Calculating Surface Water Time of Travel to Protect Public Water Intakes in West Virginia

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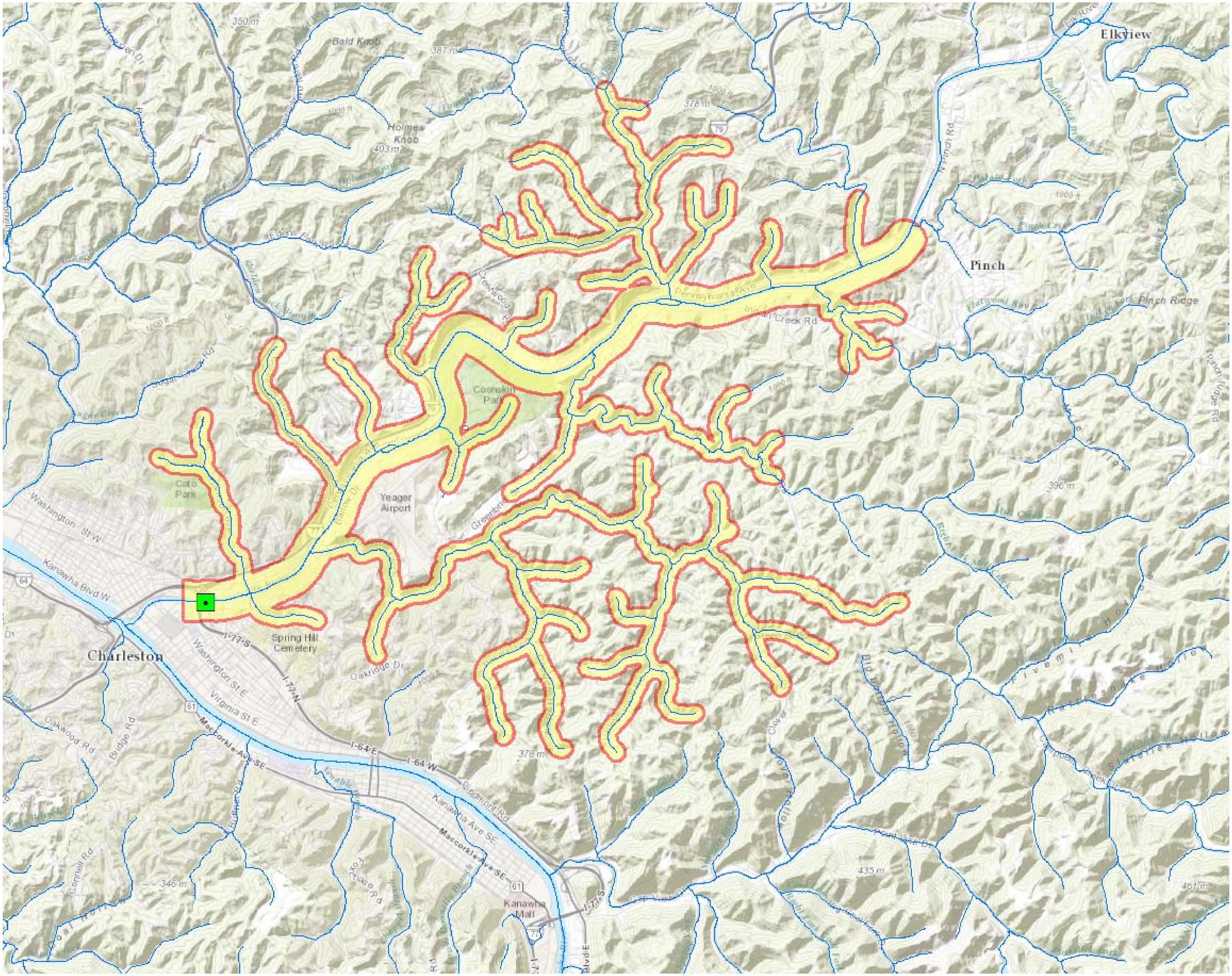
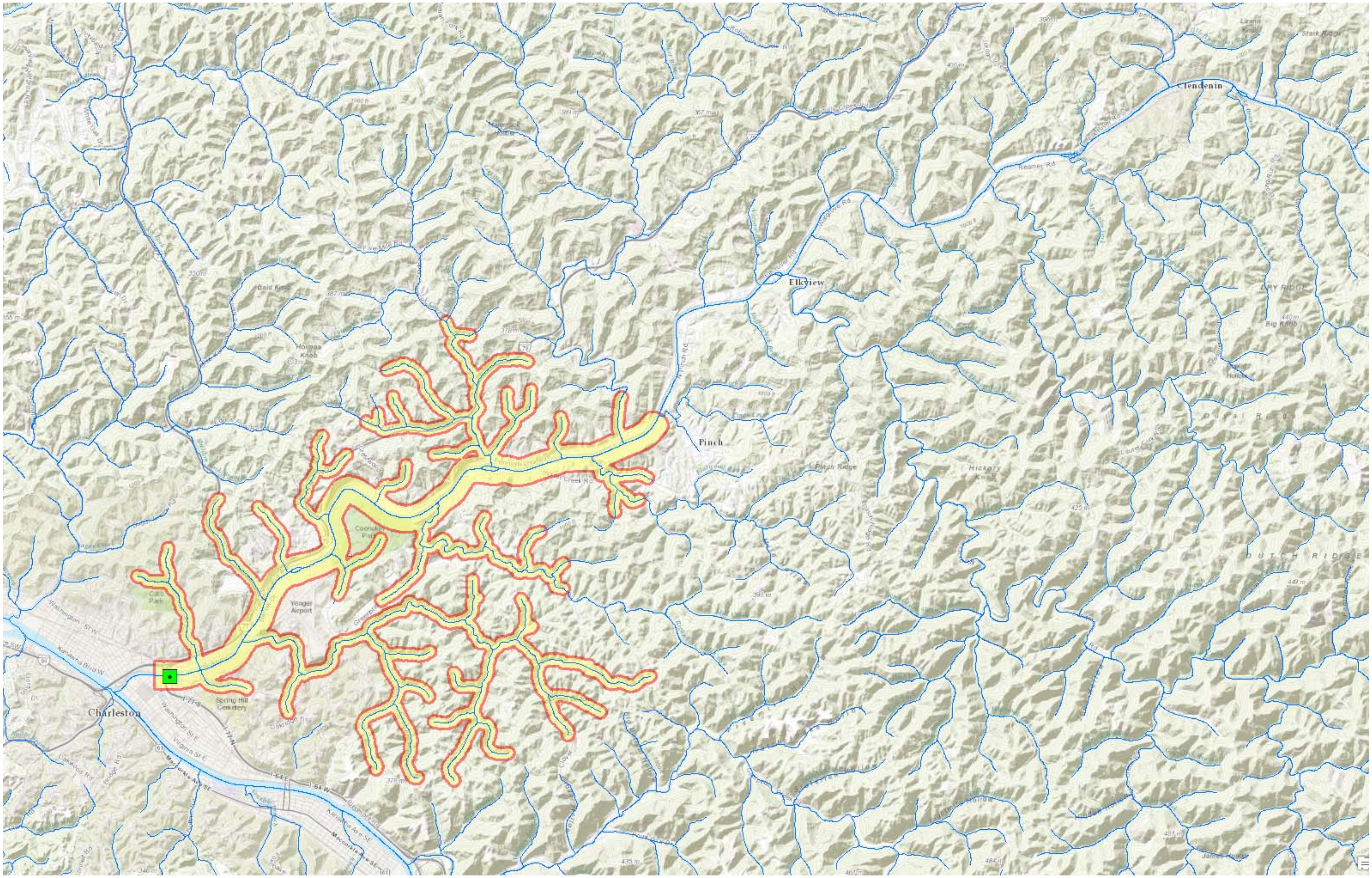
Zones of Critical Concern

