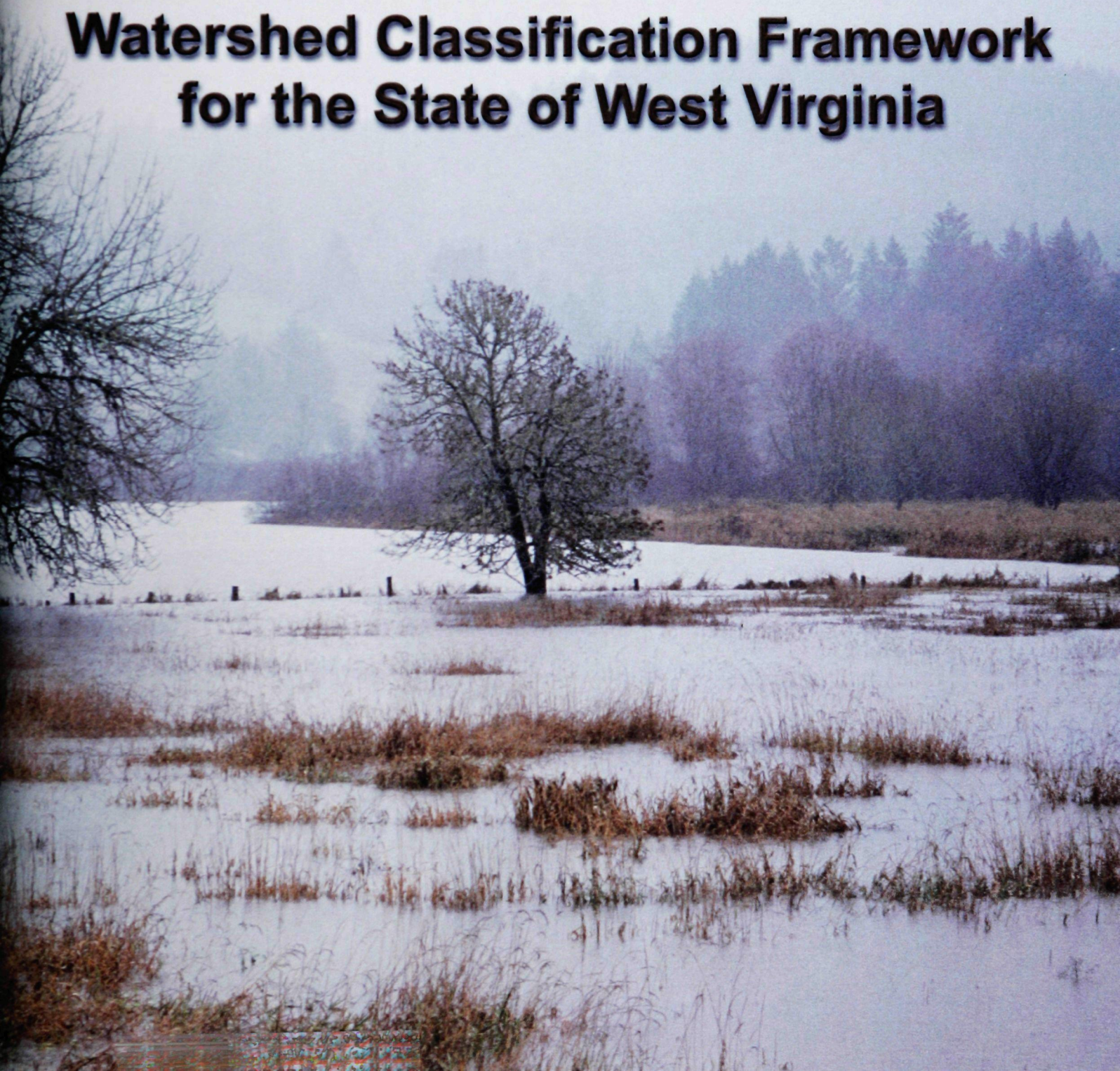# Watershed Classification Framework for the State of West Virginia

Watershed Classification Framework for the State of West Virginia

WV R-EMAP Final Report

Naomi E. Detenbeck
US EPA Mid-Continent Ecology Division
National Health and Environmental Effects Research Laboratory
Duluth, MN 55804

Leslie A. Jagger[1]
Stacey L. Stark[1]
OAO Corporation
Duluth, MN 55804

Matthew A. Starry[2]
Computer Sciences Corporation
Duluth, MN 55804

[1]EPA FAIR Contract, [2]EPA FAIR II Contract

Notice

The information in this document has been funded wholly by the U.S. Environmental Protection Agency (US EPA), including support to U.S. Geological Survey EROS Data Center (IAG DW-14938973) and West Virginia Department of Natural Resources (CR-82872001); and contract support to OAO Corporation under US EPA FAIR Contract 68-W5-0065, Delivery Order #24, and Computer Science (CSC) Corporation under US EPA FAIR II Contract 68-W01/W02-032, Task Order #024. This document has been prepared at the US EPA National Health and Environmental Effects Research Laboratory, Mid-Continent Ecology Division, in Duluth, Minnesota, with support from EPA FAIR II Contract 68-W01/W02-032 to CSC. It has been subjected to review by the US EPA National Health and Environmental Effects Research Laboratory and approved for publication. Approval does not signify that the contents reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

TABLE OF CONTENTS

LIST OF ACRONYMS

DEM	Digital elevation model
DEP	Department of Environmental Protection
DNR	Department of Natural Resources
EDNA	Elevation Dataset with National Applications
EMAP	Environmental Monitoring and Assessment Program
FGDC	Federal Geographic Data Committee
GIS	Geographic Information System
MAIA	Mid-Atlantic Integrated Assessment
NHD	National Hydrography Dataset
NWBD	National Watershed Boundary Database
NWI	National Wetlands Inventory
PRISM	Parameter-elevation Regressions on Independent Slopes Model
R-EMAP	Regional Environmental Monitoring and Assessment Program
US EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES (CD-ROM, back pocket)

INTRODUCTION

The Environmental Monitoring and Assessment Program (EMAP) is a research program to develop the tools necessary to monitor and assess the status and trends of national ecological resources. These tools include probability-based survey designs and indicators of biological condition. Regional EMAP (R-EMAP) is designed to evaluate how these tools can be applied at local and regional scales to meet the management needs of the states and regions. One of the emerging issues in monitoring programs for the states and tribes is the need to develop designs to meet multiple objectives outlined in different sections of the Clean Water Act. To meet the requirements of Section 305(b), probabilistic survey designs are needed to produce estimates of regional condition with a known level of confidence. In addition, monitoring programs must identify impaired waters and associated causes of impairment to meet the listing requirements of Section 303(d) of the Clean Water Act (US EPA 2002). Ideally, monitoring programs will provide information to allow states to more efficiently plan the next round of monitoring, in order to identify as many impaired waters of the state as possible. One approach which can accomplish both of these needs is to incorporate risk-based categories into sampling designs, either as strata in a random-stratified design, or as categories to which different probability-weights are assigned. This approach allows managers to summarize not just information about regional condition, but also information about the risk of impairment associated with different classes of aquatic resources.

A R-EMAP project was designed for the state of West Virginia to accomplish multiple objectives, including the evaluation of a risk-based random-stratified sampling process. An additional goal of the WV R-EMAP project was to refine the fish index of biotic integrity (IBI) developed through EPA's Mid-Atlantic Integrated Assessment (MAIA) project to produce separate indices for different thermal classes of streams and specific to the state of West Virginia. The purpose of this report is to describe the methods involved in producing a preliminary watershed classification and incorporating the risk-based watershed classification into a monitoring design for

the state of West Virginia. Validation and refinement of the watershed classification scheme, based on analysis of pending monitoring data, will be addressed in a subsequent report.

PURPOSE OF CLASSIFICATION AND INTENDED USE OF DATA

Purpose of watershed classification

Historically, classification systems have been used for inventory purposes, for stratifying landscapes prior to characterizing reference or regional condition, and for facilitating communication with natural resource managers and the public (Omernik and Gallant 1988; Heiskary and Wilson 1990; Herlihy et al. 2000; Pan et al. 2000; Waite et al. 2000). More recently, it has become necessary to develop classification systems that can explain differences in vulnerability of aquatic ecosystems to stressors, aid in regionalizing water quality criteria, and predict probability and causes of impairment of aquatic systems (US EPA 2002).

Most sources of stream impairment contained in state 303(d) listings are related to nonpoint source pollution (US EPA 2001, 2003). To more efficiently deal with water quality management issues, an integrated approach to small watershed assessment, diagnosis, and restoration planning is needed (Figure 1). Current guidance from US EPA supports the development of a consolidated assessment and listing approach to enable joint application of Clean Water Act Sections 305(b) and 303(d) (US EPA 2003). Monitoring strategies developed for 305(b) regional assessments also must inform the 303(d) listing process. In the 2001-2003 WV Regional Environmental Monitoring and Assessment Project (R-EMAP), use of a new watershed classification technique specific for West Virginia should allow the state to improve its ability to discern anthropogenic causes of impairment from non-anthropogenic sources of variability in reference condition (Cincotta 2000; Brazner et al. 2003) by producing a series of stressor-response relationships specific to different watershed classes.

2
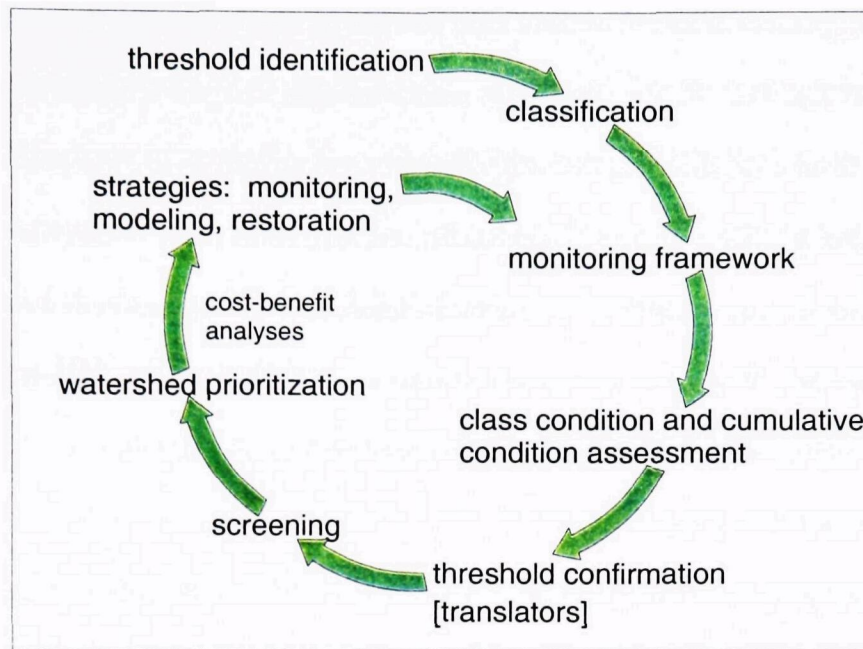
Figure 1. Use of classification in sequence of monitoring, assessment of condition, and prioritization of watersheds for further monitoring, modeling, and restoration.

In addition, use of the watershed classification scheme within a monitoring strategy will allow estimation of the condition of classes of watersheds and prediction of ecological risk for unmonitored systems.

Gradients of land-use can be studied in combination with hydrology moderating factors to establish relationships of changes in runoff, and associated water quality and biological responses, with land-use activities (Verry 1986; Detenbeck et al. 2000). Since multiple non-point stressors potentially are affecting biological condition, it is appropriate to use watersheds as the sampling and/or assessment unit. In order to establish an appropriate stratified random sampling regime to diagnose causes of impairment, watersheds within the state of West Virginia must be properly classified. The classification developed and described in this document is based on identifying the levels of hydrology-moderating factors such as watershed storage and watershed development at which rapid degradation occurs. Watershed storage capacity is operationally defined as the fraction

3

of watershed area present in lake + wetland area, and can be used to predict the magnitude of floods (Jennings et al. 1993). Peak flows are generally associated with a large fraction of nutrient and clean sediment yields from watersheds, so that watershed storage can also be used to predict attenuation of nonpoint-source loadings. Wetlands and lakes increase retention time within the watershed, allowing processes such as nutrient uptake, denitrification, and sedimentation in wetlands to improve water quality. Watershed storage can also be a good predictor of baseflow water quality (Johnston et al. 1990; Detenbeck et al. 2000; Detenbeck et al. 2003a,b).

Hydrology-based classification of watersheds

Watershed properties such as depressional storage volume and surface-water hydrogeomorphic types can be used to classify lakes or streams according to relative risk of impact. Our approach to predicting stream sensitivity to nonpoint source pollution is based on the nonlinear response of hydrologic regimes and associated loadings of non-point source pollutants to watershed properties (Richards 1990). Selected hydrologic thresholds are related to 1) variation in levels of watershed storage (either natural or anthropogenic) and 2) land-use activities affecting runoff and the hydrologic regime. In common usage, the term "threshold" refers to "the point at which a physiological or psychological effect begins to be produced" or "the point at which something starts." We define a *hydrologic threshold* as a breakpoint or inflection point in a nonlinear relationship between a watershed property and hydrologic response variable such as peak flows. For example, peak flows per unit area often increase exponentially once the storage capacity of a watershed has been exceeded. We have identified these thresholds based on a space-for-time substitution, or comparison across watersheds, as inadequate historical records are available for analysis of time series of individual watersheds.

The United States Geological Survey (USGS) has defined a series of empirical nonlinear

4

equations relating watershed properties such as watershed area, channel slope, watershed storage, and land-use (percent forested, percent urbanization, or percent impervious surface area) to peak flows of given recurrence intervals (Q_2, Q_5,... Q_{100}; Jennings et al. 1993). Peak flows increase exponentially as watershed storage decreases below a given threshold (Detenbeck et al. 2000). These thresholds form the basis for a watershed classification system.

Relationship between HUCs and watersheds

The first step in developing a classification strategy is to define the population of interest. Theoretically, an infinite number of watersheds could be defined, starting at any random point on a stream network (Detenbeck et al. 2003a). Benefits of defining a fixed set of watershed units include: a) the ability to tie assessment units to management plans and actions, b) ease in mapping classification units and classes, and c) the significance of fixed management units for stakeholders who form watershed management organizations to facilitate local environmental protection.

The USGS is coordinating with other Federal agencies and the states to develop a National Watershed Boundary Database (NWDB), which will sequentially divide existing 8-digit Hydrologic Units (HUCs) into 10-digit HUCs, and 10-digit HUCs into 12-digit HUCs (Legleiter 2001). Use of a seamless national boundary database will facilitate communication among neighboring states, and planning and management of basins that cross interstate boundaries. In addition, creation of seamless nationwide GIS layers will allow development of a series of elevation, hydrography, and derived coverages that are internally consistent with one another (Franken et al. 2001).

We chose 12-digit HUCs as the base map for our classification framework. Watersheds associated with 12-digit HUCs span the size range of wadeable streams in West Virginia (400 - 40,000 ha), correspond to the size range of most management units in the state, and fit within a hierarchical scheme of larger management units (i.e., 10- and 8-digit HUCs). A total of 36 8-digit

HUC units drain into the state of West Virginia; these 8-digit HUCs contain a total of 242 10-digit HUCs (USGS watershed units) and 1427 12-digit HUCs (USGS subwatershed units). Of these 12-digit HUCs, 883 fall predominantly within the borders of West Virginia.

Not all HUCs are equivalent to watersheds. HUCs can be defined as either basin or interbasin. Noncoastal basin HUCs are generally equivalent with watersheds at the 12-digit scale, while interbasin HUCs divide the main channel of the next larger size class of HUCs into segments. Coastal HUCs can contain multiple parallel watersheds draining to a large water body (Great Lake or ocean), but these are not an issue in West Virginia. Interbasins may include a middle segment of a larger river that encompasses many smaller side tributaries. Interbasin HUCs can be aggregated with upstream units to define full watersheds (Figure 2). Throughout this report, derivation of watershed attributes for 12-digit HUCs is based on the boundary and characteristics of the full aggregated watershed regions.

Use of Pfafstetter codes facilitates the discrimination between basin and interbasin HUCs, and identification of all upstream or downstream HUCs. Pfafstetter codes are not the same as HUC codes, but are produced by the USGS during the process of creating elevational derivatives such as watershed boundaries. Pfafstetter codes are hierarchical, with a 2-digit segment added at each new level of subdivision. The last digit of the Pfafstetter code increases consecutively from mouth to headwater sub-basins, with even numbers associated with tributaries (basin HUCs) and odd numbers associated with HUCs along the mainstem (interbasin HUCs) (Verdin and Verdin 1999; Figure 3).

