types

Mapping Detail Type	Description
Detailed Floodplain Mapping with Base Flood Elevations (BFEs) and Floodway (*Detailed*)	Most detailed floodplain mapping, requires extensive modeling and field data gathering
Limited Detail Floodplain Mapping only with BFEs (*Limited Detail*)	Sufficient for many low density population areas, but still requires some field work
Unnumbered Zone A Floodplain Mapping with only Floodplain Boundaries (*Zone A*)	Usually developed almost entirely from existing data with little or no field work, majority of current mapped water bodies in this type

The current mapping detail type can be determined from the existing floodplain mapping. The more difficult thing to determine is whether the water body needed updated mapping and what mapping detail type is required. Simple Zone A floodplain mapping is the cheapest to produce, but also is developed with lower precision and little, if any, new field data collection. However, in many locations simply fitting a Zone A floodplain to updated topographic information would be sufficient for the planning needs of a community. Limited and Detailed floodplain mapping is necessary in areas with high population density and growth, and can be very expensive and time consuming to produce.

Floodplain Length and Width Measurement Techniques

Once the water body was identified as needing an update and the new mapping detail type was known, then CGIT gathered the geographic information required for the MNUSS database. For all flooding types, both riverine and coastal, MNUSS required a reach length and average width. From a GIS analysis standpoint, length and width can simply be determined using the "Measure" Tool. However, having the floodplain mapping projected and georectified to perform this measurement was very time consuming. Table 3 summarizes the techniques used for distance and width measurements for each floodplain mapping format. DFIRM data have sufficient detail to provide length and width information with little extra GIS processing. Q3 only has the floodplain boundaries for a community, so some background information like community boundaries and a stream names layer was needed, which required some reprojection of data. The most problematic format was the scanned FIRM images, which required reprojection and georectification of each individual FIRM panel image for a community. For larger counties, there may be 20 or 30 panels and longer streams and rivers may run through a larger number of panels. Often, length measures had to be done panel by panel, because of the slow screen refresh rate if more than 1 or 2 georectified images were being displayed. Using these techniques, CGIT evaluated 110 Virginia communities (including counties, independent cities, and towns) and entered over 2,500 mapping needs for various communities' flood maps. Figure 2 shows the communities with MNUSS entries, along with those with completed or ongoing DFIRMs, and community designation by DCR as medium or low priorities.

Table 3. Measurement Techniques for Different Floodplain Mapping Formats

Mapping Detail Type	Measurement Technique Steps
DFIRM	1. Reproject GIS layers to state plane 2. Use Measure Tool for length (center of floodplain) and width (at least 3 width measurements averaged)
Q3	1. Gather needed background information (streets, municipal boundaries, stream names layer) 2. Reproject all GIS layers (including Q3) to state plane 3. Use Measure Tool for length (center of floodplain) and width (at least 3 width measurements averaged)
FIRM Scanned to *.tif image	1. Gather needed background information (streets, municipal boundaries, stream names layer, aerial photography) 2. Reproject background GIS layers to state plane 3. Georectify each FIRM panel image within community to state plane using background data 4. Use Measure Tool for length (center of floodplain) and width (at least 3 width measurements averaged)

For the business plan, standard ESRI ArcMap 8 tools were used for all reprojecting, georectifiying, and mapping. CGIT is currently beginning a new project were the length and widths will be gathered for the rest of the state, so a customized ArcMap extension is being developed by CGIT to automate some of the repetitious tasks for each of these techniques.

Floodplain Map Update Clusters

After the MNUSS entries were completed, the final step in developing the map update priority for Virginia was to create a schedule for when these updates would occur. DCR and CGIT evaluated the results for the high priority (MNUSS) communities to determine the possibilities of "clustering" those communities together with other communities. By doing so, mapping projects could take advantage of shared resources, more comprehensive watershed analyses, reduced requirements for project management, and reduction of redundant data collection and analysis in adjacent communities.