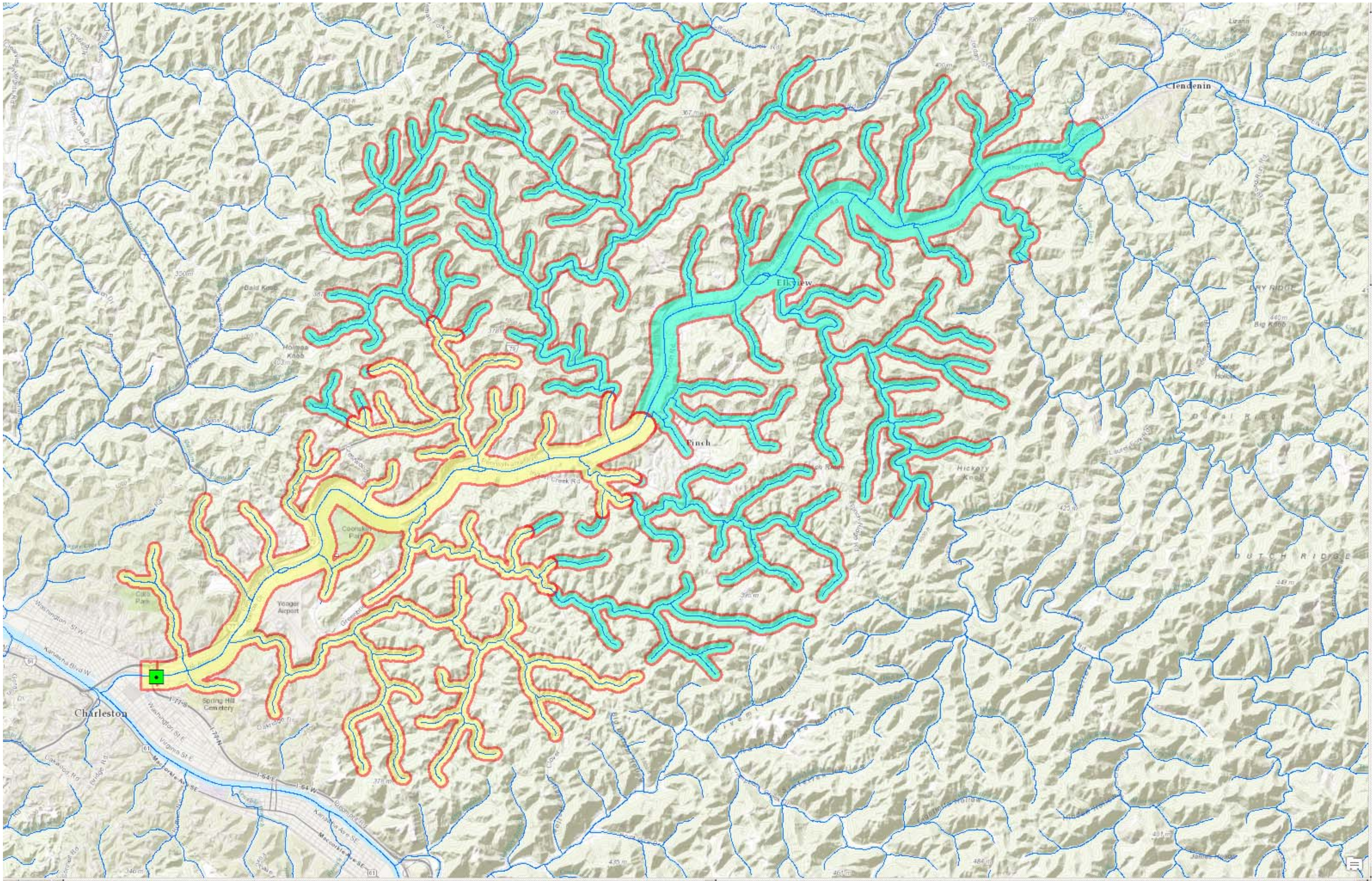
- 5 hour travel time above source water intakes
- 10 hour for Zones of Peripheral Concern
- Mainstem buffer of 1,000 ft
- Tributary buffer of 500 ft

165 completed sites as of Oct 1, 2015 with ZCC and ZPCs which include Ohio River Intakes which follow different delineation rules