Use of watershed classification as a sampling and assessment framework

Once a fixed set of watersheds is identified, delineated, characterized, and classified, this set can be used to define a sample population and survey design. At least two options exist for
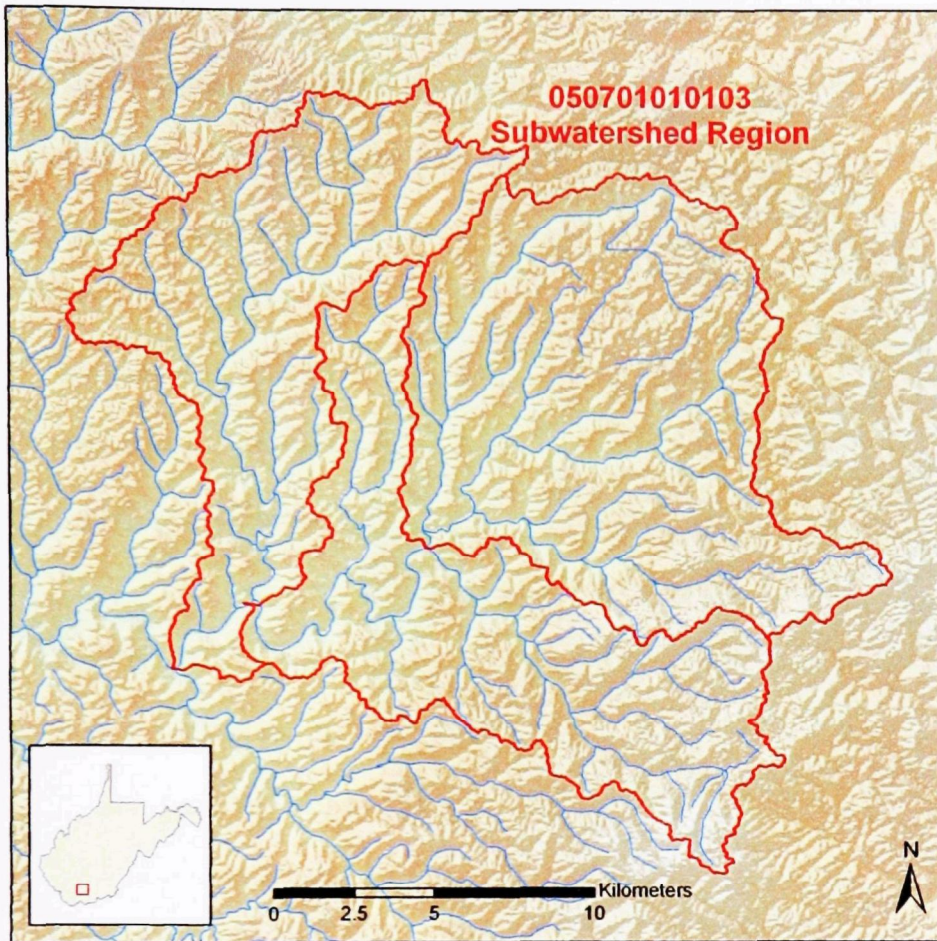
6
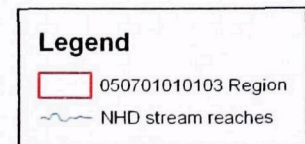
Figure 2. Definition of a subwatershed region for 12-digit HUC 050701010103 through aggregation of 05 additional upstream HUCs.
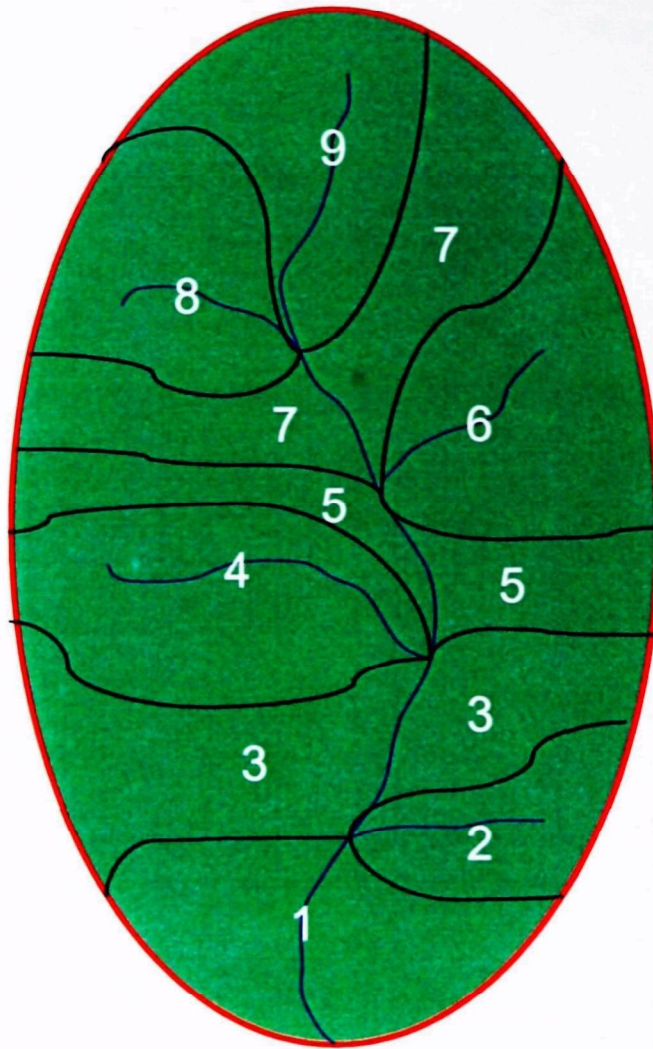
Figure 3. Generic example of Pfafstetter coding for an 8-digit HUC (red outline). The base of the main channel is coded as "1" while the headwater portion of the main channel is coded as "9". Each of the four largest tributaries (basin HUCs) is assigned an even number between 2 and 8, in ascending sequence from the mouth towards the headwaters. Likewise, each of the segments draining to the mainstem between the tributaries (interbasin HUCs) is assigned an odd number between 3 and 7, in ascending sequence from the mouth to the headwaters. Coding of subdivisions within one of these 9 HUCs would proceed in a similar fashion, with the addition of a second digit to the code.

incorporating watershed classes into a survey design framework: 1) classes can be used as strata in a stratified random design, or 2) classes can be assigned unequal probability weights to influence the distribution of selected watershed units across classes (Detenbeck et al. 2003a). Both options allow a rare but significant watershed class (e.g., one with high associated probability of impact) to be sampled at a higher frequency than would be possible if a simple random survey design were implemented. Monitoring data can then be assessed for classes of watersheds as well as for an entire region, and a series of appropriate management strategies devised.

METHODS

USGS watershed delineation

To define hydrologic thresholds, gaging stations with long-term flow records and derived peak flow statistics were identified from previous studies in the state of West Virginia (Frye and Runner 1970; Runner 1980; Figure 4). Watersheds associated with USGS gaging stations were delineated onscreen in ArcInfo using digital raster graphic (DRG) backdrops (1:24,000) and National Hydrography Dataset (NHD) coverages.

Delineation and coding of hydrologic units for the state of WV

In contrast to manual delineations for USGS gaged watersheds, hydrologic units in West Virginia were delineated through a two or three stage process as part of the development of the Elevation Dataset with National Applications (EDNA, Franken et al. 2001; http://edcnts12.cr.usgs.gov/ned-h/). The EDNA process produces HUC boundaries suitable for inclusion in the National Watershed Boundary Dataset (Figure 5). Delineation tasks were accomplished through an interagency agreement with the USGS EROS Data Center and collaborative efforts of US EPA Region III staff. Stage I of the EDNA process previously had been

9

USGS Gaging Station Watersheds

Legend:
- Gaging Station Points
- Gaging Station Watersheds

Level III Ecoregions
Name
- Western Allegheny Plateau
- Central Appalachians
- Central Appalachian Ridges and Valleys

Kilometers
0 25 50 100

N

Map Projection: Albers Equal Area Conic
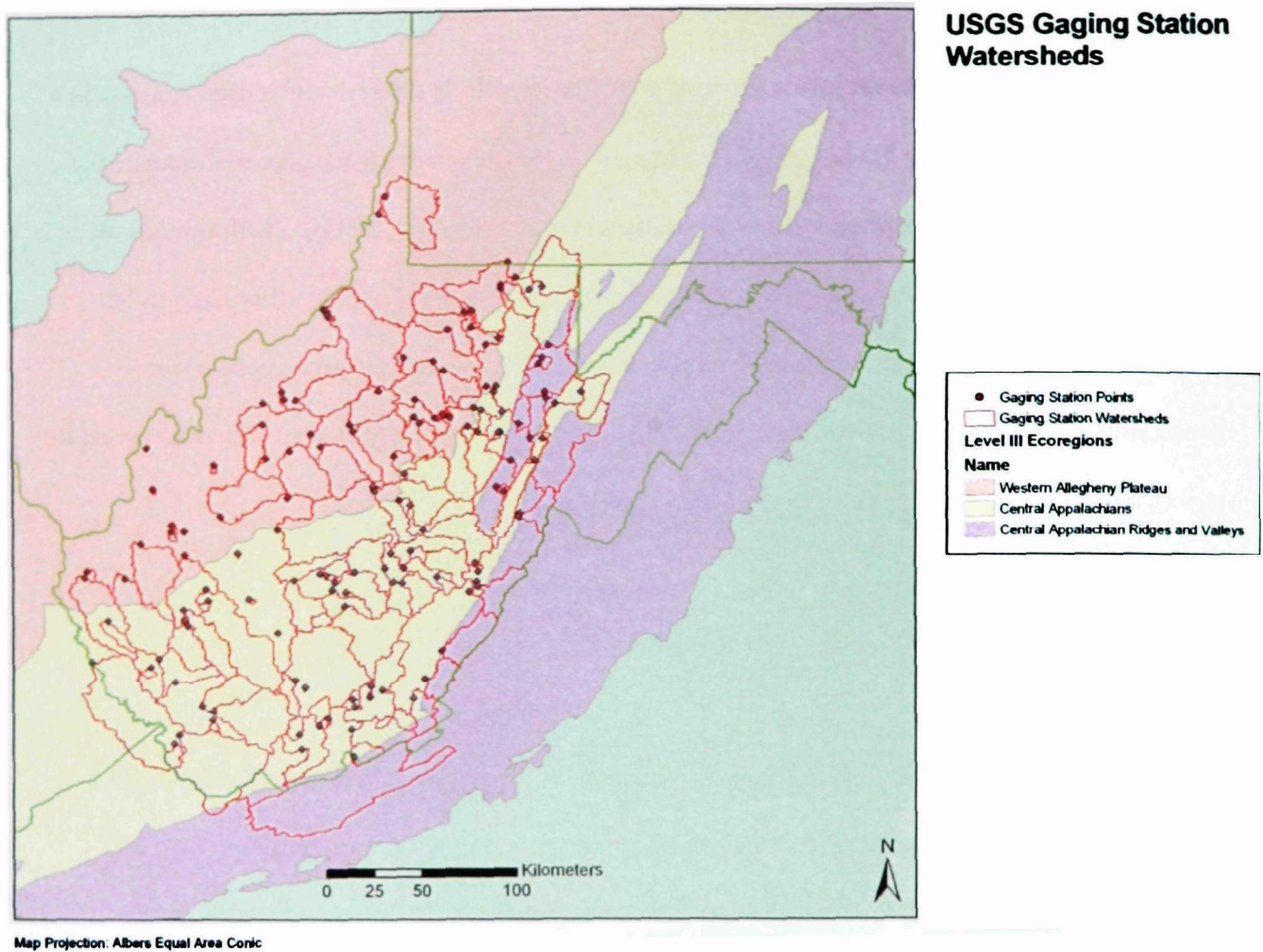
Figure 4. Location of USGS gaging stations and associated watershed boundaries used for derivation of hydrologic thresholds in West Virginia.
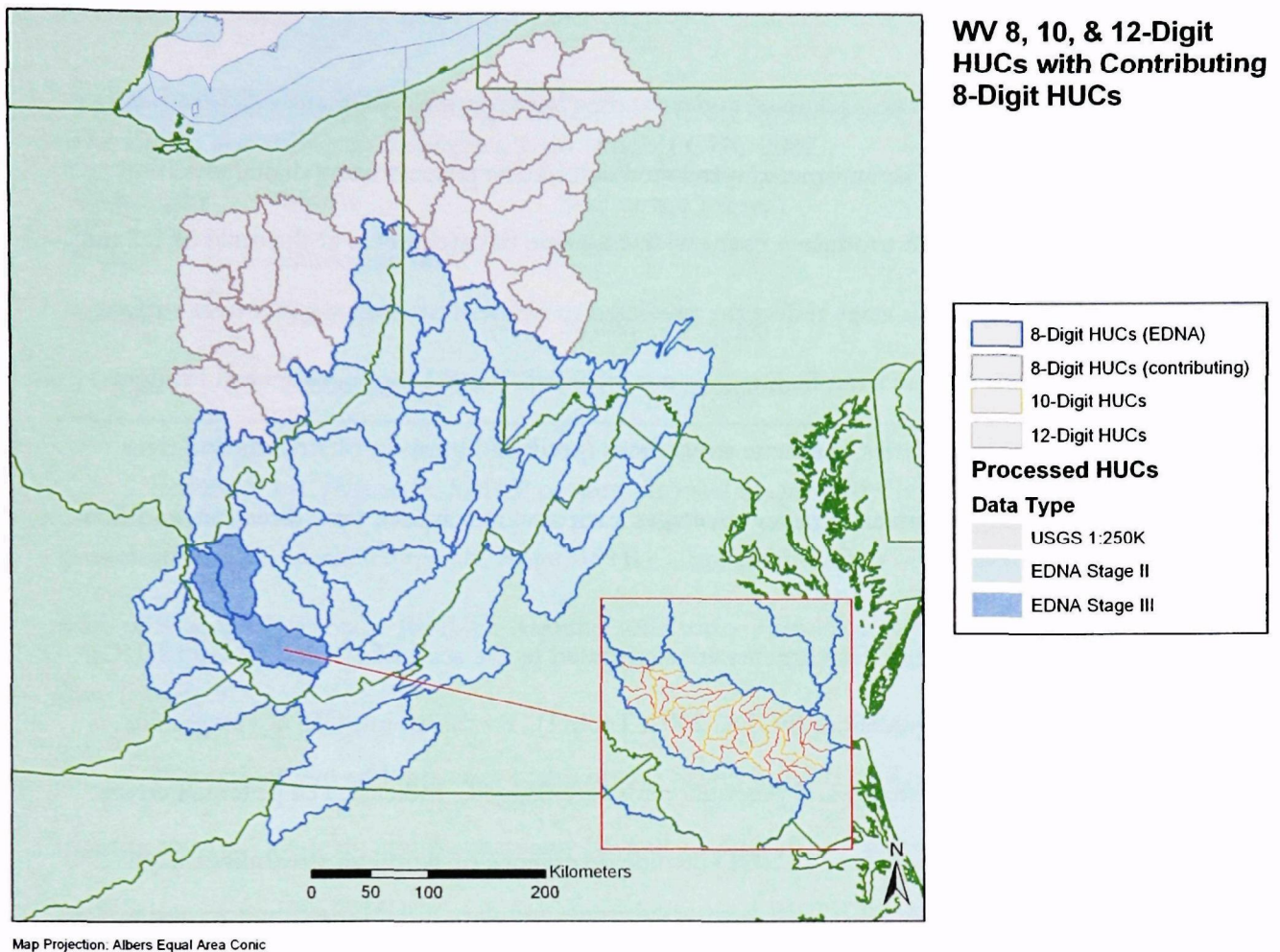
Figure 5. Map of 8-digit hydrologic catologing units (HUCs), 10-digit watersheds, and 12-digit subwatershed units produced for West Virginia. Stage III 12-digit HUCs are shown only for three of the 13 8-digit HUCs completed as of June 2003, i.e., those three 8-digit HUCs requiring additional processing beyond Stage II to correct flow directionality.

accomplished through a memorandum of understanding between the USGS and US Weather Service. Stage I consists of an automated watershed delineation process using digital elevation models (DEMs) with GIS to produce a nationwide coverage of catchments at the scale of 1-2 mil^2. Catchments produced at this stage reflect the predicted movement of surface water over surface topography; elements such as karst features are not included. Stage I produces several products, including catchment boundaries, synthetic streamlines (predicted location of streams and river courses), and elevational derivative raster coverages such as slope, aspect, flow direction, and flow accumulation.

During Stage II, Stage I catchments are aggregated to the scale of 10- and 12-digit HUCs, based on a set of national guidelines (FGDC 2002; Table 1). At this point, GIS coverages are evaluated for internal consistency and potential errors are flagged. Indicators of potential errors either in digital elevation models or in NHD include divergence of synthetic streamlines from mapped NHD streams and inconsistencies between HUC boundaries and other sources of mapped watershed boundaries. During Stage III, a series of ArcView tools are used to correct small regions of the original digital elevation models near the flagged errors to represent the actual flow of surface water. For example, a highway overpass could be detected as a barrier to flow in an original DEM, when in fact, water can freely flow underneath the underpass. Creating a small "notch" in the original DEM at that neighborhood allows the stream course to be correctly predicted. After the hydrologically-corrected DEMs have been created, boundaries for 10- and 12-digit HUCs are regenerated, as are raster coverages for other hydrologic derivatives.

Table 1. Guidelines for hydrologic unit subdivision for National Watershed Boundary Database, according to interagency protocol (FGDC 2002).

Unit digits	Name	Size range (acres)	Subdivisions/unit
8-digit	cataloging unit		5 - 15
10-digit	watershed	40,000 to 250,000	5 - 15
12-digit	subwatershed	10,000 to 40,000	

For the West Virginia R-EMAP project, we used Stage II HUCs to develop the watershed classification framework. Currently, Stage III HUCs are only partially completed for the state, and were only used where Stage II HUCs required substantive correction, e.g., to correct direction of flow (Figure 5).