A baseline was used to establish which communities should be worked into the prioritization process. "Current" communities where those which either had all or a major portion of their special flood hazard areas remapped and/or restudied within the past six to seven years without reports of any significant problems with those maps. Also, the communities that are currently in the process of being restudied or remapped were considered current. Neither group of communities were included in DCR's process of determining remapping/restudy priorities.

The remaining communities were then initially ranked based on population. The state priority ranking was used to further refine the ranking. The state priority rankings of high, medium, and low were based on information gathered from the local community floodplain mangers and existing FIRMs including map age, number of letters of map change and amendment, population growth, and local knowledge of problem stream reaches and mapping quality. Finally, the Virginia Decile List provided to Virginia by FEMA in 2003 was used to provide ranking for communities with similar population and state priorities to reflect the unique criteria used by FEMA for the deciles.

Starting with this ranked list, clusters of communities were developed to satisfy FEMA population goals for a 5-year period (funding from FY 2004 thru FY 2008), as shown in Figure 3. The clusters were based on geographic proximity, shared watersheds and common Planning District Commissions (PDCs). PDCs boundaries were used to develop clusters, because communities in Virginia often conduct regional projects through their PDCs. In addition, most PDCs in Virginia are currently developing FEMA All Hazards Mitigation Plans for their communities and have existing planning committees discussing flooding and other hazard issues. Table 4 shows the information about each of the years that the clusters cover and how almost all of the population in Virginia will be addressed by updates in years 1 and 2 (over 90%).

Table 4. Virginia Business Plan for Flood Map Modernization Yearly Summary

Year	No. of Communities	State Area	State Population	Cumulative Population
Have Been Addressed	33	24%	52%	52%
1 (2004)	28	16%	28%	80%
2 (2005)	29	22%	11%	91%
3 (2006)	26	21%	5%	96%
4 (2007)	10	9%	2%	98%
5 (2008)	10	8%	2%	100%
Totals	136	100%	100%	100%

GIS for All-Hazards Mitigation Plans

GIS techniques were critical in developing the Virginia Hazard Mitigation Plan, specifically in conducting the HIRA, where hazards and targets are identified, mapped, and compared to determine vulnerability and loss. The Virginia Plan focused only on natural hazards where information was available for analysis. Human-caused hazards, including terrorism and hazardous materials, were not directly addressed in the GIS analysis. The Plan will include references to existing emergency operations plans, which address many human-caused hazards, but FEMA did not require analysis for this plan on these hazards because of funding limitations and the need to establish consistent evaluation methods.

Locations

The Virginia Plan only looked at state owned, leased, or managed facilities. The most comprehensive source of this information was the Virginia Agency Property System (VAPS) database, maintained by the Division of Risk Management in the Virginia Department of the Treasury. VAPS contains information for almost 13,000 locations for around 230 state agencies in Virginia. The term “locations” was used instead of “structures”, because VDEM decided that all analyses needed to be summarized by locations of state agencies. Certain structures, especially in Richmond, VA (the state capitol), have multiple state agency locations in the same structure.

In the attempt to locate these facilities spatially, several methods were utilized. Using ArcMap 8.3 and ESRI StreetMap for geocoding produced points for about 1/3 of the locations in the VAPS database. Many of the VAPS address fields were incomplete or not in an E911 style format. Also, many of the higher value structures in the state (the Governor’s Mansion, State Capitol Building, major university buildings) did not have detailed state addresses or only contained the administrative address of the agency. Therefore, an alternative approach for detailing polygons was needed for the higher value locations. First, the VAPS database was sorted by property and contents values. Those locations that could be considered “institutions”, such as hospitals, correctional facilities, state parks, community colleges and state colleges/universities, were lumped together and spatially located to an appropriate location using various methods (such as ESRI data and online map search engines). After the institution was located, USGS DOQQ imagery was added to the GIS and ArcMap editing tools were used to draw a “polygon” around the perimeter of the facilities. The resulting facility polygon was then used in analyses to represent all the appropriate locations listed in the VAPS database. If a VAPS database entry could not be located by the polygon or geocode method, then the “county” method was used to at least assign a county or independent city to the location. Table 5 summarizes the number and dollar value of location using the geocode, polygon, or county methods. Figure 4 shows the geocode locations in Virginia and Figure 5 shows the polygon locations.