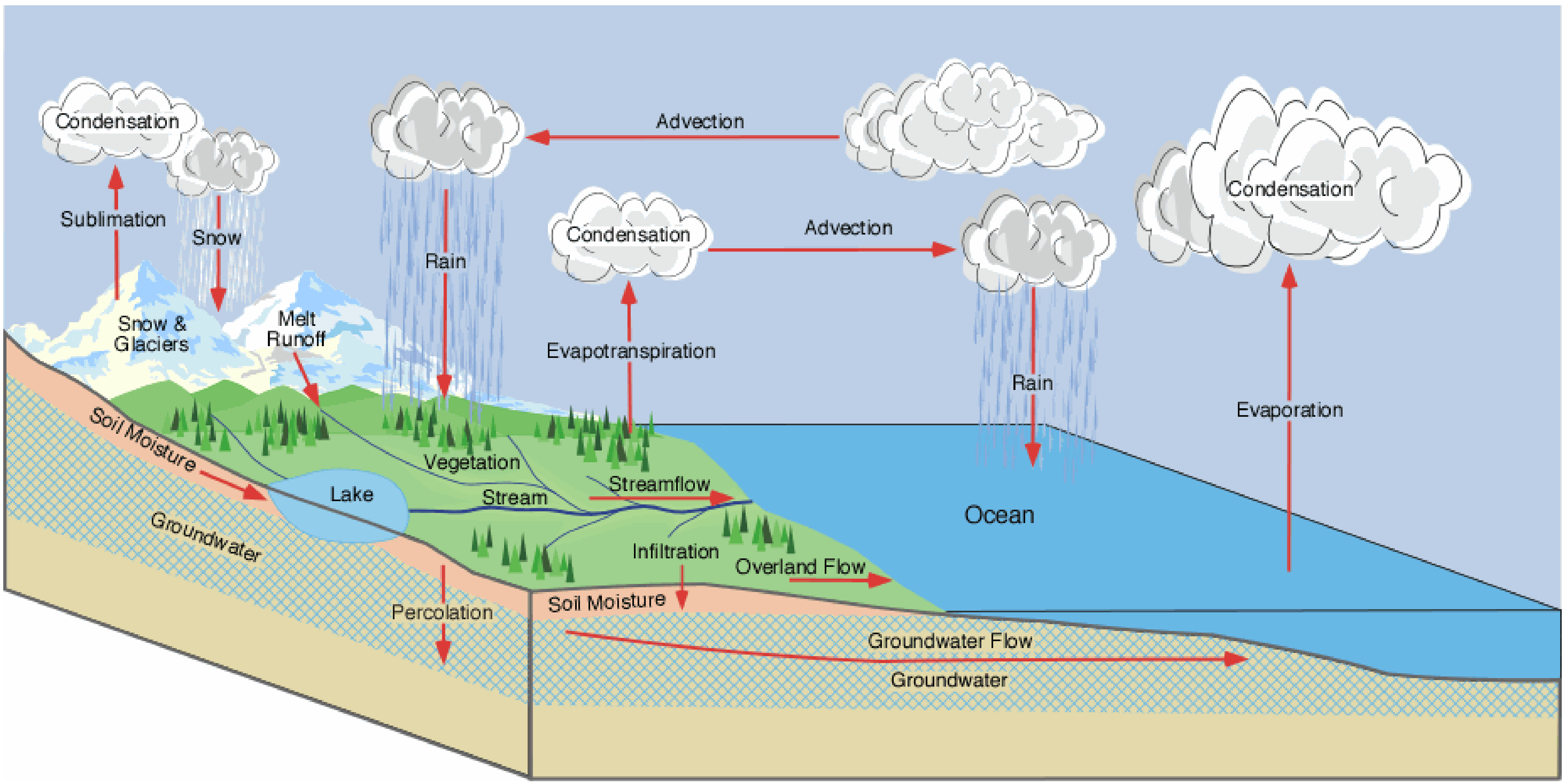
Elkview
Pinch
Pinch Ridge
Bald Knob
Holmes Knob
403 m
350 m
387 m
378 m
Pennsylvania Ave
Indian Creek Rd
Coonskin Park
Cato Park
Yeager Airport
Washington St W
Kanawha Blvd W
Charleston
Spring Hill Cemetery
Washington St E
Virginia St E
Oakridge Dr
Oakwood Rd
Bridge Rd
Maccorkle Ave SE
I-64 E
I-64 W
I-77 S
I-77 N
Kanawha Ave SE
Kanawha Mall
Greenbrier
396 m
435 m
461 m
346 m
N Pinch Rd
Pinch Ridge Rd


Clendenin
Elkview
Pinch
Charleston
DRY RIDGE
Big Knob
Pinch Ridge
Hickory Knob
Bald Knob
Holmes Knob
Yeager Airport
Spring Hill Cemetery
Kanawha Blvd W
Washington St W
Washington St E
Virginia St E



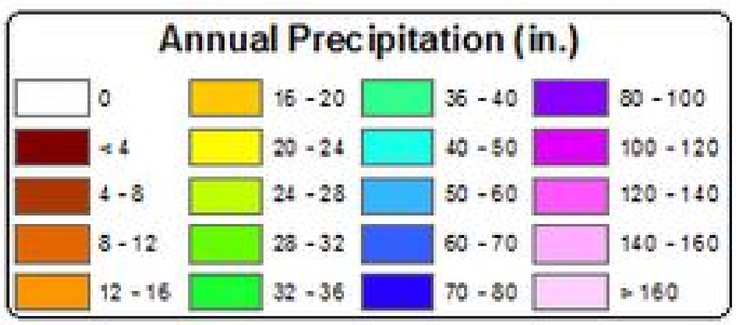
Clendenin
Elkview
Finch
Charleston
Bald Knob
Holmes Knob
DRY RIDGE
Big Knob
Hickory Knob
DUTCH RIDGE
Yeager Airport
Coonskin Park
Spring Hill Cemetery
Stark Ridge