The assignment of Pfafstetter codes during Stages I and II of the process allows ready identification of upstream and downstream 10- and 12-digit HUCs within 8-digit HUCs, and thus aggregation of interbasin HUCs to define watersheds using REGION processes in ArcInfo. Definition of ArcInfo regions is desirable considering the nested nature of watersheds. Regions are model areal geographic features described by one or more polygons. Regions are efficient ways to model nested or overlapping data because of the concept of shared geometry. For example, one polygon feature can belong to multiple regions without the topology being duplicated. Two files store the region-arc relationship and the region-polygon relationship "behind the scenes." Regions are stored as subclasses within a polygon coverage and each region subclass has its own separate attribute table.

The bulk of the work was completed using individual Arc Macro Language (AML) scripts developed for each component of the characterization process. The scripts were used to create and combine region subclasses into an integrated coverage for further geoprocessing using the

REGIONQUERY command in ArcInfo (ESRI, Redlands CA). The REGIONQUERY command mimics traditional overlay commands on region subclasses in an integrated coverage. So, for example, if a single coverage had a 12-digit watershed subclass and a wetland subclass, the REGIONQUERY command could be used to create a new subclass computed from the geometric intersection of the two subclasses (watersheds and wetlands). The region tables keep track of which wetland polygons belong to each watershed polygon while only physically representing the polygons once. One table could then be created that summarized wetland type by area for each watershed region.

Due to the size of input datasets and software/hardware limitations, 8-digit HUCs containing 12-digit watersheds were processed individually. This presented an issue when a 12-digit watershed required additional upstream 8-digit HUC(s) to be considered a true watershed. A method was needed to identify these "interbasin" watersheds and combine the output for their required counterparts. Each interbasin watershed was given a special identifier code in the watershed region attribute table. A table was made listing all possible interbasin codes and the 12-digit watersheds needed to complete the full watershed. This table was imported into a Microsoft Access database. The individual output tables for 12-digit watersheds within an 8-digit HUC were combined into one table for each characterization process and imported into the same database. A series of queries were performed to combine the individual output values to determine the total output values for interbasin watersheds for each characterization process.

Watershed characterization

Watershed regions associated with all 12-digit HUCs in the state of West Virginia and long-term gaging stations were characterized for attributes expected to be related to generation of peak flows (Frye and Runner 1970; Runner 1980): watershed area, main channel length, main channel

14

slope, watershed storage, mean January minimum temperature, snowpack, and percent forest cover. In addition, watersheds were characterized for other major land-use and land-cover characteristics related to generation of runoff and nonpoint source pollution: percent mined land, percent impervious surface area, and percent agriculture. GIS databases used to calculate watershed characteristics are described in Table 2.

Table 2. Geographic information system databases used to characterize West Virginia watersheds. EDNA = Elevation Dataset with National Applications, NHD = National Hydrography Database, NWI = National Wetlands Inventory, OWI = Ohio Wetlands Inventory, NYWI = New York Wetlands Inventory, PRISM = Parameter-elevation Regressions on Independent Slopes Model.

Database	Layers and attributes	Derived variables	Last update	Scale	Source
EDNA	10-digit watershed boundaries	sample units	2003	1:24,000	USGS EROS Data Center
	12-digit watershed boundaries	watershed boundaries		(30 m grid)	
	Pfafstetter codes	watershed areas			
	elevation grids	upstream connections			
		main channel slope			
NHD	stream reaches	main channel slope	1999	1:100,000	USGS
	stream level	upstream connections			
NLCD-mining modified	land-use, with updates for surface mining	percent land-cover	2001	1:24,000 (30 m grid)	NLCD - EPA surface mining grid - Tennessee Valley Authority Thru: US EPA Region 3, Wheeling, WV
NWI	palustrine wetland polygons	percent wetland + lake area	1981 to present	1:24,000	US FWS, WV DEP composite coverage
	lacustrine polygons				
OWI	wetland and open water types by grid cell	percent wetland + lake area	based on 1985-1987 TM scenes	1:24,000	Ohio Department of Natural Resources
PRISM	monthly snowfall	snowfall	1998, based on 1961-1990 climate data,	1:250,000	Climate Data Source, Corvallis, OR
	annual precipitation	mean annual precipitation			
	minimum January temperature	mean minimum January temperature			

The PRISM (Parameter-elevation Regressions on Independent Slopes Model; Climate

Source, Corvallis, OR) GIS coverage was used to generate climatic summaries across watersheds.

PRISM is a continuous grid (raster coverage) of climatic variables generated from weather station

data and regional nonlinear regressions that take into account regional precipitation averages as well

as orographic effects associated with altitude, and proximity/influence of large surface water bodies

(Daly et al. 1994).

We used National Wetlands Inventory (NWI) coverages, supplemented by the Ohio

Wetlands Inventory coverages to define watershed storage. Total areal coverage of palustrine and

lacustrine polygons was added and divided by watershed area. For the Ohio Wetlands Inventory

coverage, polygons coded as 34 to 38 (wetland and open water classes) were included. For the New

York Wetlands Inventory, cover classes 1-4 and 9 were included (all classified or unclassified

wetland polygons).

Fraction impervious surface area was derived as a function of land-use intensity as:

fimperv = (0.55*flwintrs)+(0.90*fhintres)+fcomind,

    where fimperv = fraction impervious area in watershed,

        flwintrs = fraction low intensity residential area in watershed,

        fhintres = fraction high intensity residential area in watershed, and

        fcomind = fraction commercial, industrial, and transportation land-use area in

        watershed.

based on median of estimated constructed materials associated with different land-use classes in

NLCD (http://www.epa.gov/mrlc/definitions.html). These weightings are higher than those

reported for northern Virginia (NVPDC 1980), because the latter included only effective impervious surface area (unconnected rooftops were not included), but are consistent with classification guidelines for NLCD.

Main channel slope was defined first by selecting main channel reaches from the NHD coverage based on the minimum value for the reach LEVEL attribute within a watershed. Main channel reaches were buffered by 30 meters, and this buffer was used to clip a subset of elevation grids from the DEM coverages. Frequency analyses were used to estimate the 10th and 85th percentile of elevation values from the stream elevation buffer files; combined with main channel length, these could be used to calculate main channel slope (Figure 6).

*Creation of sample frame and sample design for 12-digit HUCs*

Although we developed the classification framework for the entire state of West Virginia, in practice, we restricted membership in the sample frame for the 2001-03 WV R-EMAP project. Sample frames were defined based on drainage basin, ecoregion, and 12-digit HUC watershed region size (Table 3). The Potomac River basin was excluded from study because of species differences related to biogeography, and because the fish IBIs developed for adjacent regions in Maryland should be adequate for the state of WV to apply in that basin (Figure 7). In practice, we also excluded watersheds with ill-defined drainage networks related to karst topography (e.g., no single outlet, underground streams). Selection of 12-digit HUCs from within the sample frame each year was based on a random-stratified design. Strata were based on watershed classes defined by hydrologic thresholds and land-use intensity. After defining 12-digit HUCs as single independent watersheds (basin HUCs) or groups of hydrologically adjacent (dependent) interbasin units,
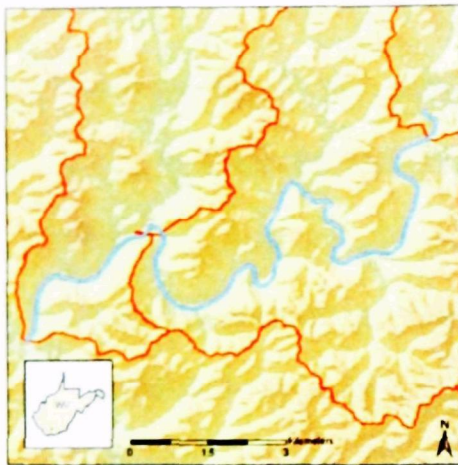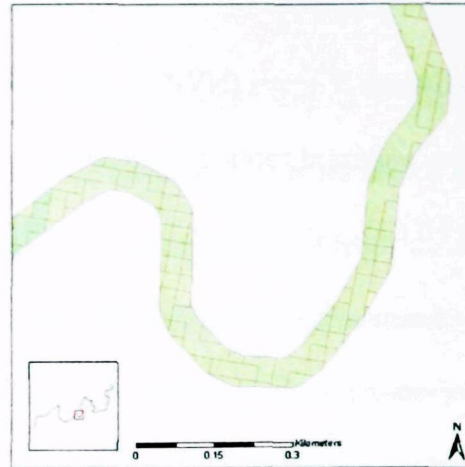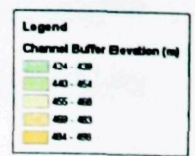
Derivation of main channel slope
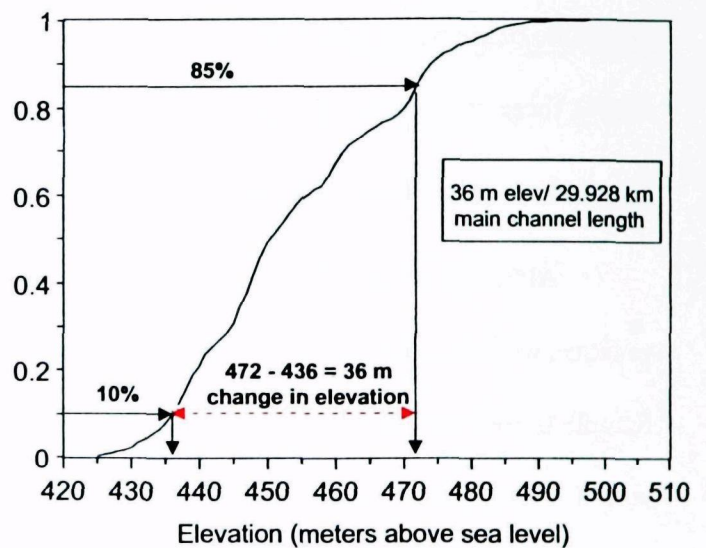
Figure 6. Automated derivation of main channel slope. The main channel is identified based on finding stream reaches with the minimum "LEVEL" attribute in NHD (top left), then is buffered and intersected with a digital elevation model (top right). A frequency analysis of output elevation grid cells yields estimates of the 10th and 85th percentiles. Combined with main channel length, these can be used to calculate main channel slope.
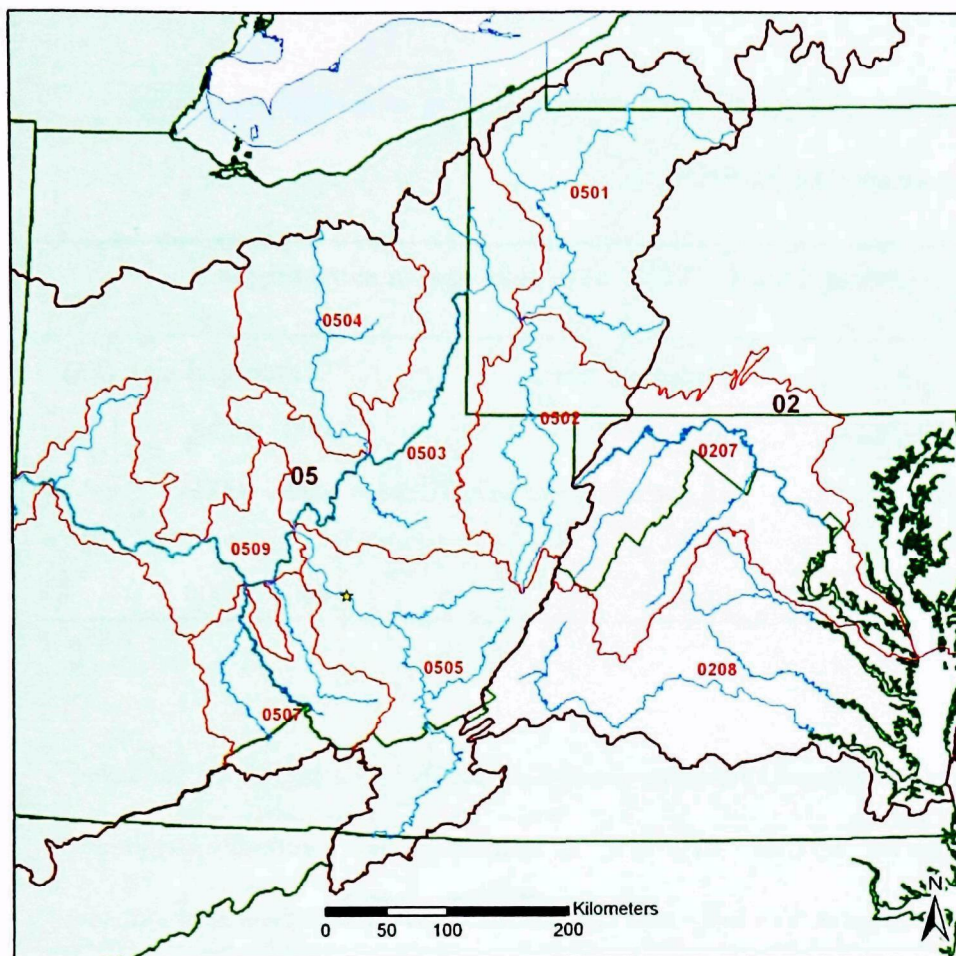
Major Drainage Basins

☐	2-Digit HUCs
☐	4-Digit HUCs

HUC_02	REGION NAME
02	Mid Atlantic Region
05	Ohio Region
HUC_04	**SUBREGION NAME**
0207	Potomac
0208	Lower Chesapeake
0501	Allegheny
0502	Monongahela
0503	Upper Ohio
0504	Muskingum
0505	Kanawha
0507	Big Sandy-Guyandotte
0509	Middle Ohio

Map Projection: Albers Equal Area Conic

Figure 7. Major drainage basins associated with the state of West Virginia and surrounding states, as defined by 2- and 4-digit HUCs.

19

unequal probability-weighting was used to limit the chance of selecting subwatersheds directly

upstream or downstream of one another (Figure 8).

Table 3. Definition of sample frame for R-EMAP wadeable stream sampling in West Virginia, 2000-2001.

Year	Ecoregion(s)	Drainage basin	Watershed size (ha)
2000	Central Appalachian Plateau	inclusive	400 - 40000
2000	Central Ridge and Valley Ecoregion	all excluding Potomac River basin	400 - 40000
2001	Western Allegheny Plateau	inclusive	400 - 40000

Response threshold derivation

We carried out analyses and applied sampling designs separately by ecoregion for studies in

2000 and 2001 (Table 3, Figure 9). To define hydrologic thresholds related to natural watershed

attributes, we identified gaging stations with long-term flow records and derived peak flow statistics

from previous studies in the state of West Virginia (Frye and Runner 1970; Runner 1980; Figure 4).

We delineated watersheds for each gaging station and characterized these watersheds based on

attributes recorded in Frye and Runner (1970) and Runner (1980). We updated watershed storage

estimates from Frye and Runner's values using GIS analysis of National Wetlands Inventory

coverages and calculation of fraction watershed area covered by palustrine and lacustrine systems.