Table 5. Virginia Agency Property System (VAPS) Database Location Summary

Location Method	Number of Locations	Percent of Total Value in Virginia
Geocode	2,406	22%
Polygon	5,081	73%
County	5,431	5%
Totals	12,918	100%

These three location methods relate to the "target" versus hazard risk issue discussed previously. The geocode method provides the most precise location, but data was only available for a limited number of locations. The polygon method provides less precise locations, but at a sufficient detail (as will be shown) for most natural hazards analyses. This method can also account for most of the dollar value of structures and contents in the state. The county method is the least precise, accounting for only a small dollar value, yet can be used for some natural hazards analyses.

Natural Hazards

Besides mapping location, the HIRA also requires hazards mapping. Table 5 lists the natural hazards addressed in the Virginia Plan, their data source, figure number in this paper, and the analysis level for each hazard.

Table 6. Virginia Natural Hazards Addressed in Hazard Mitigation Plan

Hazard	Data Source	Graphic
Flooding (Riverine & Coastal)	FEMA DFIRM, Q3, and FIRM Mapping (FEMA 2003a)	Figure 6
Wind - Hurricane	ASCE Design Wind Speed Maps (ASCE 1998)	Figure 7 (Tracks only) (NOAA 2004)
Wind - Tornado	NOAA National Weather Service Records (NOAA 1999)	Not included, little distinction statewide
Winter Storm	NOAA National Weather Service Records (NOAA 2002, SERCC 2004)	Figure 8
Wildfire	Virginia Department of Forestry (VDOF 2004)	Figure 9
Landslide	USGS (USGS 2002a)	Figure 10
Karst (limestone geology)	USGS (USGS 2002b)	Figure 11
Earthquake	USGS (USGS 2003)	Not included, little distinction statewide

Several natural hazards were not addressed in the Virginia Plan due to lack of information statewide, including drought, land subsidence, and coastal erosion. Figure 6 shows the extent of available flood information statewide. Available DFIRM or Q3 mapping was used when appropriate, and some floodplain boundaries were digitized from georectified FIRM images in the vicinity of location polygons and in communities with high numbers of state facilities. Figure 7 shows historical hurricane track information. This information is used as the basis for hurricane design wind models, which form the basis of ASCE design wind maps, and were used to develop county-by-county exceedance probabilities for hurricane winds of 90 mph or greater. Tornado hazards were included in the analysis, but the probabilities were much lower than the huuricane winds and had only slight variation statewide. Winter storm hazard was based on average annual snowfall, where the counties and cities in Virginia were split into high, medium, or low categories, as shown in Figure 8. Wildfire Hazard mapping was developed by the Virginia Department of Forestry based on a 30 m raster GIS analysis, where each cell was assigned low, medium, or high fire potential (Figure 9). Landslide and Karst both came from USGS national maps. These hazards are primarily limited to the mountainous regions of Virginia, as shown in Figures 10 and 11. Finally, earthquake hazard mapping was obtained from the USGS, but probabilities were so low that Virginia building codes do not have any special earthquake design considerations. Therefore, earthquake hazards were not included in the analysis.

Risk Assessment Methods

Once the location and hazard data had been developed, CGIT conducted analyses to determine the impact of natural hazards on state agency locations. The precision of both the location mapping and the hazard mapping dictated the analysis level, as indicated by Table 7.