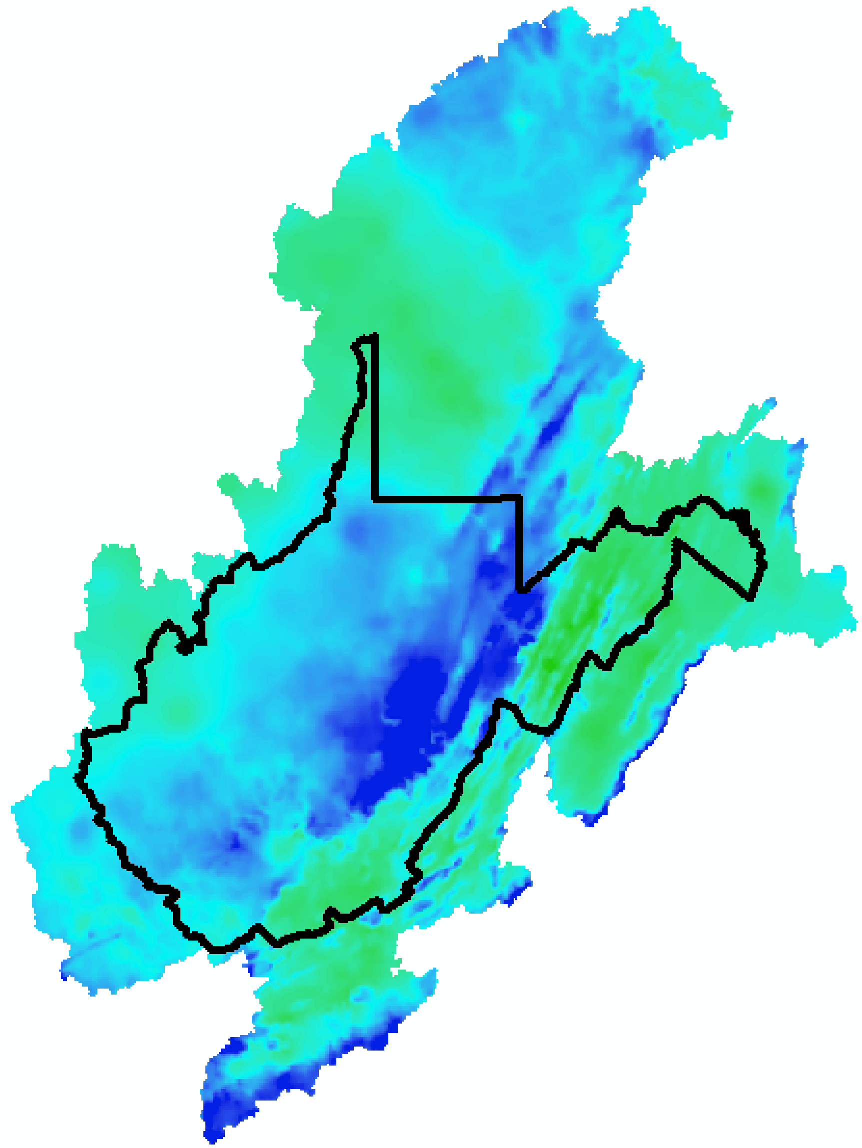
Hydro Cycle


Condensation
Sublimation
Snow
Snow & Glaciers
Melt Runoff
Rain
Advection
Condensation
Advection
Condensation
Evapotranspiration
Rain
Evaporation
Soil Moisture
Lake
Vegetation
Stream
Streamflow
Groundwater
Infiltration
Overland Flow
Ocean
Percolation
Soil Moisture
Groundwater Flow
Groundwater

Controls on the Hydro Cycle

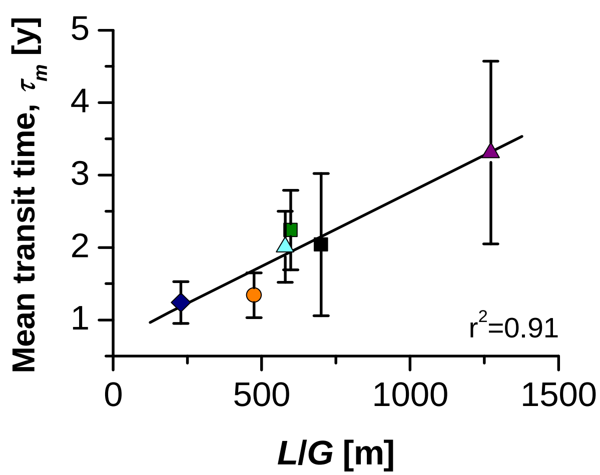
- Climate

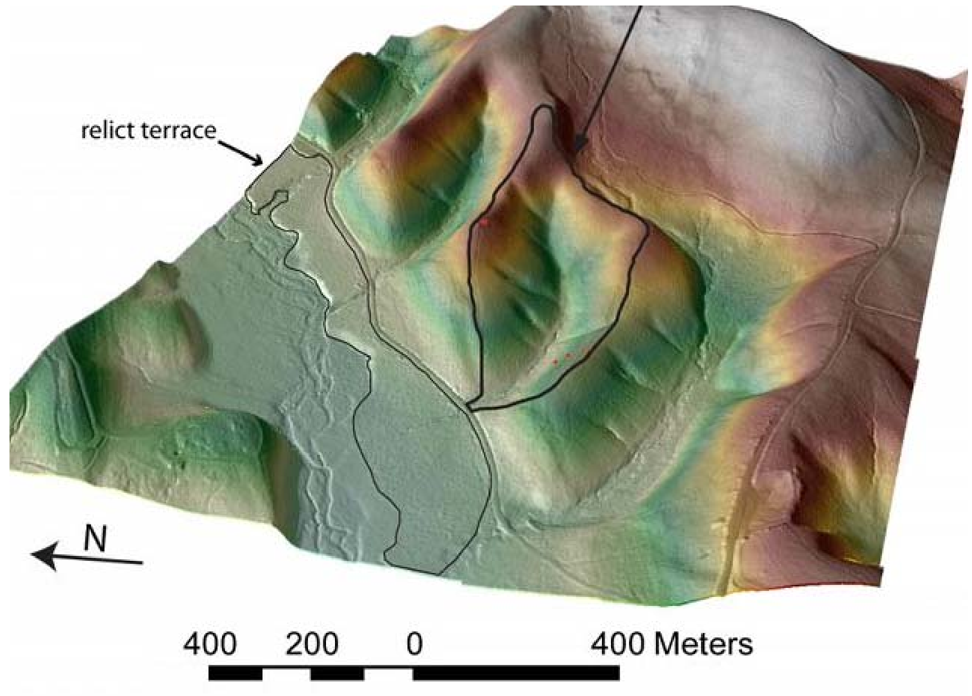




Controls on the Hydro Cycle

- Morphology

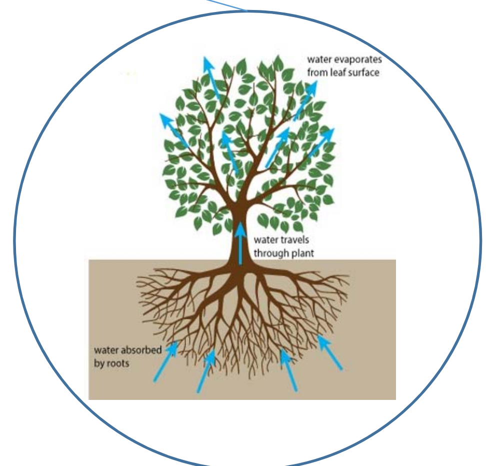




McGuire et al., 2005 WRR

Controls on the Hydro Cycle

- Landcover



Prediction of Traveltime and Longitudinal Dispersion in Rivers and Streams

By Harvey E. Jobson

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4013

Reston, Virginia
1996

Prediction of Traveltime and Longitudinal Dispersion in Rivers and Streams

by Harvey E. Jobson

Abstract

The possibility of a contaminant being accidentally or intentionally spilled upstream from a water supply is a constant concern to those diverting and using water from streams and rivers. Although many excellent models are available to estimate traveltime and dispersion, none can be used with confidence before calibration and verification to the particular river reach in question. Therefore, the availability of reliable input information is usually the weakest link in the chain of events needed to predict the rate of movement, dilution, and mixing of contaminants in rivers and streams.