In earlier analyses conducted before GIS was widely available, Frye and Runner calculated watershed

storage by overlaying a point grid on USGS topographic quadrangles and counting intersections

with wetlands, lakes, and ponds. With a rare aquatic resource such as wetlands occurring in West

Virginia or other regions with well-developed drainage systems, the accuracy of such methods is

limited by the temporal accuracy of maps, the density of grid points used, and number of grid
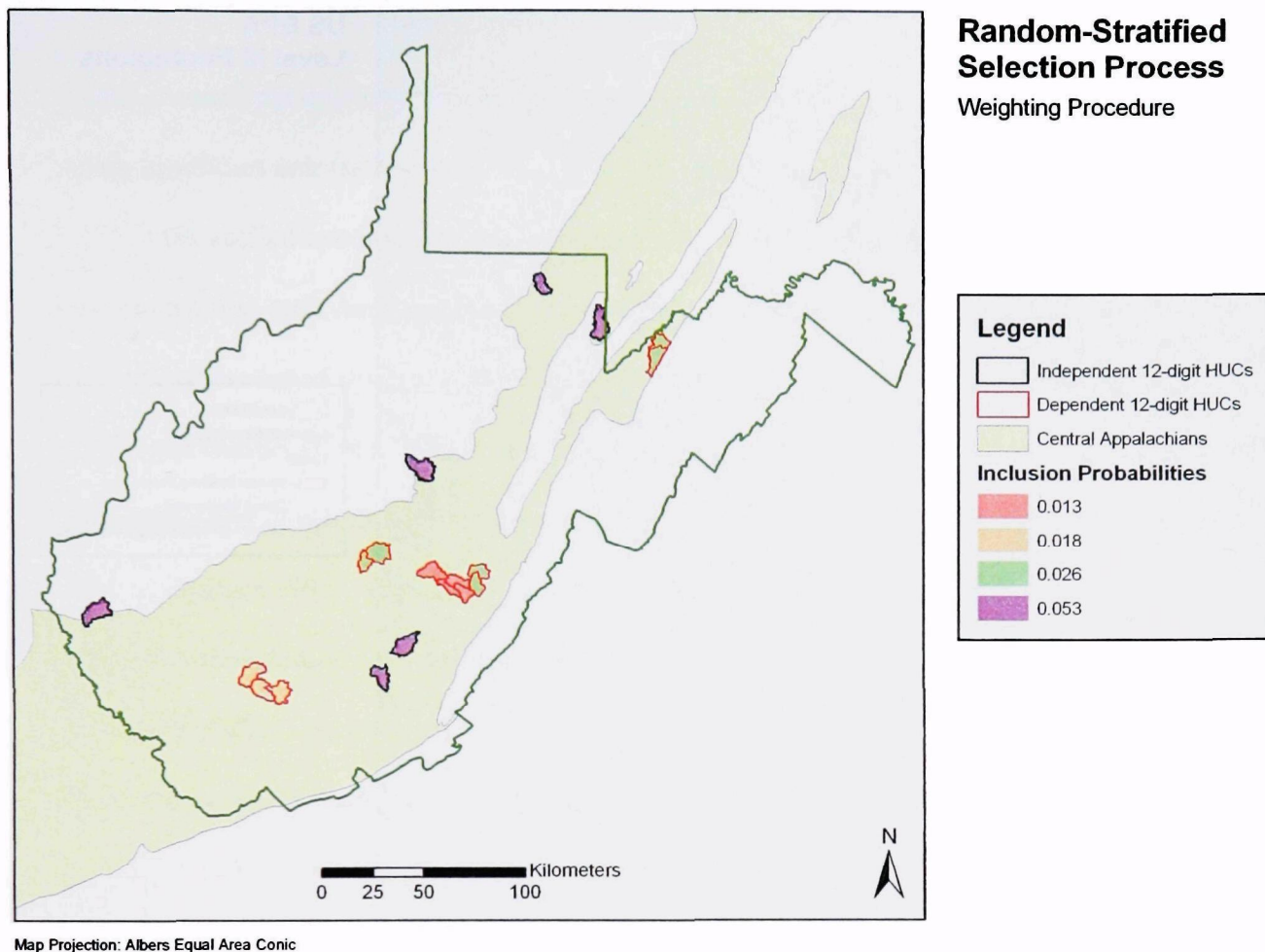
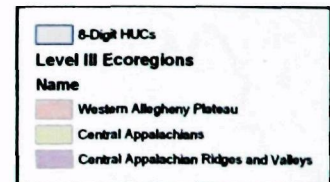**Figure 8.** Example of unequal weighting of interbasin HUCs for one watershed class in the Central Appalachian Plateau ecoregion of West Virginia.
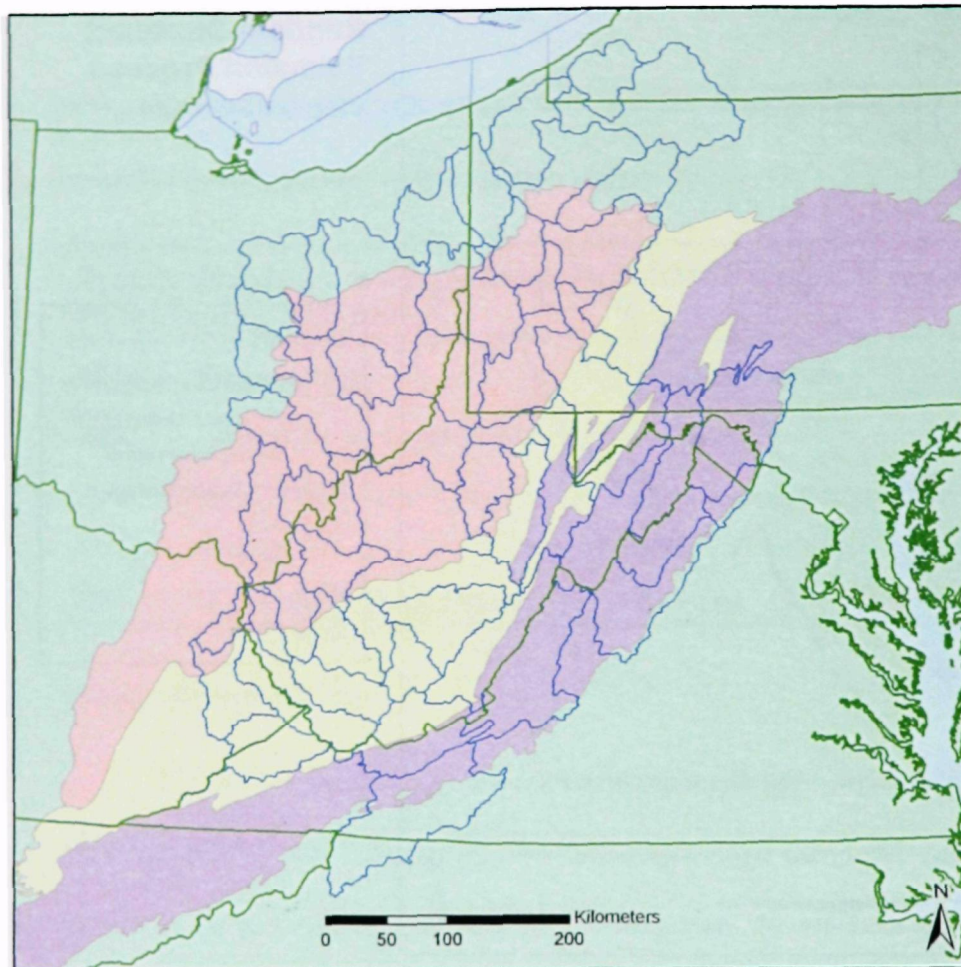
Figure 9. Map of ecoregions overlapping with West Virginia watersheds.

points counted per unit area. For West Virginia, percent coverage had only been recorded to a single significant unit (as 0 or 1).

We applied two different methods to identify hydrologic thresholds, i.e., regions in plots of area-normalized peak discharge (e.g., Q2/watershed area) showing nonlinear discrete shifts along a gradient of watershed attributes. We obtained values for 2-year peak flows from Frye and Runner (1970) and Runner (1980). We chose a recurrence interval of two years as an endpoint because this is the frequency of flooding associated with development of channel morphology and sediment delivery (Rosgen 1996). Our first method, applied in 2000, involved screening potential parameters of interest identified by Frye and Runner (1970; see Table 4) using linear regression analysis of log-transformed Q2/area, with observations weighted by period of record to account for differences in level of uncertainty (Tasker and Stedinger 1989). We chose the best number and combination of predictive variables using Mallow's Cp statistic (SAS 1990). We identified thresholds through visual graphical analysis, by plotting (nontransformed) Q2/area as a function of single variables or combinations of variables and observing where nonlinearities in relationships were observed.

In 2001, we applied a second technique, based on classification and regression tree (CART) analysis of potential variables in SYSTAT (Wilkinson 1999). Nonlinear regression analysis followed by visual analysis of graphic bi-plots was less successful in 2001 because of collinearities in independent variables. CART is a nonparametric technique that sequentially bisects observations into subpopulations based on a single response variable, and identifies dependent variables associated with breaks in the distribution. In this way, CART is able to identify nonlinearities in relationships, as well as interactions among predictor variables, based on a minimum set of assumptions (Wilkinson 1999).

Table 4. Potential watershed characteristics related to peak flows, Frye and Runner (1970).

| Code	Definition	Units
A	watershed area	mil^2
S	channel slope	feet mil^{-1}
St	storage (area in lakes and ponds +1)	%
F	forest area	%
L	main channel length	miles
E	mean basin elevation	feet above sea level
S_n	snowfall index	inches
P	average annual precipitation - 20	inches
$I_{24,2}$	precipitation intensity/24 hours, 2-year recurrence interval	inches
S_i	soil infiltration index	
T_1	average minimum January temperature	deg F

We identified potential thresholds of response related to land-use change from the literature because insufficient data were available from gaged sites with significant periods of record. We based potential land-use thresholds of response on previous analyses of data from the Maryland Biological Stream Survey (MBSS, Boward et al. 1999). For the MBSS data set, species loss in fish communities had been found at levels of impervious surface area above 2% of watershed area. Nonlinear shifts in water quality were associated with levels of agricultural land-use above 25%. Other studies have shown a change in peak snowmelt associated with loss of mature forest cover greater than 40-60% (Verry 1986). This approach is similar to trying to bracket expected response thresholds in bioassays for suspected toxicants.

Less information is available from the literature to detect thresholds of impact related to mining activity in the Appalachian region. Scott (1984) identified percent disturbed area as the best

predictor of changes in stream hydrology in a subset of mined watersheds of West Virginia, presumably associated with changes in water quality (Scott 1984). However, Scott did not have long hydrologic time series for these watersheds, but instead based his conclusions on modeled results; his analysis showed an apparent threshold at 30% disturbed area. We chose to use a conservative estimate of 10% for the mining threshold, similar to that shown as a threshold for percent impervious surface area in most literature reviews (Schueler 1994), with the knowledge that the magnitude of mining thresholds would have to be refined in the future.

We defined land-use coverage for watersheds associated with 12-digit HUCs by intersecting watershed boundaries with a mining-modified NLCD coverage (Table 2, Figure 10). We defined percent watershed storage by intersecting watershed boundaries with wetland inventory coverages (Figure 11).
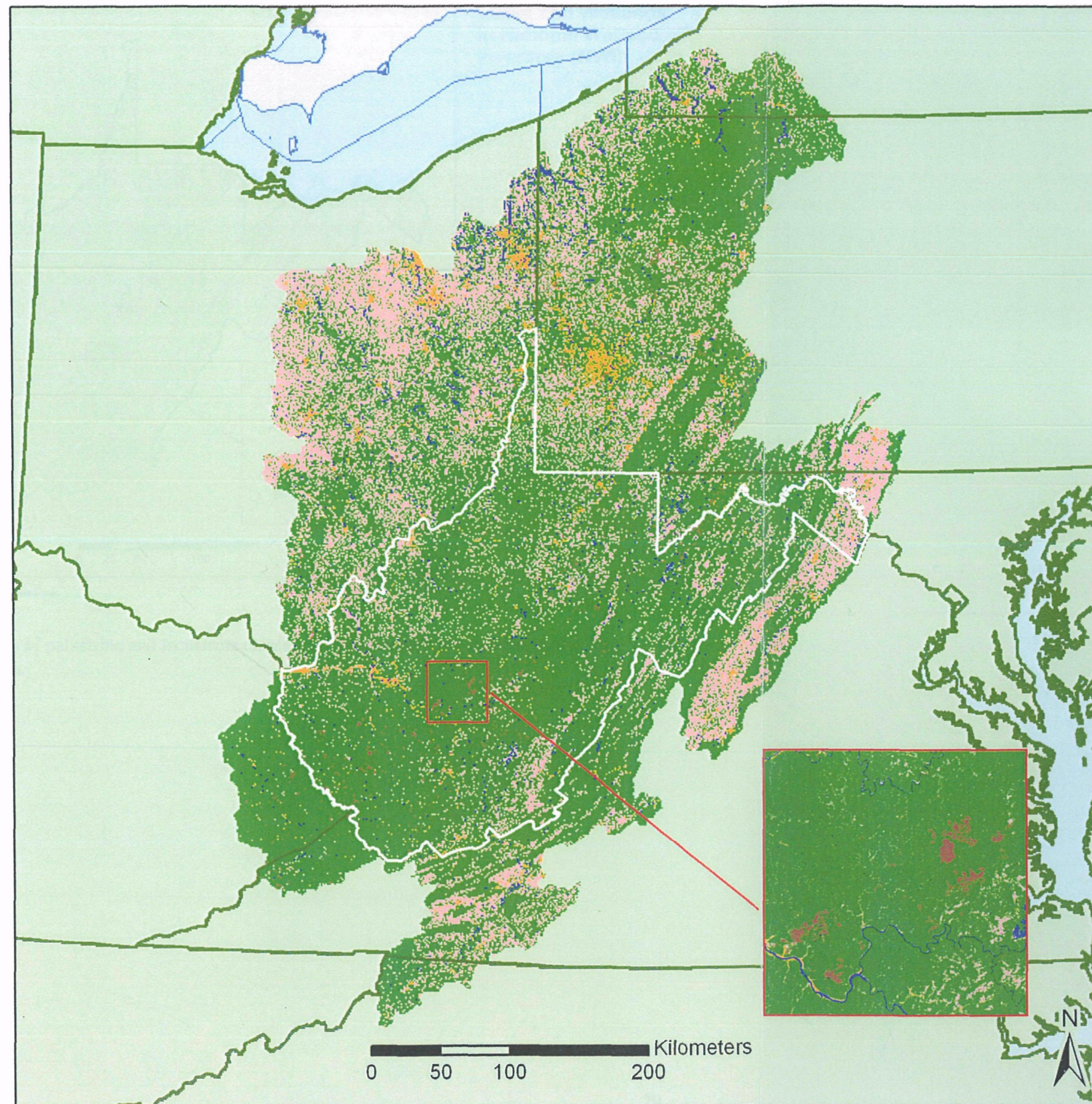
Mining-Modified NLCD Land-Use/Land-Cover

Mining-Modified NLCD Grouped Land-Use Codes
- Mining
- Agriculture/Orchards
- Forest
- Grassland
- Urban/Residential
- Open Water/Wetlands
- Barren

Kilometers
0   50   100   200

Map Projection: Albers Equal Area Conic

Figure 10. Map of land-use covering West Virginia watersheds, based on National Landcover Characterization Database, updated for mining category.
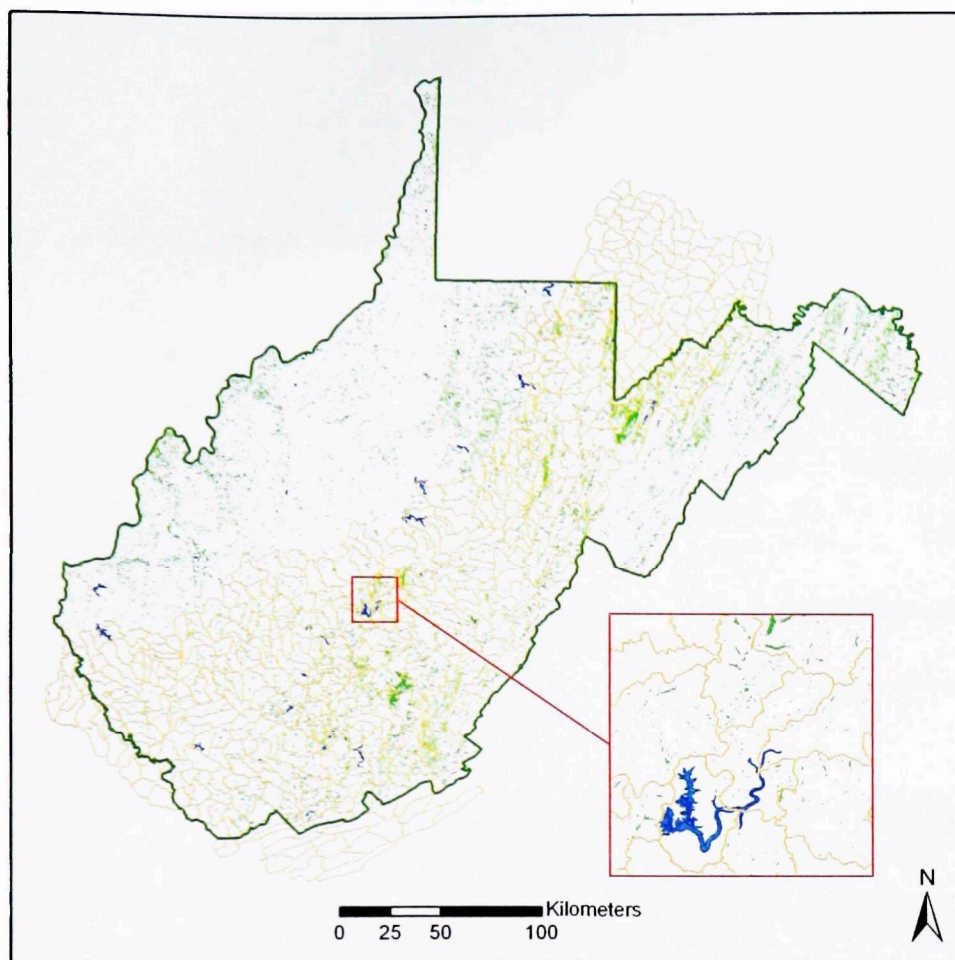
Lakes and Wetlands in National Wetland Inventory (NWI)

Legend
- 12-digit HUCs

NWI SYSTEM
- Lacustrine
- Palustrine

Kilometers
0   25   50   100
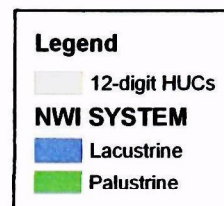
Map Projection: Albers Equal Area Conic

Figure 11. Map of palustrine and lacustrine classes from National Wetlands Inventory for the state of West Virginia.

CLASSIFICATION RESULTS

Hydrology thresholds

In year 2000, the nonlinear equation we derived to describe 2-year peak flows (Q2) for the

Central Appalachian Plateau and Central Ridge and Valley ecoregions, was:

$Q2 = A^a \ P^p \ T^t \ Sn^{sn} \ St^{st}$ (p < 0.05)

where Q2 = 2-year peak flow

    A = watershed area

    P = average annual precipitation

    T = average minimum January temperature

   Sn = snowfall

    St = watershed storage.