Table 7. Analysis Methods Used for the Virginia Hazards Mitigation Plan

Hazard	Analysis Level	Risk Method
Flooding (Riverine & Coastal)	Geocode	Probability
Wind - Hurricane	County	Probability
Wind - Tornado	County	Probability
Winter Storm	County	Relative Risk
Wildfire	Geocode	Relative Risk
Landslide	County	Relative Risk
Karst (limestone geology)	County	Relative Risk
Earthquake	None	None

For hazards with detailed location information (flood and wildfire), the limiting resolution factor was the location mapping. For geocoded locations, locations were "yes", "no", or "unknown" for being in a floodplain. Elevation data for the structures and floodplain was unavailable, so a matrix based on building age and value was used to approximate damage levels. For polygon locations, flooding was calculated as the portion of the polygon area that intersected with a floodplain boundary polygon. The percent of the polygon in the floodplain was used, along with the damage level assumption, to provide a weighted damage approach for all actual locations assigned to a polygon. For example, if 10% of a polygon was in a floodplain and the polygon represented 40 structures, then it was assumed that 4 structures were in the floodplain. For county locations, the VAPS database already indicated "yes", "no", or "unknown" for being in a floodplain, so these used, since no other site specific information was available. Using this method, the number of unknowns went from 64% of locations to around 40% of locations, with most of these being designated as not being in the floodplain.

Fire hazards presented a different challenge. For geocoded locations, relative risk levels (low=1, medium=2, high=3) were assigned. For polygons and counties, an area-weighted average was calculated and assigned to the location.

For all other hazards, the limiting resolution factor was the hazard mapping precision at only the county level. For these hazards, each location was assigned the probability or relative risk value only based on the pertinent county. Therefore, the only "unknown" hazards for all of these locations was for flooding where the mapping was not in the vicinity of a geocoded location, or for county locations where the VAPS database did not have a value. For all other hazards, every location was assigned either a hazard probability or relative risk.

The relative risk method used for many of the hazards, took into account a relative probability of hazard occurrence (low=1, medium=2, high=3) and the possible relative impact of that hazard on a structure, contents, and continuity of business operations. When supplemental information was available, it was used to differentiate between locations. For example, the VAPS database included fire construction rating for all locations and noted if a location was a critical facility. For the fire relative risk calculation, a better fire rating for a location lowered the overall relative risk. For all relative risk calculations, a critical facility has a higher relative risk for continuity of business operations.

The final step in the HIRA was summarizing these results for each of the approximately 230 state agencies. Crystal Reports was used to provide this summary capability. Since each hazard had a unique combination of analysis level and risk method, there was a need to provide some sort of common basis to compare between hazard and between agencies. Therefore, each state agency was ranked versus all other agencies using the average probability or relative risk for all locations of that agency. These rank percentiles were then presented with the actual probability or relative risk values in the HIRA report. This allowed each agency to see how they fared internally (what was the highest hazard risk) and externally (what hazards were above the 50th, 75th, etc. statewide). By providing this common basis, the HIRA gave each agency valuable information that was then used to develop mitigation strategies and projects.

Conclusions

This paper has highlighted some of the different GIS techniques used for flood mapping updates and hazard mitigation planning. While these techniques were used for Virginia, they are applicable for similar work nationwide and worldwide. The balance of mapping resolution between hazards and at risk entities will continue to be important as hazard mitigation mapping and plans move beyond natural hazards to human-caused hazards. GIS will play an even greater role in future planning and decision making, where spatial information not only goes in the plan document, but is used daily for mitigation activities and plan maintenance.

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Author Information

Dr. Shane Parson, PE, CFM
Senior Project Associate
Center for Geospatial Information Technology
200 Patton Hall
Virginia Tech
Blacksburg, VA 24061-0105
PH: 540-231-7147
FAX: 540-231-7532
sparson@vt.edu
www.cgit.vt.edu

Dr. Randy Dymond, Director
Center for Geospatial Information Technology
Assoc. Prof. of Civil & Env. Engineering
200 Patton Hall
Virginia Tech
Blacksburg, VA 24061
PH: 540-231-9023
FAX: 540-231-7532
dymond@vt.edu

Rachael Heltz Herman
Environmental GIS Manager
Center for Geospatial Information Technology
200 Patton Hall
Virginia Tech
Blacksburg, VA 24061-0105
PH: 540-231-4421
FAX: 540-231-7532
heltz@vt.edu