Measured tracer-response curves produced from the injection of a known quantity of soluble tracer provide an efficient method of obtaining the necessary data. The purpose of this report is to use previously presented concepts along with extensive data collected on time of travel and dispersion to provide guidance to water-resources managers and planners in responding to spills. This is done by providing methods to estimate (1) the rate of movement of a contaminant through a river reach, (2) the rate of attenuation of the peak concentration of a conservative contaminant with time, and (3) the length of time required for the contaminant plume to pass a point in the river. Although the accuracy of the predictions can be greatly increased by performing time-of-travel studies on the river reach in question, the emphasis of this report is on providing methods for making estimates where few data are available.

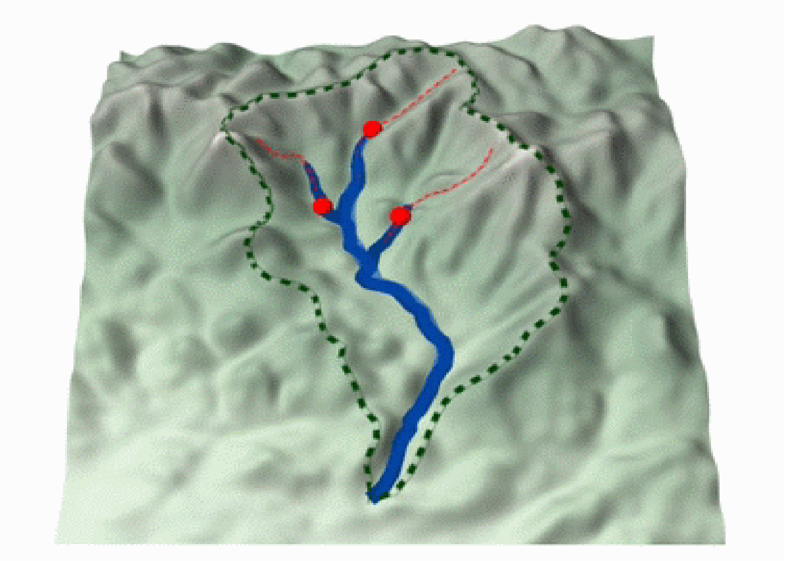
Results from rivers of all sizes can be combined by defining the unit concentration as that concentration of a conservative pollutant that would result from injecting a unit of mass into a unit of flow. Unit-peak concentrations are compiled for more than 60 different rivers representing a wide range of sizes, slopes, and geomorphic types. Analyses of these data indicate that the unit-peak concentration is well correlated with the time required for a pollutant cloud to reach a specific point in the river. The variance among different rivers is, of course, larger than for a specific river reach. Other river characteristics that were compiled and included in the correlation included the drainage area, the reach slope, the mean annual discharge, and the discharge at the time of the measurement. The most significant other variable in the correlation was the ratio of the river discharge to mean annual discharge.

The prediction of the traveltime is more difficult than the prediction of unit-peak concentration; but the logarithm of stream velocity can be assumed to be linearly correlated with the logarithm of discharge. More than 980 subreaches for about 90 different rivers were analyzed and prediction equations were developed based on the drainage area, the reach slope, the mean annual discharge, and the discharge at the time of the measurement. The highest probable velocity, which will result in the highest concentration, is usually of concern after an accidental spill. Therefore, an envelope curve for which more than 99 percent of the velocities were smaller was developed to address this concern.

The time of arrival of the leading edge of the pollutant indicates when a problem will first exist and defines the overall shape of the tracer-response function. The traveltime of the leading edge is generally about 89 percent of the traveltime to the peak concentration.

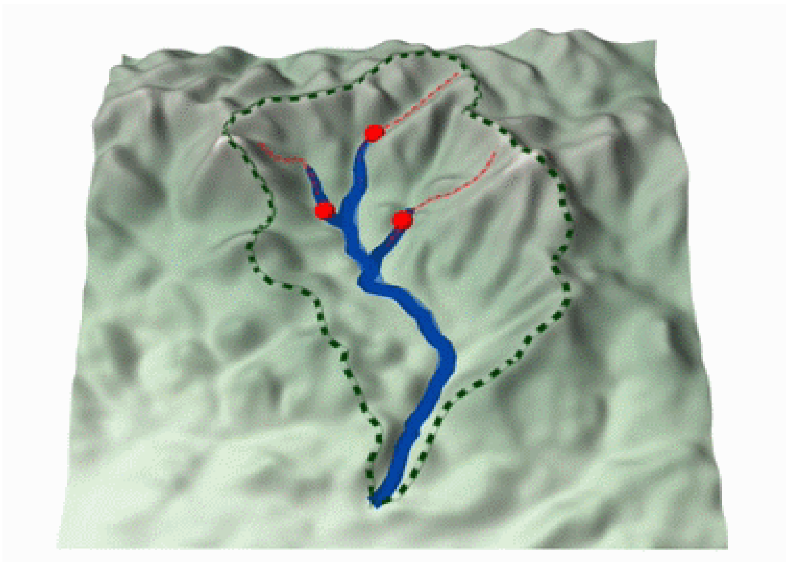
Travel time estimation

<u>Travel time</u> – time it takes a unit volume of water to travel between two points;



- Flow path length/velocity;
- Generally determined for overland flow; does not consider surface/subsurface interactions;
- Therefore, sheetflow moving in response to gradient (topography).

Travel time estimation



Jobson, 1996 determined that unit-peak concentration of tracer, C_{up}:

$$C_{up} = 857T_p^{-0.760(Q/Q_a)^{-0.079}}$$

T_p= elapsed time from injection to peak concentration, hrs.

Q= event streamflow, ft^3/s

Q_a= mean annual streamflow, ft^3/s

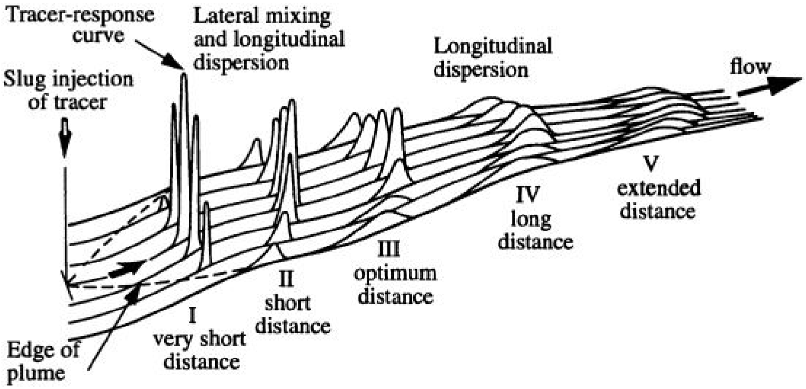


Figure 1. Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center, slug injection of tracer. (Modified from Kilpatrick, 1993, p. 2.)