Percent forest was not included in the equation for 2-year peak flow, probably because of

a lack of significant variation in percent forest cover in these two ecoregions. When gaging station

data were combined for the full state, percent forest cover was included as a significant predictor

variable in peak flow equations for 5- and 10-year recurrence intervals, but not for 2-year recurrence

intervals. Visual graphical analysis showed that percent forest alone showed no threshold effect on

peak flows normalized to watershed area, but the product of percent forest cover, snowfall, and

minimum January temperature did show a noisy threshold with a lot of scatter. The sharpest

threshold for Q2/A identified based on visual graphical analysis was for percent watershed storage

(Figure 12), with a threshold identified at ~0.5% storage (fraction storage = 0.005).

We identified variables and associated threshold levels for Q2/A for the Western Allegheny

Plateau in 2001 through CART analysis. At each step, the CART procedure sequentially divided

observations into two categories based on the magnitude or category of the predictor variable (in

30
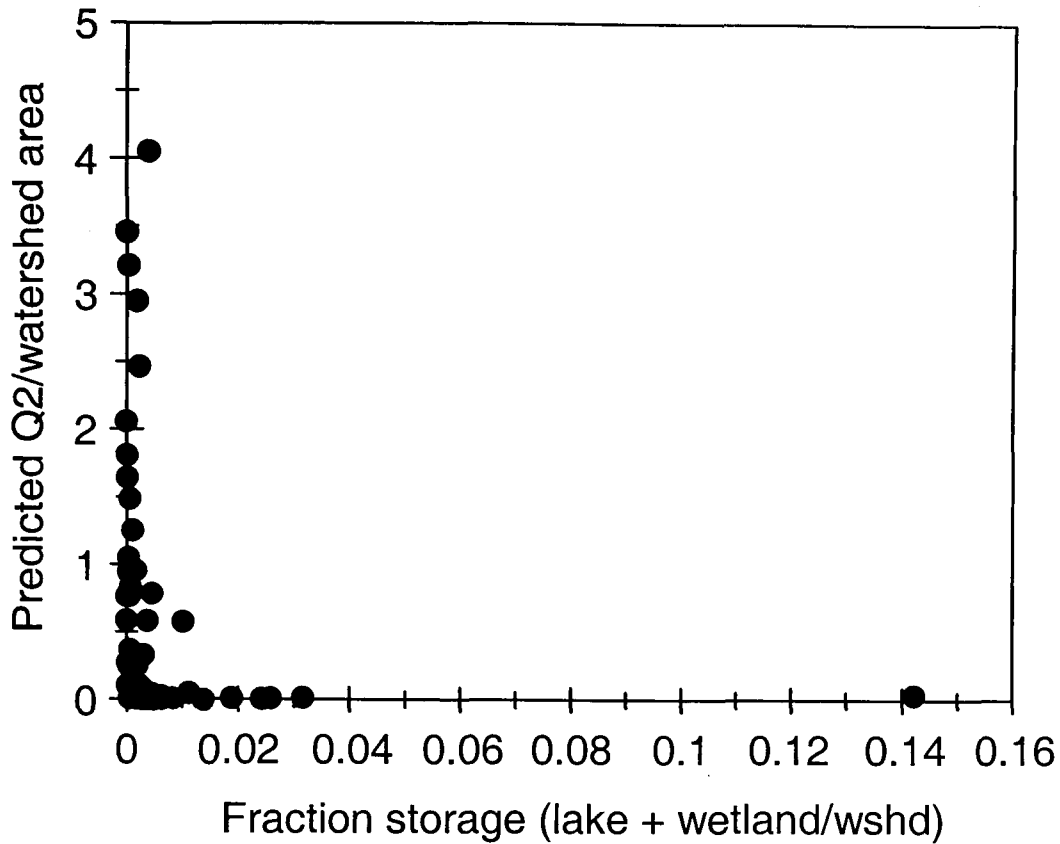
Figure 12. Predicted 2-year flood normalized to watershed area (cfs/mil2) as a function of watershed storage (lake + wetland area/watershed area) for USGS gaging station watersheds in the Central Appalachian Plateau and Central Ridge and Valley ecoregions of West Virginia.

this case fraction storage or main channel length) that best separated the response variable, Q2/watershed area, into low and high magnitude subpopulations. Each box in the output is basically a frequency plot, with each observation represented by a colored dot, and each color representing the final subclass assignment. Separation of the dataset based on combination of two variables accomplished a 67% reduction in total variance (Figure 13). Flashy hydrologic regimes (significantly larger Q2/A) for the Western Allegheny Plateau ecoregion occurred in low storage watersheds (< 0.03% watershed storage) or relatively short drainage basins (main channel length < 13.5 km).

31
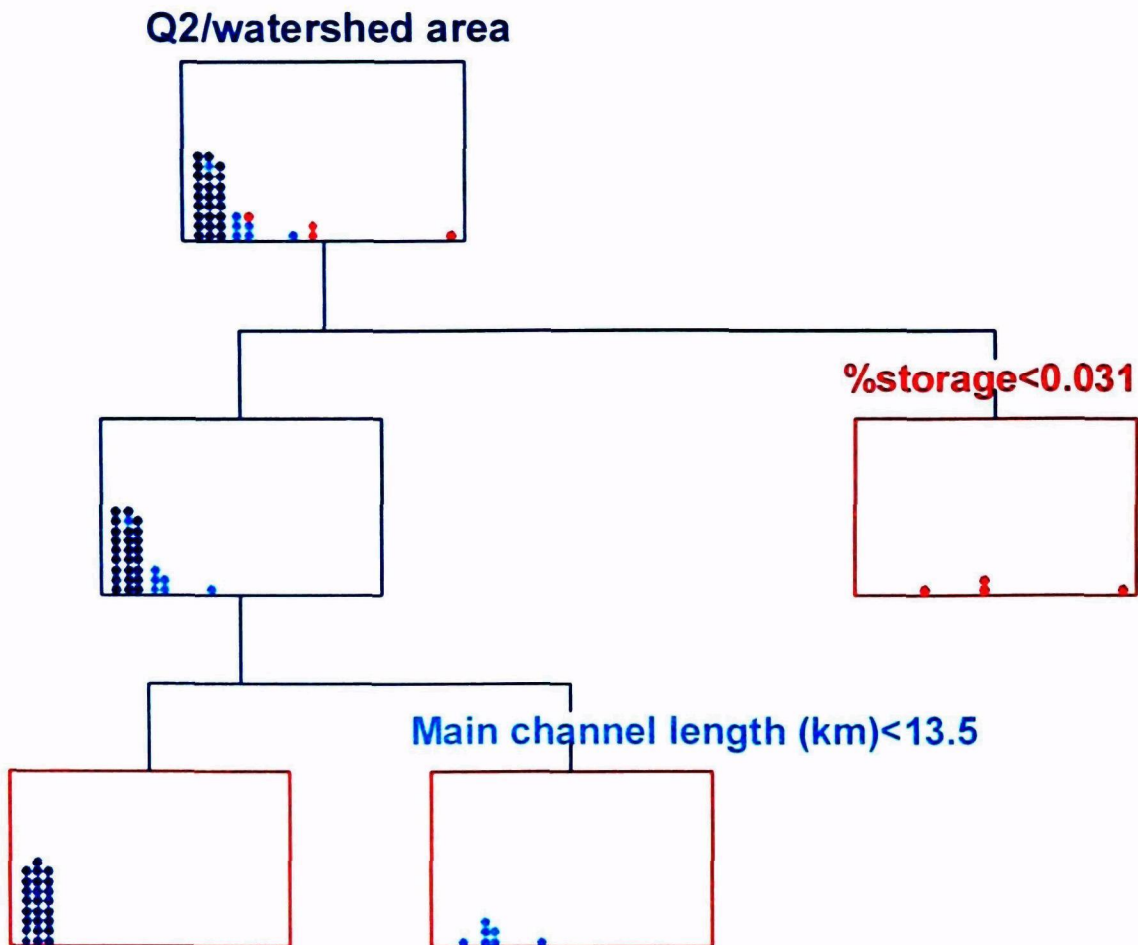
Figure 13. Results of Classification and Regression Tree (CART) analysis of 2-year flood normalized to watershed area (cfs/mil^2) as a function of watershed attributes for USGS gaging station watersheds in Western Allegheny Plateau ecoregion of West Virginia (percent reduction in error = 67 %). At each step, the CART procedure sequentially divided observations into two categories based on the magnitude or category of a predictor variable (in this case fraction storage or main channel length) that best separated the response variable, Q2/watershed area, into low and high magnitude subpopulations. Each box represents a frequency plot, with each observation represented by a colored dot, and each color representing the final subclass assignment.

Distribution of land-use/land-cover variables across 12-digit subwatersheds in West Virginia
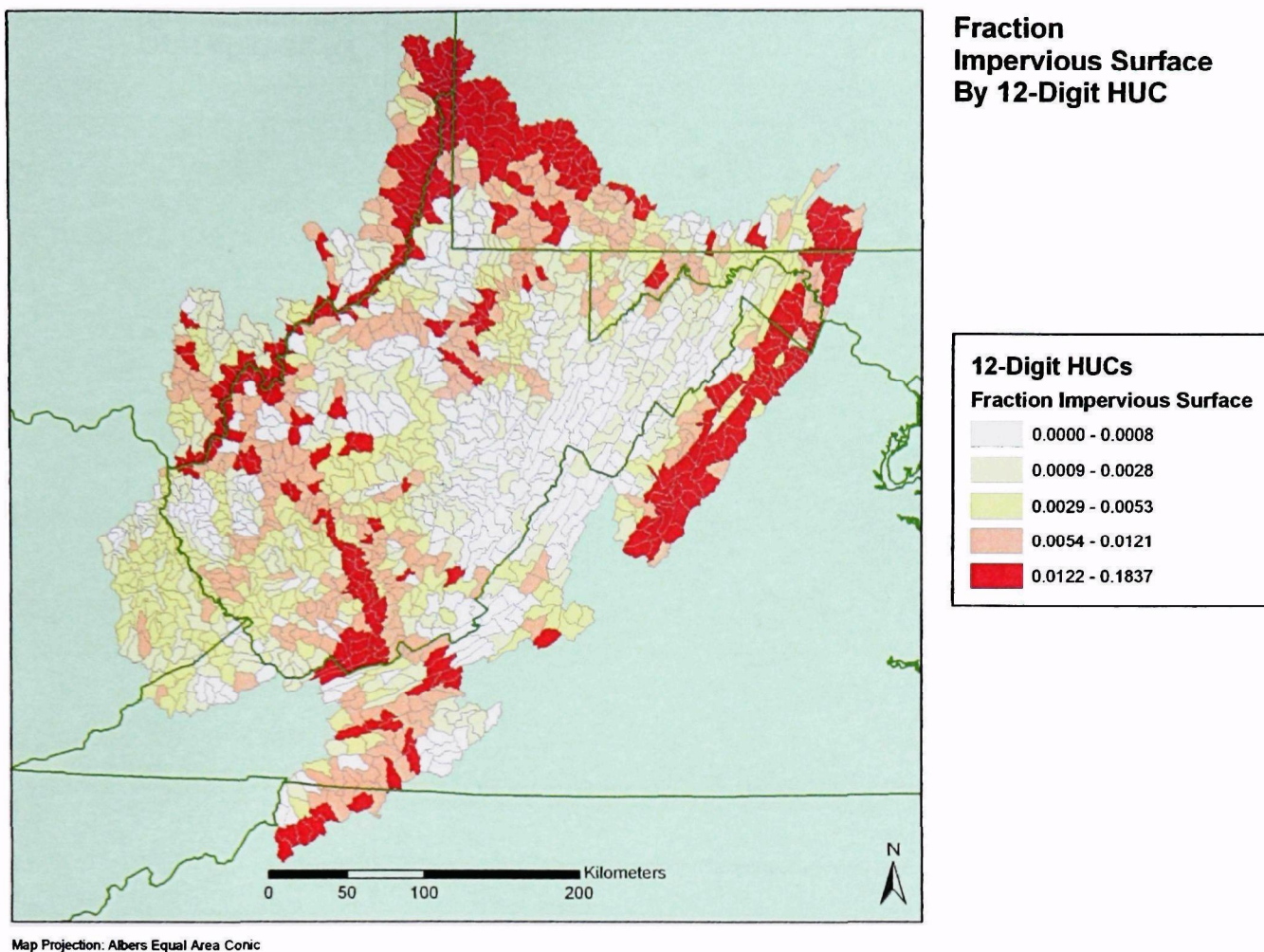
Overall, the level of watershed storage in West Virginia is very low. For all watersheds associated with 12-digit HUCs in the 8-digit HUCs characterized (those within or overlapping with WV state borders), the top 20th percentile of HUCs had a range of 0.8 to 18.6% watershed storage (Figure 14). Most 12-digit HUCs in the top 20th percentile were actually located near the border or even outside of WV state boundaries, in the headwaters of the Upper and Middle Ohio River basins. Nonetheless storage thresholds associated with a marked change in hydrologic regime were low enough so that both high and low storage classes could be identified within each set of ecoregions (Figure 14).

The range of percent impervious surface area in watersheds associated with the 12-digit HUCs characterized is also relatively low (0-18.4 %), with the top 20th percentile covering a range of only 1.2 - 18.4 %. The spatial distribution of the top 20th percentile of percent impervious surface area is similar to that of the top 20th percentile of watershed storage, paralleling development along road or river corridors, and probably the creation of reservoirs (Figure 15). As for urban development, the highest concentration of agriculture within West Virginia drainage basins (top 20th percentile = 48-83 %) occurs outside of the state boundaries in the Upper Ohio or Potomac drainages (Figure 16). In contrast, the highest concentration of mining activity (top 20th percentile = 1.4-16.4% watershed area) occurs within the Central Appalachian Plateau, in the southwestern portion of the state (Figure 17). Forest cover across the state is relatively high and constant; most instate HUCs are in the top 40th percentile of HUCs characterized (79 - 100 % forest cover; Figure 18.)

**Fraction
Watershed Storage
By 12-Digit HUC**

12-Digit HUCs
FractionStorage

	0.0000 - 0.0010
	0.0011 - 0.0023
	0.0024 - 0.0042
	0.0043 - 0.0082
	0.0083 - 0.1860