Travel time estimation

Jobson ,1996 – determined velocity of peak concentration could be estimated as f(drainage area, streamflow, & slope)

Developed for 980 sub-reaches based on drainage area, reach slope, mean annual streamflow, and streamflow at time of measurement;

Log of stream velocity is assumed to be linearly correlated with log (Q);

Developed for free-flowing streams, not applicable to regulated streams.

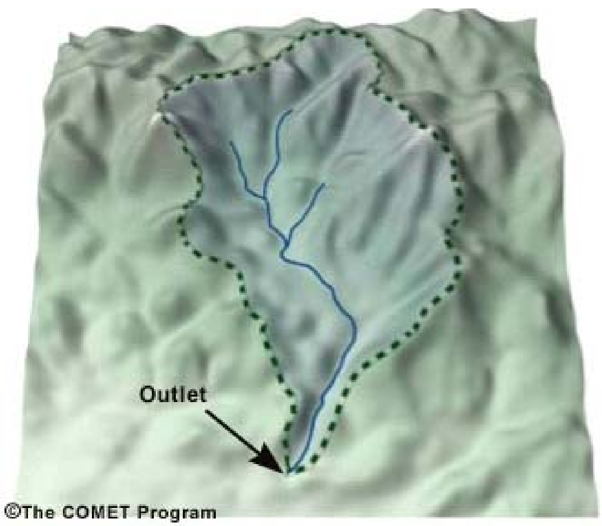
$$V_p = 0.308 + \left(0.0143 * \; D_a'^{0.919} \; Q_a'^{-0.469} \; S^{0.159} \; \frac{Q}{D_a}\right)$$

Travel time estimation

$$V_p = 0.308 + \left(0.0143 * \boxed{D_a'^{0.919}} \quad Q_a'^{-0.469} \quad S^{0.159} \quad \frac{Q}{D_a}\right)$$

D_a' Drainage area index:

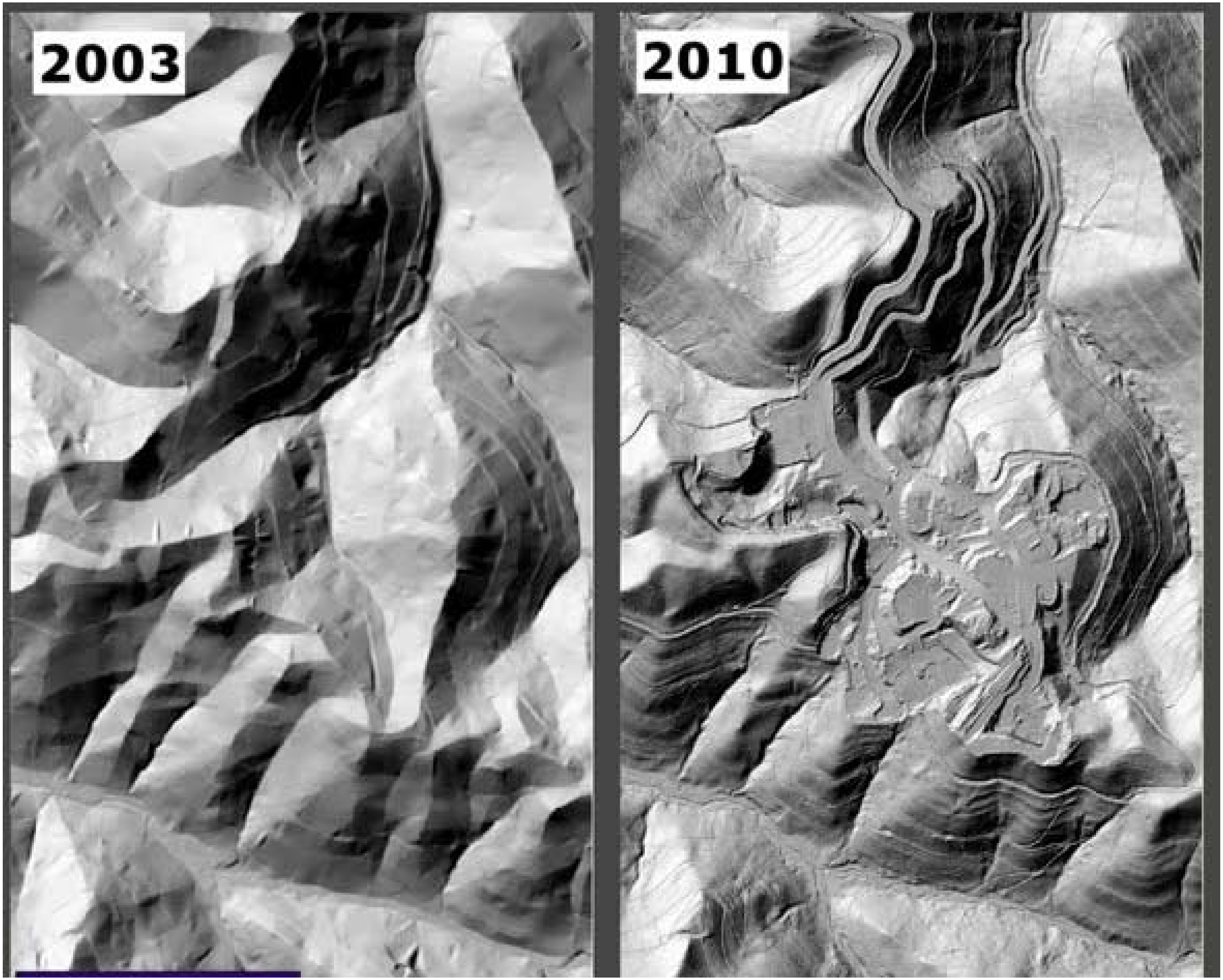
$$D_a' = \frac{D_a^{1.25} \quad g^{0.5}}{Q_a}$$



D_a: drainage area; DEM-driven; updated using the 2010 WV Lidar data DEM & 2003 SAMB DEM;

g: acceleration due to gravity – constant;

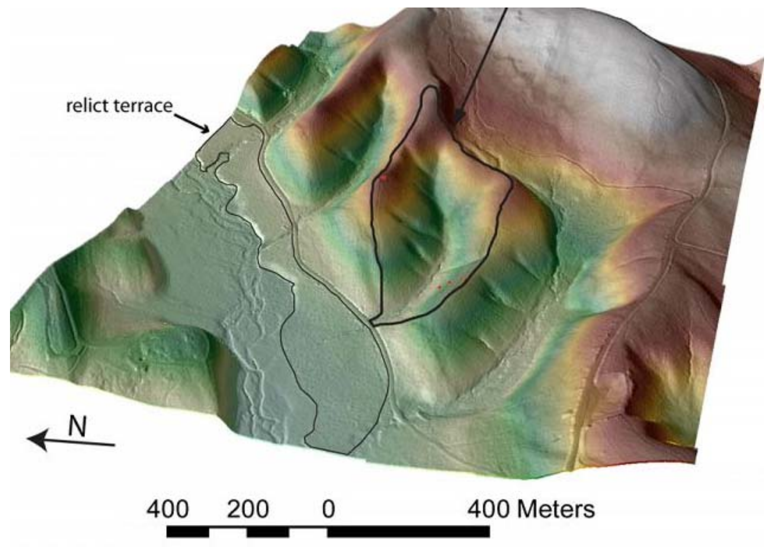
Q_a*:* mean annual streamflow;