Map Projection Albers Equal Area Conic
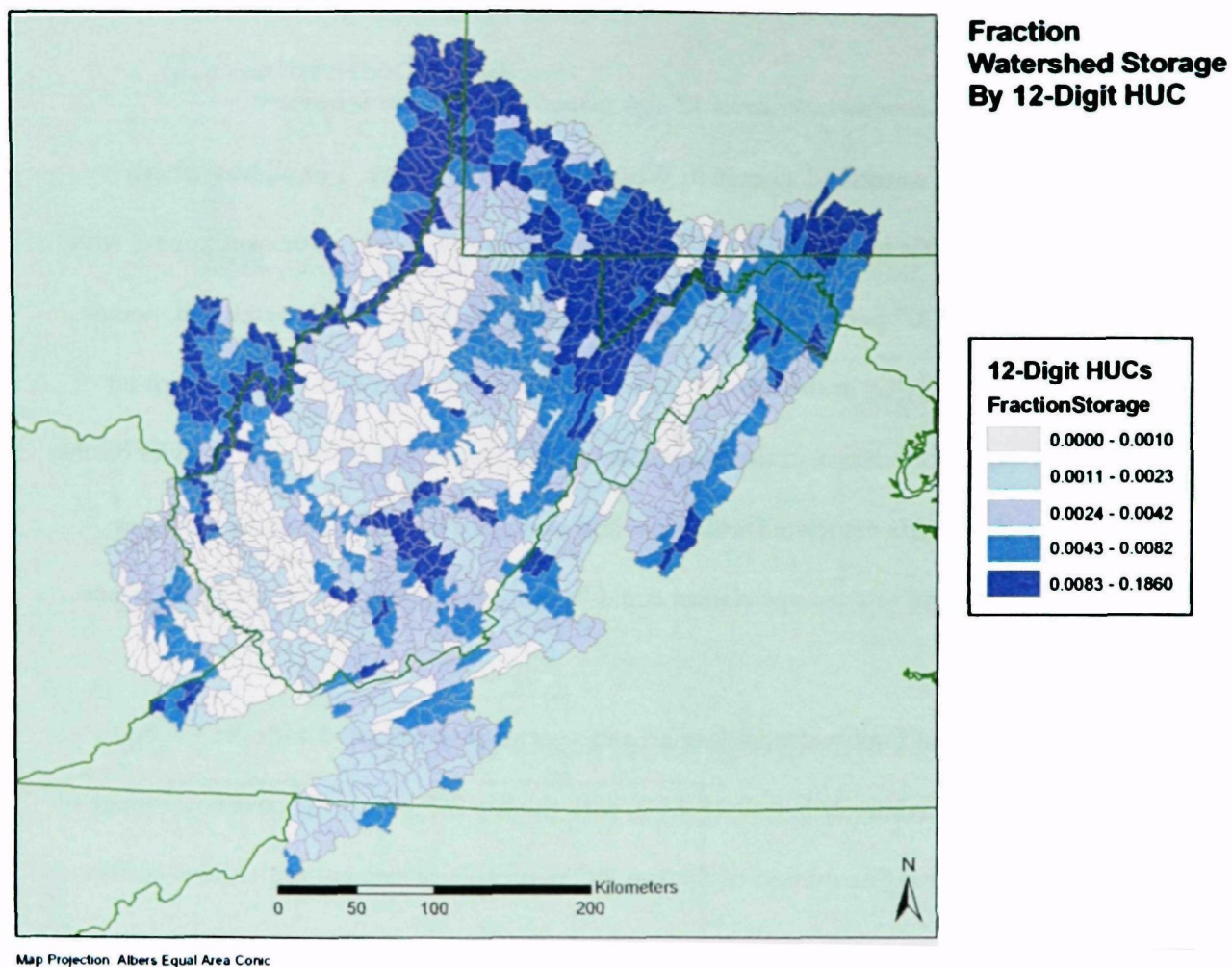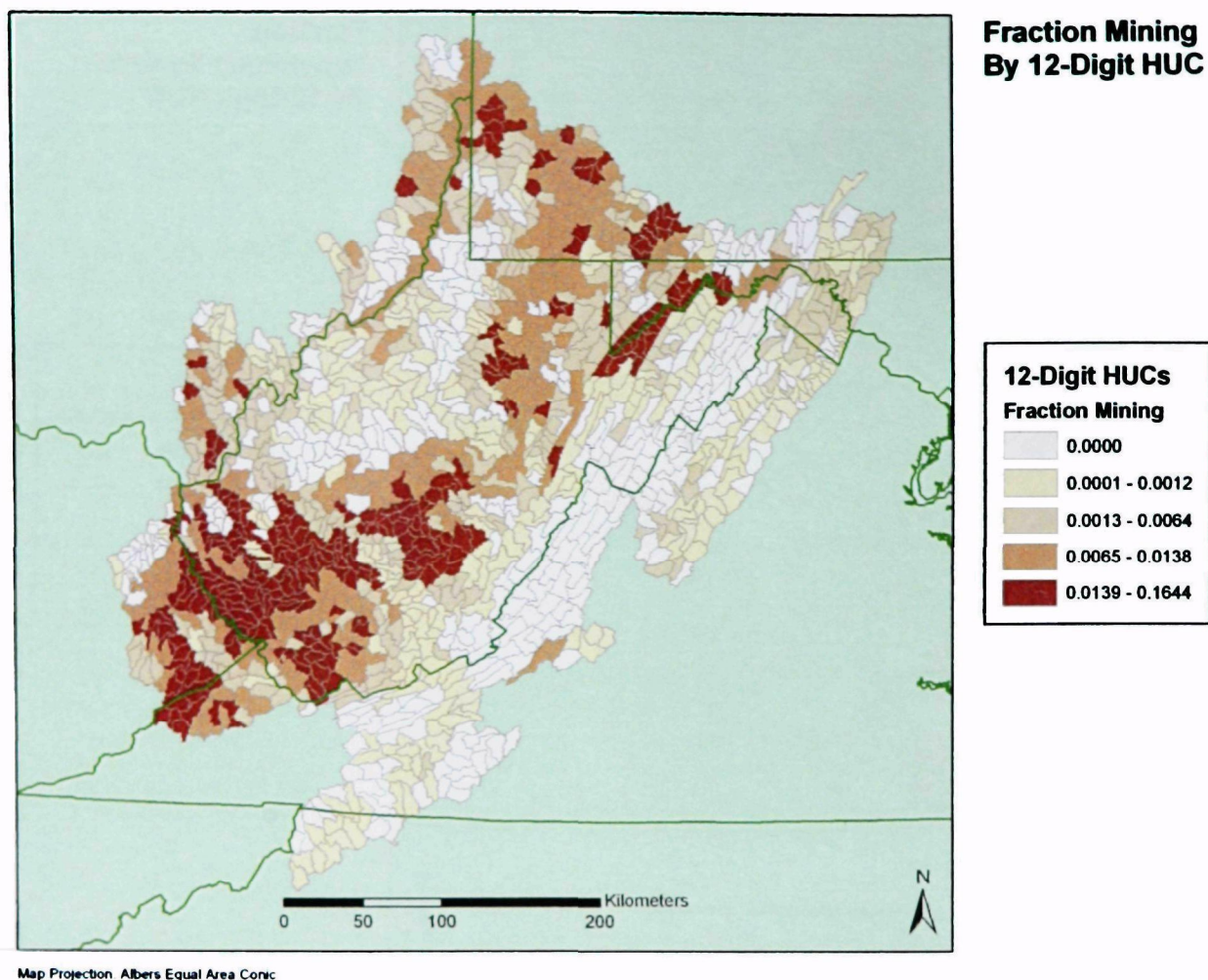
Figure 14. Map of 12-digit HUCs within 8-digit HUCs overlapping with West Virginia, coded by fraction watershed storage ([lake + wetland area/watershed area] x 100). Classes mapped are not equal interval classes, but represent population quintiles.

Fraction Impervious Surface By 12-Digit HUC

12-Digit HUCs
Fraction Impervious Surface
- 0.0000 - 0.0008
- 0.0009 - 0.0028
- 0.0029 - 0.0053
- 0.0054 - 0.0121
- 0.0122 - 0.1837

Kilometers
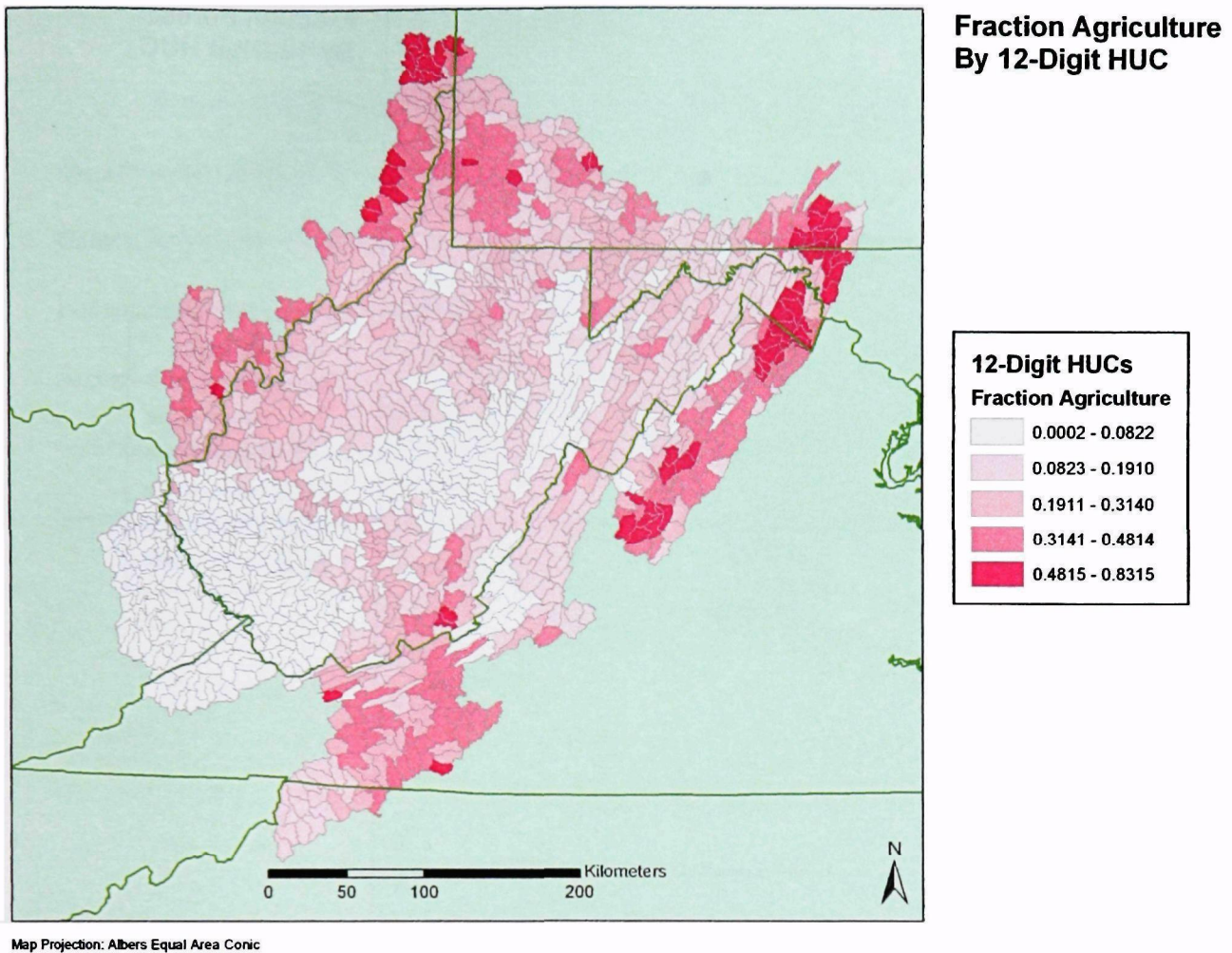0   50   100   200

N

Map Projection: Albers Equal Area Conic

Figure 15. Map of 12-digit HUCs within 8-digit HUCs overlapping with West Virginia, coded by estimated fraction impervious surface area in associated watersheds. Classes mapped are not equal interval classes, but represent population quintiles.

**Fraction Mining
By 12-Digit HUC**

**12-Digit HUCs
Fraction Mining**

	0.0000
	0.0001 - 0.0012
	0.0013 - 0.0064
	0.0065 - 0.0138
	0.0139 - 0.1644

Kilometers

0   50   100   200

N

Map Projection Albers Equal Area Conic

Figure 16. Map of 12-digit HUCs within 8-digit HUCs overlapping with West Virginia, coded by estimated fraction surface mining area in associated watersheds. Classes mapped are not equal interval classes, but represent population quintiles.

Fraction Agriculture By 12-Digit HUC

12-Digit HUCs
Fraction Agriculture
0.0002 - 0.0822
0.0823 - 0.1910
0.1911 - 0.3140
0.3141 - 0.4814
0.4815 - 0.8315

Map Projection: Albers Equal Area Conic

Figure 17. Map of 12-digit HUCs within those 8-digit HUCs overlapping with West Virginia, coded by fraction agricultural area in associated watersheds. Classes mapped are not equal interval classes but represent population quintiles.
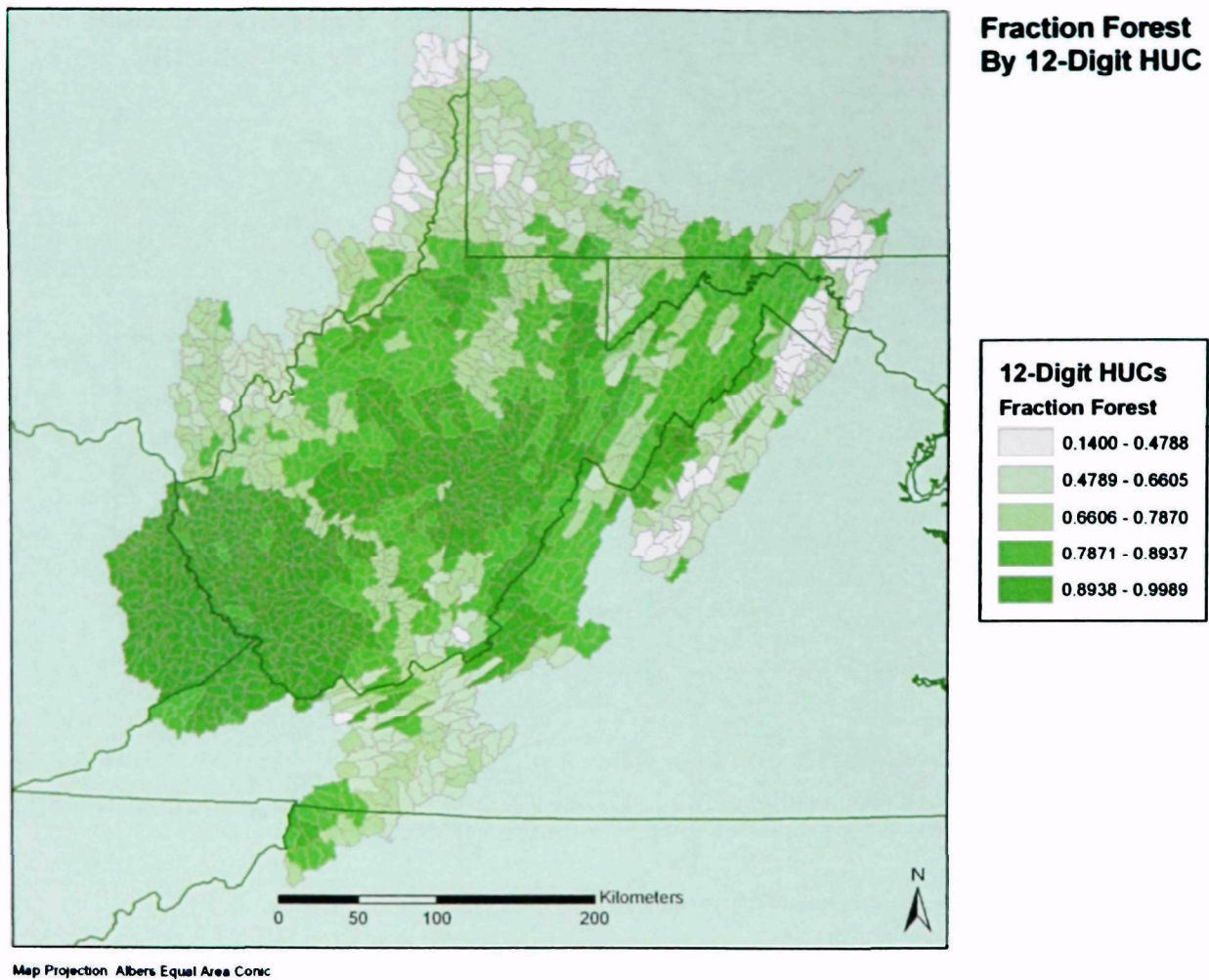
Figure 18. Map of 12-digit HUCs within those 8-digit HUCs overlapping with West Virginia, coded by fraction forested area in associated watersheds. Classes mapped are not equal interval classes but represent population quintiles.

Because of the uneven distribution of watershed storage, watershed morphology, and land-use across the state of West Virginia, the distribution of 12-digit HUCs is not even across watershed classes; in fact some combinations of watershed classes are not even represented (Figures 19-20). For example, in the Western Allegheny Plateau ecoregion, only one 12-digit HUC watershed occurred in the high urbanization/low storage class, and no 12-digit HUC watersheds occurred with combinations of moderate or high agriculture and low storage. Thus, not all potential watershed classes can be compared within each ecoregion (Figures 21-22).
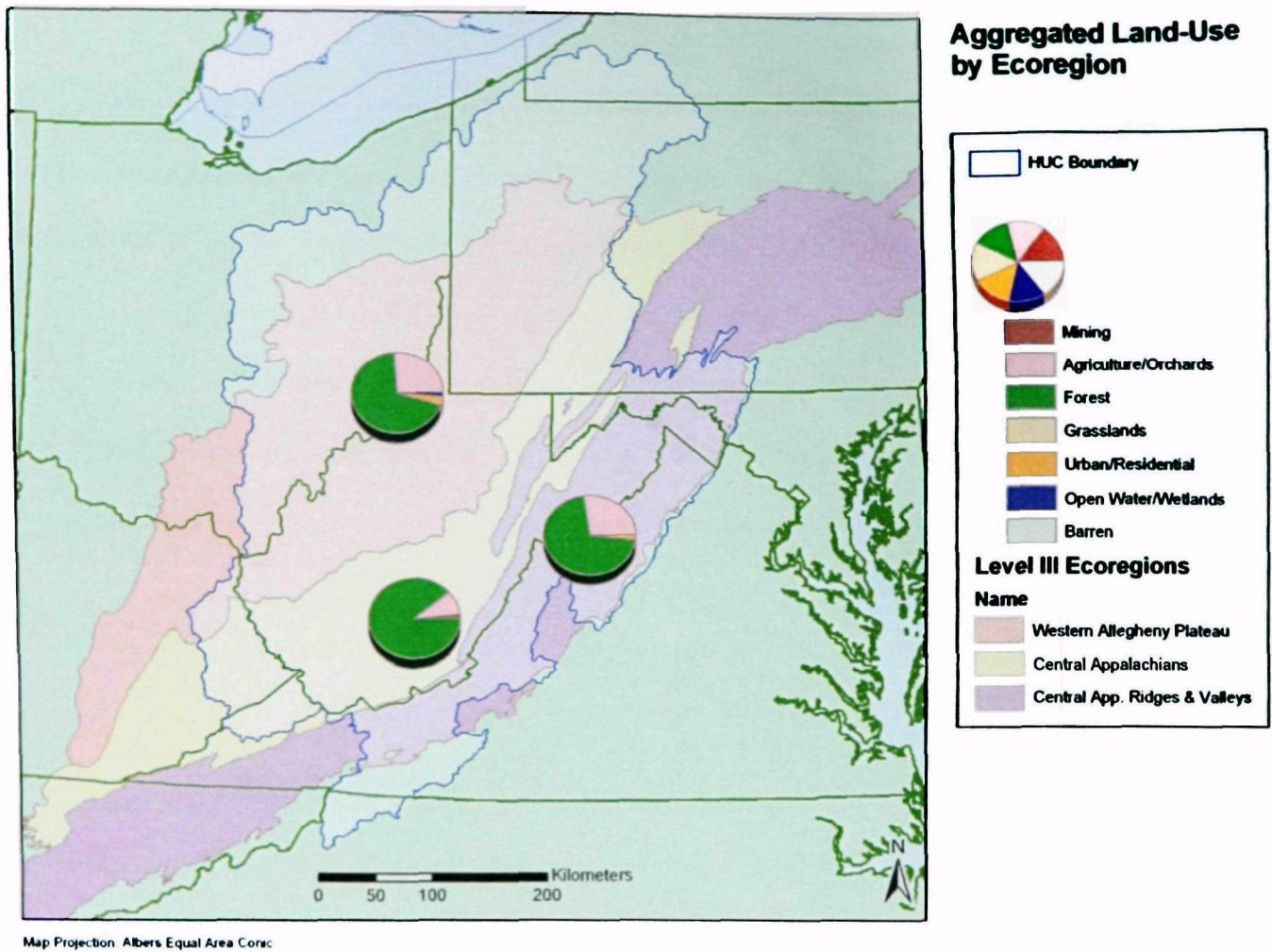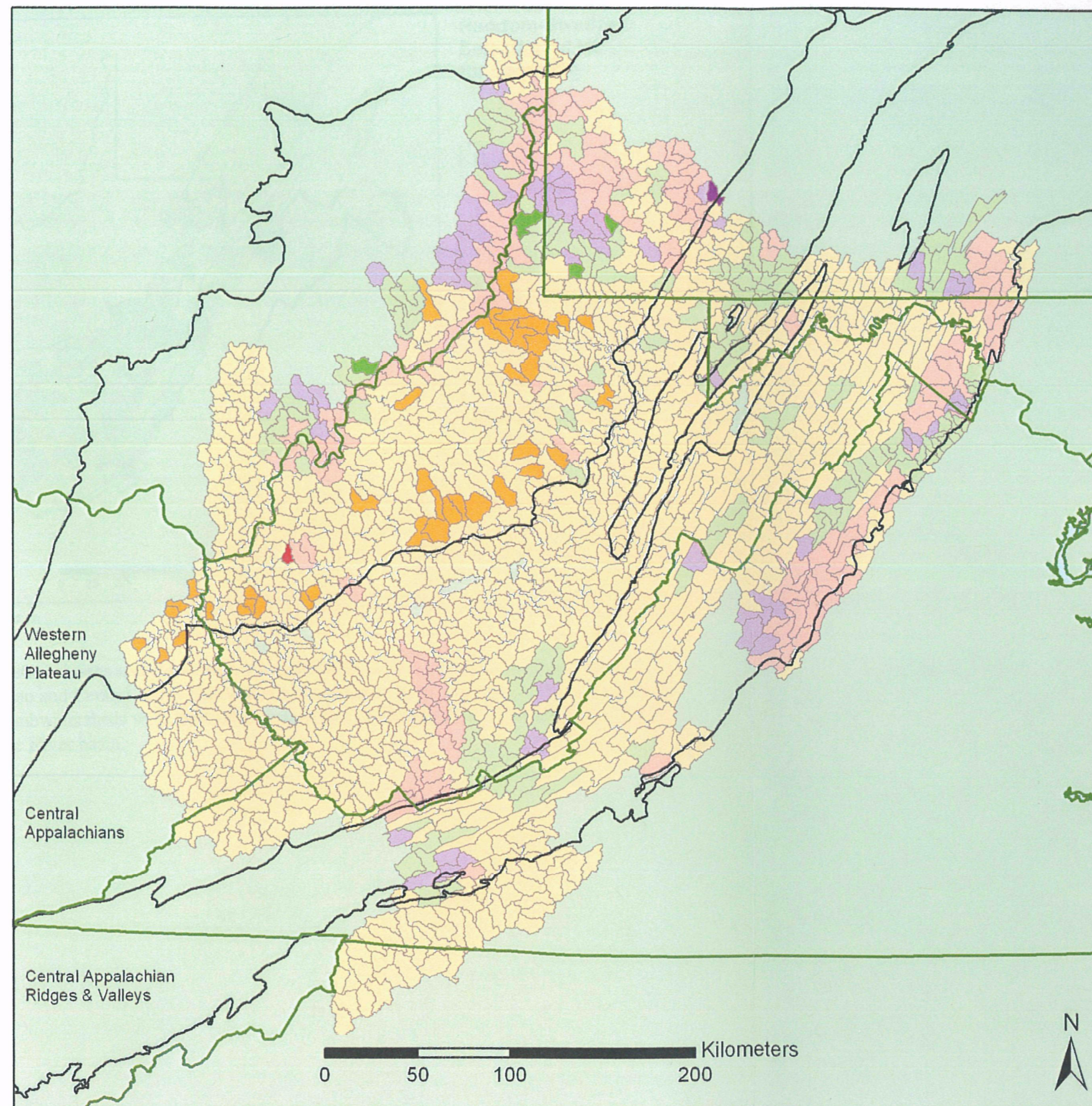
Figure 19. Map of Omernik Level III ecoregions within state of West Virginia, and associated land-use summaries at ecoregion level for region within WV watersheds.

12-Digit HUC Watershed Classes

Watershed Classes

- Low Impact/Low Storage
- Low Impact/High Storage
- High Urbanization/Low Storage
- High Urbanization/High Storage
- Moderate Agriculture/Low Storage
- Moderate Agriculture/High Storage
- High Agriculture/Low Storage
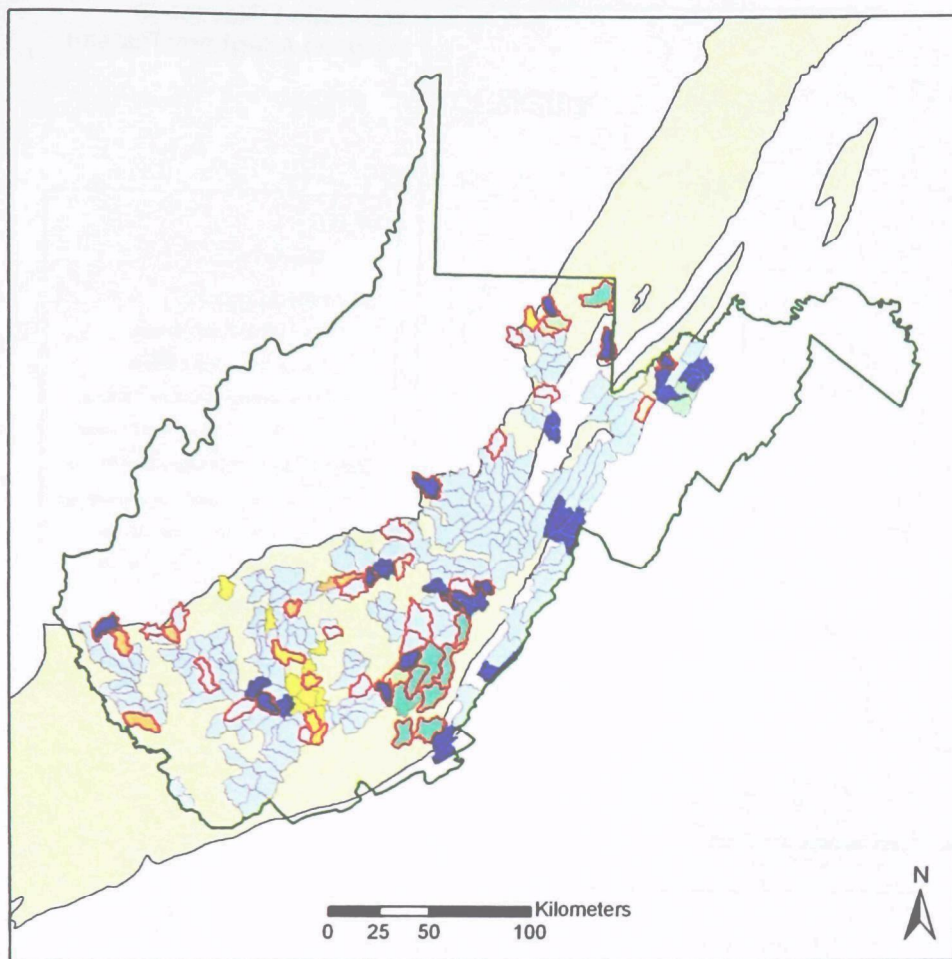- High Agriculture/High Storage

Level III Ecoregions

- Level III Ecoregions

Western Allegheny Plateau

Central Appalachians

Central Appalachian Ridges & Valleys

Kilometers

0   50   100   200

N

Map Projection: Albers Equal Area Conic

Figure 20. Map of 12-digit subwatershed units within West Virginia's 8-digit HUCs, classified by land-use and watershed storage classes. Storage classes are based on empirical hydrologic thresholds for watershed storage (CA, CARV ecoregions) or combinations of storage and main channel length (WAP ecoregion).

Random-Stratified
Selection of HUCs
for Sampling

Legend

☐ HUCs selected for sampling

Thresholds

Reference, low storage
Reference, high storage
High mining, low storage
High mining, high storage
High agriculture, low storage
High agriculture, high storage
High impervious, low storage
High impervious, high storage

Level III Ecoregions
Name

Central Appalachians

Kilometers
0 25 50 100

N
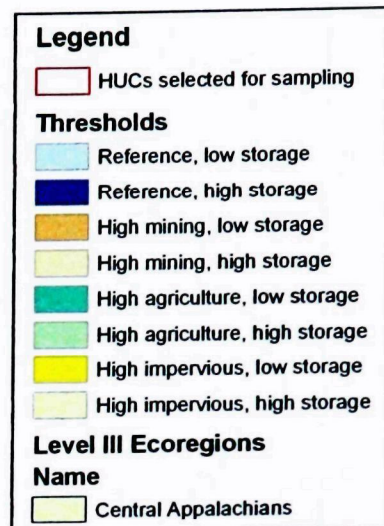
Map Projection: Albers Equal Area Conic

Figure 21. Watershed classes associated with 12-digit HUCs in sample population for Central Appalachian Plateau and Central Ridge and Valley ecoregions in West Virginia. Sample population included 12-digit subwatersheds with associated watersheds in size range of wadeable streams and outside of Potomac River basin.
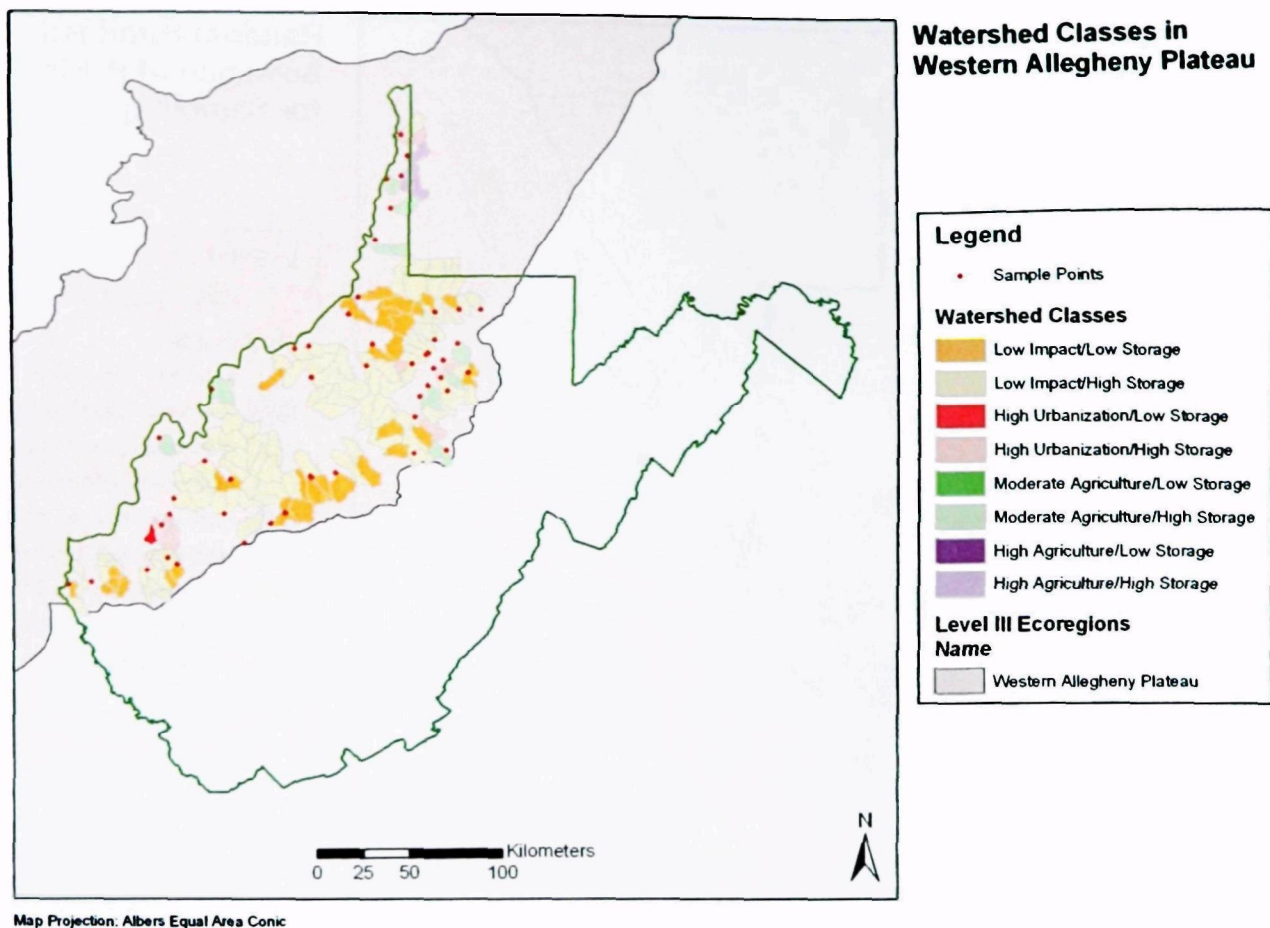
Figure 22. Watershed classes associated with 12-digit HUCs in sample population for Western Allegheny Plateau ecoregion in West Virginia. Sample population included 12-digit HUCs with associated watersheds in size range of wadeable streams.

FUTURE UPDATES AND CLASSIFICATION REFINEMENTS

Potential future improvements to the watershed classification system for West Virginia include the following:

- Examination and documentation of differences in reference condition among low and high storage reference ("low impact") classes based on WV R-EMAP data, EMAP data from the MidAtlantic Integrated Assessment (MAIA), and macroinvertebrate and water quality data collected as part of the WV Department of Environmental Protection (DEP) rotating basin monitoring program

- Examination and documentation of differences in condition between reference and "impacted" watershed classes within storage categories based on WV R-EMAP data, EMAP MAIA data, and macroinvertebrate and water quality data collected as part of the WV DEP rotating basin monitoring program

- Examination and adjustment of thresholds of impact associated with watershed storage and land-use intensity based on the analyses described above.

- Potential refinement of watershed impact classes based on empirical analysis of existing data with the addition of other watershed attributes such as development within stream and river corridor buffers, road density, and density of stream or river road crossings. Land-use impacts in a mountainous region might be better reflected by estimation of valley development, as compared to land-use intensity on a whole-watershed basis.

- Improved estimation of percent impervious surface area in WV watersheds. The method used for estimation in this project was indirect. However, the Chesapeake Bay program is currently mapping impervious surface area directly based on satellite imagery from Landsat 7, IKONOS, and MODIS platforms (http://chesapeake.towson.edu/data/), and

additional studies are underway to calibrate percent impervious surface area estimation equations based on actual measurements from aerial photographs (David Jennings, US EPA, Reston, VA, personal communication).

- Improved estimation of percent mined area (surficial disturbance). Current estimates were based on interpretation of TM + SPOT satellite imagery by Tennessee Valley Authority under contract to Canaan Valley Institute for permitted mining areas (Hope Childers, US EPA Region III). The state of West Virginia is currently constructing coverages of mining activity that might eventually allow better definition of areal extent and different sources of mining impacts (e.g., valley fill vs mountaintop mining, http://www.nrac.wvu.edu/hollowfill/, http://gis.dep.state.wv.us/data/omr.html); however, current coverages are based on permit boundaries which do not always reflect mining activity.

- Slight adjustments in boundaries and characterizations from Stage II to Stage III 10- and 12-digit HUCs as Stage III EDNA process is completed for the state of West Virginia.

There are several ways in which derivation of thresholds could be improved, depending on the objectives of a monitoring project. CART analysis objectively maximizes the separation of two subpopulations of a dependent variable (e.g., Q2/A) as a function of the best predictive variable, e.g., fraction watershed storage. Thresholds derived from graphical analysis could be verified through application of a statistical procedure such as CART (Wilkinson 1999). Reanalysis of USGS data for the Central Appalachian ecoregions using CART yielded an apparent threshold of fraction storage = 0.001, or 0.1%, very close to the threshold of 0.5% derived through visual examination).

46

Alternatively, thresholds could be chosen by optimizing the chance of correctly identifying watersheds with high normalized peak flows, i.e., those with greater potential for bank erosion and transport of nonpoint source pollutants, while minimizing the chance of misidentifying watersheds expected to have low normalized peak flows. If watershed storage is used as the indicator of normalized peak flows, then the probability of the two types of misclassification error will depend on the strength of the relationship between normalized peak flows and watershed storage, the error associated with the relationship between the two variables, and the underlying distribution of watersheds across the range of watershed storage. The absolute value of the exponent term in the equation relating storage and peak flows is a measure of the "strength" of the relationship. An exponent of zero would indicate that there is no relationship between storage and normalized peak flows, while a highly negative value indicates a rapid rate of increase in peak flows as storage is reduced (Figure 23).

Several examples are shown below to illustrate the combined effect of the magnitude of the exponent (-2 versus -0.01), the magnitude of a desired breakpoint in Q/A relative to its underlying distribution (median versus 95th percentile), and the effect of differing levels of error of prediction (standard error of estimate = 0 to 100%; Figures 24a-h). In these simulations, an even distribution of watersheds across storage classes was used. In all cases there is a tradeoff between maximizing the proportion of correct predictions for high normalized peak flows (Figures 24a,c,e,g) and minimizing the proportion of incorrect predictions for the low normalized peak flow class (Figures 24b,d,f,h). As we reduce the chosen threshold for percent watershed storage, our ability to predict watersheds with high normalized peak flows improves, but the misclassification error rate for the low peak flow class also increases (e.g., compare Figure 24a with Figure 24b). Our chances for

Effect of exponent term for storage
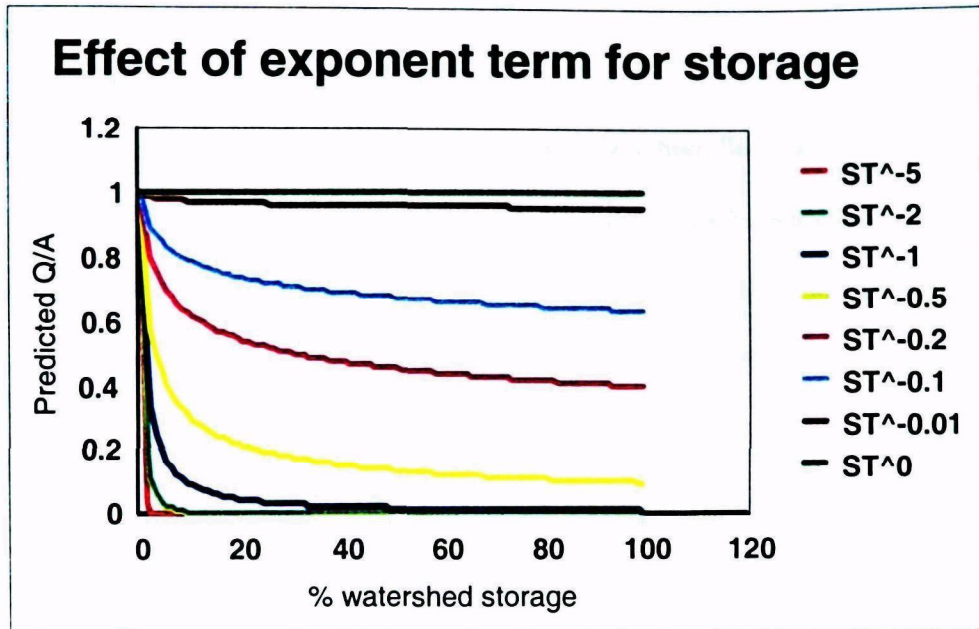
Figure 23. Effect of magnitude of exponent term for storage on shape of relationship between watershed storage and normalized peak flow (Q/area = ST^a).

making correct high flow predictions and minimizing errors in predicting low flow watersheds are generally better the stronger the relationship is between storage and peak flows (e.g., compare Figure 24a with Figure 24c and Figure 24b with Figure 24d). The greater the error in the relationship between storage and normalized peak flows (higher SEE), the worse our predictions will be. (Compare different color lines within Figure 24a or 24b.) However, prediction error appears to have little influence if we wish to distinguish only those watersheds with the most extreme peak flows (> 95th percentile of Q/A; Figures 24e and f). In this example, our ability to avoid making misclassification errors for low peak-flow watersheds is relatively small if our breakpoint for Q/A is high (Figures 24f and h). If at the same time, the strength of the relationship is weak (e.g., exponent = -0.01), however, we also have little chance of correctly identifying the high peak-flow watersheds (Figure 24g).

48
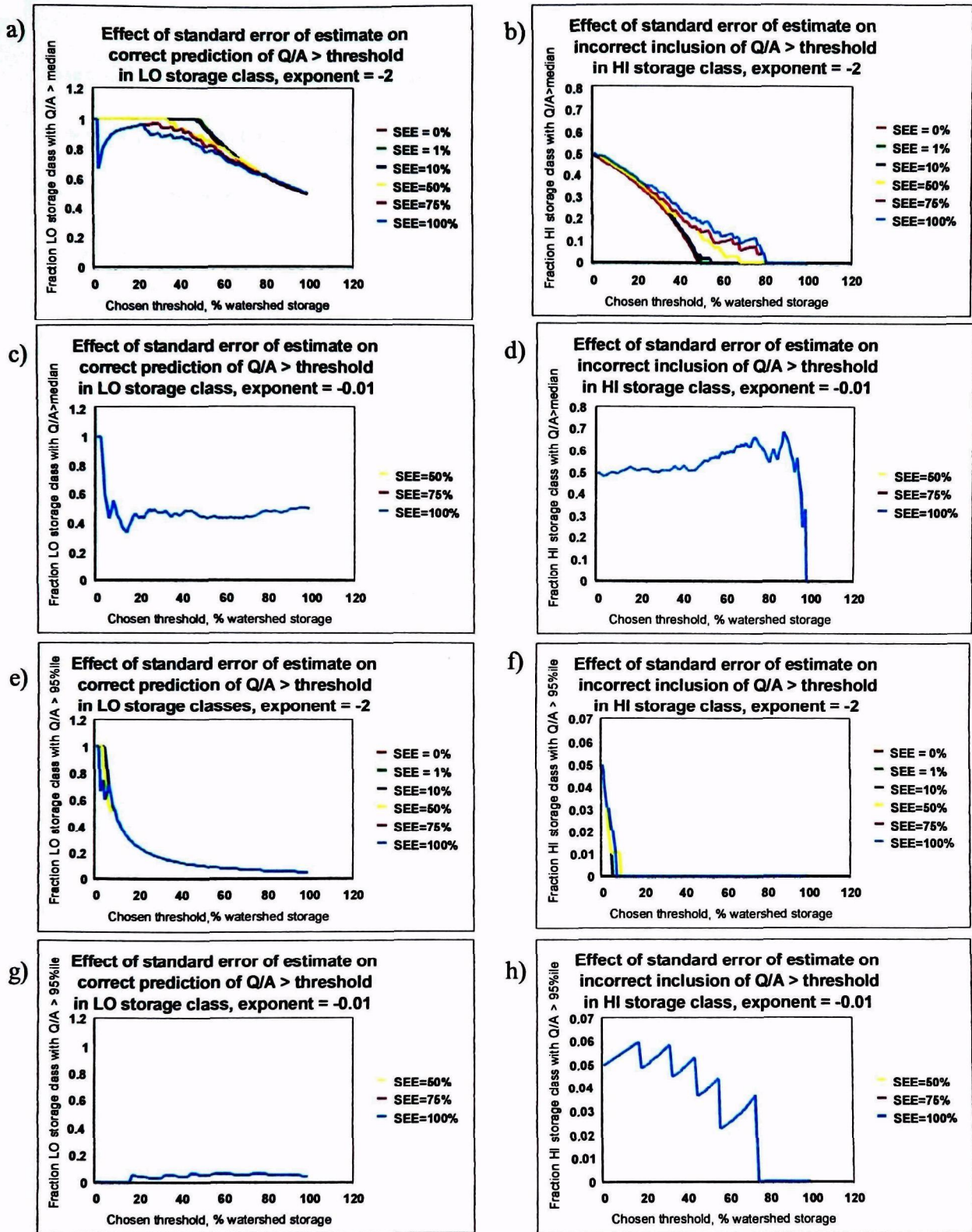
Figure 24. Effect of peak flow breakpoint (Q/A > median [a-d] versus Q/A >95th percentile [e-h]), magnitude of exponent term in relationship, Q/area = ST^a (a = -2 [a,b,e,f] versus a = -0.01[c,d,g,h]) and prediction error on correct classification rate for high peak flow class [a,c,e,g] or misclassification rate for low peak flow class [b,d,f,h].

CONCLUSIONS

In some regions such as West Virginia, the watershed classification framework for monitoring will be limited initially by available regional data and information on relationships between land-use and hydrologic or biological response. However, the process is iterative and classification schemes can be validated and improved upon based on initial monitoring results. In previous approaches to watershed classification, we have developed thresholds based on land-use attributes calculated as a fraction of watershed area. Land-use variables described as a fraction of watershed area might be less useful in montane regions where development is concentrated in valleys; in these cases it might be more appropriate to express land-use as a fraction of stream buffer zone area.

Watershed storage was one to two orders of magnitude lower in West Virginia than in Great Lake regions for which we have derived hydrologic thresholds for storage. However, the hydrologic threshold for watershed storage was also an order of magnitude lower for WV as compared to the upper Midwest, suggesting that storage is still a critical component in determining hydrologic regime. Both removal and addition of watershed storage elements is affected by human activities. Thus, it is possible that not all combinations of land-use and watershed storage classes will occur within a region, as was found for the Western Allegheny Plateau ecoregion. If examination of all potential interactions between hydrologic and land-use classes is necessary or desired, we will need to include data from adjacent states with a wider gradient of watershed conditions.

The use of nonlinear regression analysis followed by visual analysis of bi-plots to identify variables of interest for hydrologic thresholds is less objective and will be of limited use in cases of collinearity of independent variables, or where classes have alternative definitions, e.g., Condition B < X OR Condition C < Y, as was observed for the Western Allegheny Plateau ecoregion. In these

50

cases, CART analysis should be a more powerful approach to define thresholds. It is possible, however, that graphical analysis will be more useful when interactive terms (Condition B < X and Condition C < Y) are important in defining thresholds. In the current analysis, visual graphical analysis was used because of the form of the equation relating peak flows and watershed variables; no inflection point can be defined in an exponential curve because the second derivative is constant. Graphical analysis can be followed by CART analysis to confirm the placement of the threshold in an unbiased fashion.

ACKNOWLEDGMENTS

REFERENCES

Boward, D.M., P.F. Kazyak, S.A. Stranko, M.K. Hurd, and T.P. Prochaska. 1999. From the Mountains to the Sea: The State of Maryland's Freshwater Streams. EPA/903/R-99/023. Maryland Department of Natural Resources, Monitoring and Nontidal Assessment Division, Annapolis, MD.

Brazner, J.C., D.K. Tanner, N.E. Detenbeck, S.L. Batterman, S.K. Stark, L.A. Jagger, and V.M. Snarski. 2003. Landscape influences on fish assemblage structure and function in western Lake Superior tributaries. Submitted to *Environmental Management*.

Cincotta, D. 2000. A Small Watershed Characterization, Classification, and Assessment for West Virginia Utilizing EMAP Design and Tools. R-EMAP proposal submitted to US EPA Mid-Continent Ecology Division, Duluth, MN and US EPA Region III, Philadelphia, PA.

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology,* *33:140-158.*

Detenbeck N.E., D. Cincotta, J.M. Denver, S.K. Greenlee, and A.R. Olsen. 2003a. Watershed-based survey designs. Submitted to *Environmental Monitoring and Assessment* (accepted with minor modifications).

Detenbeck N.E., C.M. Elonen, D.L. Taylor, L.E. Anderson, T.M. Jicha, and S.L. Batterman. 2003b. Effects of hydrogeomorphic region, watershed storage and mature forest on baseflow and snowmelt stream water quality in second-order Lake Superior Basin tributaries. *Freshwater Biology 48(5):911-27.*

Detenbeck, N.E., S.L. Batterman, V.J. Brady, J.C. Brazner, V.M. Snarski, D.L. Taylor, J.A. Thompson, and J.W. Arthur. 2000. A test of watershed classification systems for ecological risk assessment. *Environmental Toxicology and Chemistry 19(4):1174-1181.*

FGDC. 2002. Federal Standards for Delineation of Hydrologic Unit Boundaries. Federal Geographic Data Committee. http://www.ftw.nrcs.usda.gov/huc_data.html

Franken, S.K., D.J.Tyler, and K.L. Verdin. 2001. Development of a National Seamless Database of Topography and Hydrologic Derivatives, Paper 730 in Proceedings, 2001 ESRI International User's Conference, San Diego, CA.

Frye, P.M. and G.S. Runner. 1970. A Proposed Streamflow Data Program for West Virginia, U.S. Dept. of the Interior, Geological Survey Water Resources Division, Open-file report, Charleston, WV.

Heiskary, S.A. and C.B. Wilson 1990. Minnesota lake water quality assessment report. Minnesota Pollution Control Agency, St. Paul, MN.

Herlihy A.T., D.P. Larsen, S.G. Paulsen, N.S. Urquhart, and B.J. Rosenbaum. 2000. Designing a spatially balanced, randomized site selection process for regional stream surveys: The EMAP Mid-Atlantic pilot study. *Environmental Monitoring and Assessment, 63:95-113*.

Jennings, M.E., W.O. Thomas, Jr., and H.C. Riggs. 1993. Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites, 1993. U.S Geological Survey, Reston,VA. Water Resources Investigations Report WRI 94-4002.

Johnston, C.A., N.E. Detenbeck, and G.J. Niemi. 1990. Cumulative impacts of wetland loss on stream water quality and quantity. *Biogeochemistry 10:105-141*.

Legleiter, K.J. 2001. Interagency Development of National Watershed and Subwatershed Hydrologic Units, Paper 492 in Proceedings, 2001 ESRI International User's Conference, San Diego, CA.

NVPDC (Northern Virginia Planning District Commission). 1980. In Schueler, R.T. 1984. The importance of imperviousness. *Watershed Protection Techniques 1(3):100-111*.

Omernik, J.M. and A.L. Gallant. 1988. Ecoregions of the upper Midwest states. EPA/600/3-88/037, U. S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Pan, Y., R.J. Stevenson, B.H. Hill, and A.T. Herlihy. 2000. Ecoregions and benthic diatom assemblages in Mid-Atlantic Highlands streams, USA. *Journal of the North American Benthological Society, 19:518-540*.

Richards, R.P. 1990. Measures of flow variability and a new flow-based classification of great lakes tributaries. *J. Great Lakes Res. 16:53-70*.

Rosgen, D. 1996. Applied river morphology. *Wildland Hydrology*, Pagosa Springs, CO.

Runner, G.S. 1980. Hydrologic Data for Runoff Studies on Small Drainage Areas, West Virginia Department of Highways, Research Project 16, Open-File Report 80-560, Charleston, WV.

SAS. 1990. SAS/STAT Users Guide. Version 6, Fourth edition. SAS Institute, Cary, NC.

Schueler, T.R. 1994. The importance of imperviousness. *Watershed Protection Techniques 1(3):100-111*.

Scott, A.G. 1984. Analysis of characteristics of simulated flows from small surface-mined and undisturbed Appalachian watersheds in the Tug Fork basin of Kentucky, Virginia, and West Virginia. U.S. Geological Survey, Reston, VA. Water Resources Investigations Report WRI 84-4151.

Tasker, G.D., and J.R. Stedinger. 1989. An operational GLS model for hydrologic regression. *Journal of Hydrology 111:361-375.*

US EPA. 2001. The National Costs of the Total Maximum Daily Load Program (Draft Report). U.S. Environmental Protection Agency, Office of Water, Washington, DC EPA/841/D-01/003.

US EPA. 2002. Consolidated Assessment and Listing Methodology: Toward a Compendium of Best Practices. First Edition. U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds. Washington, DC (http://www.epa.gov/owow/monitoring/calm.html).

US EPA. 2003. National 303(d) List Fact Sheet. (http://oaspub.epa.gov/waters/national_rept.control).

Verdin, K.L., and J.P. Verdin. 1999. A topological system for delineation and codification of the earth's river basins. *J. Hydrol. 218:1-12.*

Verry, E.S. 1986. Forest harvesting and water: The Lake States experience. *Water Resources Bulletin 22:1039-1047.*

Waite, I.R., A.T. Herlihy, D.P. Larsen, and D.J. Klemm. 2000. Comparing strengths of geographic and nongeographic classifications of stream benthic macroinvertebrates in the Mid-Atlantic Highlands, USA. *Journal of the North American Benthological Society, 19:429-441.*

Wilkinson, L. 1999. Systat 9.0 Statistics I. SPSS Inc. Chicago, IL.

♻EPA

United States
Environmental Protection
Agency

Office of Research
and Development (8101R)
Washington, DC 20460

Official Business
Penalty for Private Use
$300

EPA 600/R-03/141
July 2004
www.epa.gov