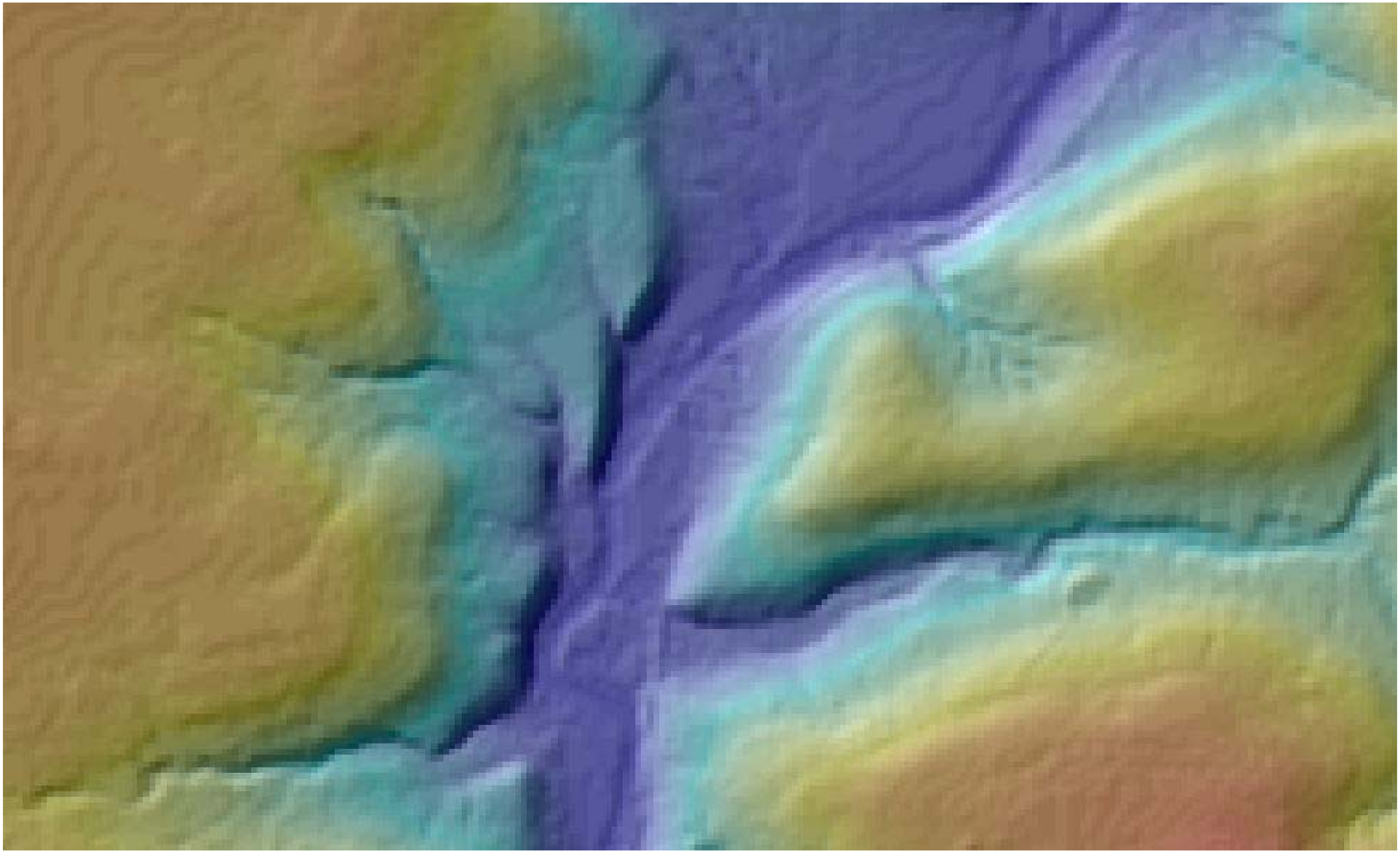

2003
2010

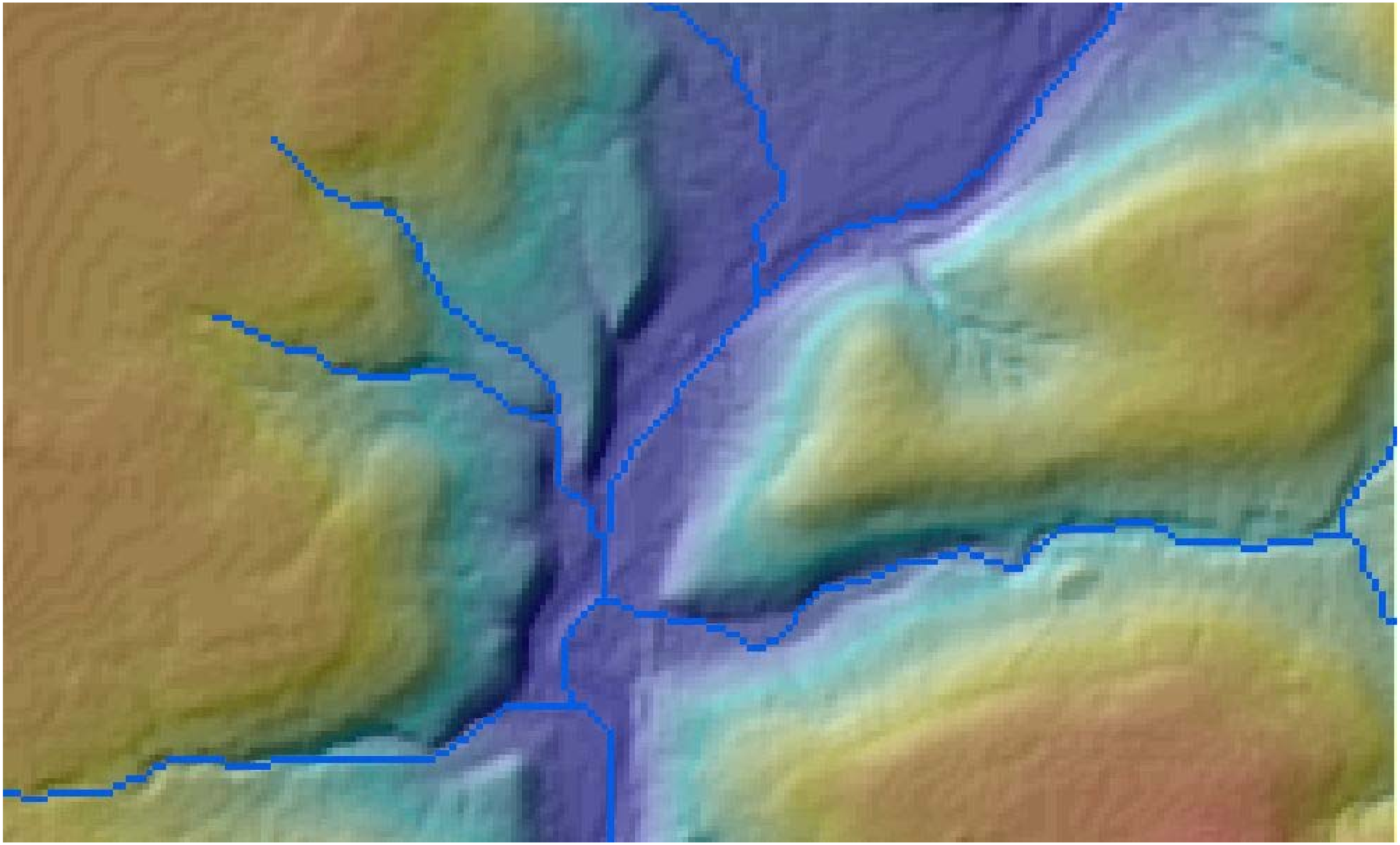
Travel time estimation

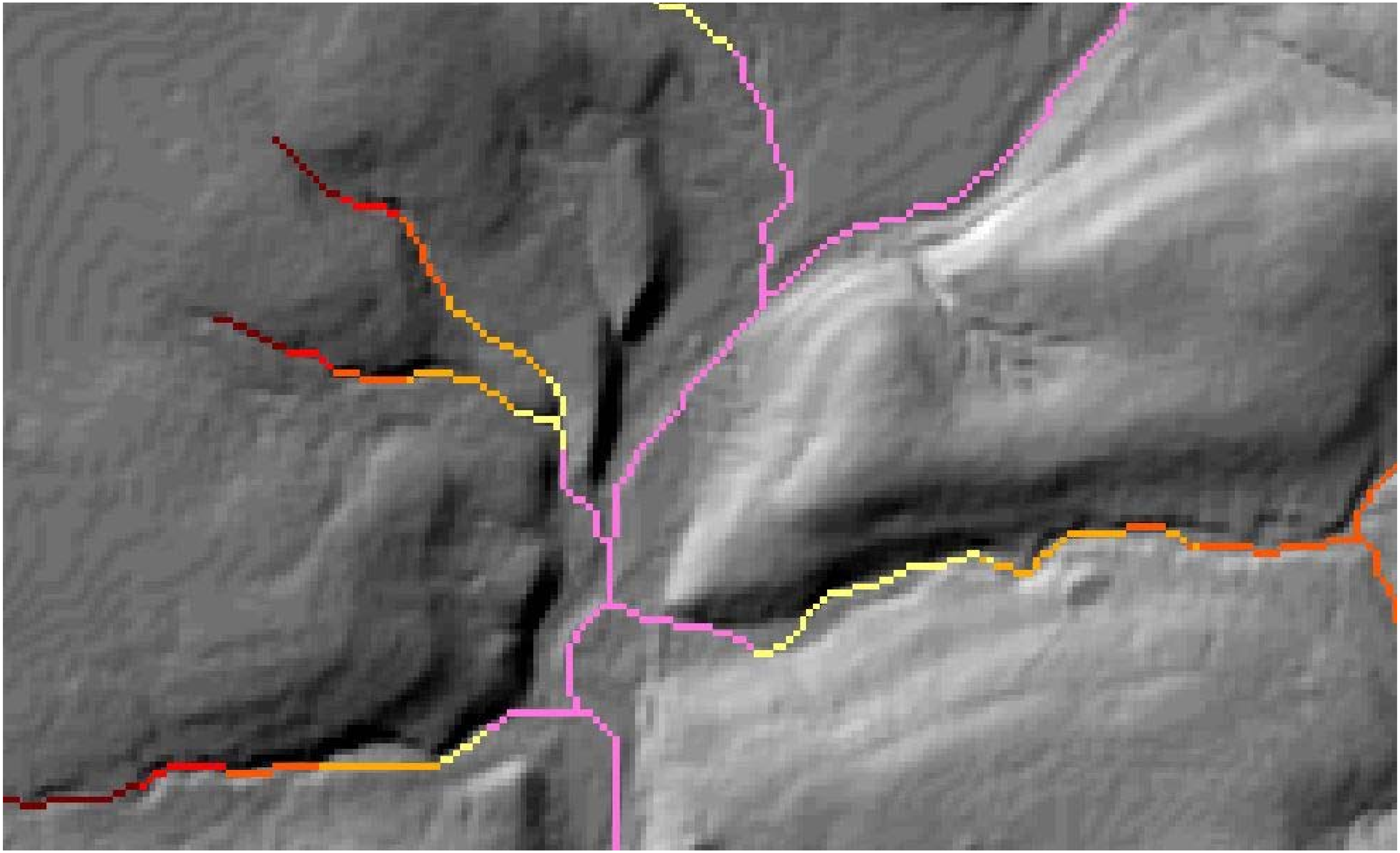
$$V_p = 0.308 + \left(0.0143 * \; D_a'^{0.919} \; Q_a'^{-0.469} \; S^{0.159} \; \frac{Q}{D_a}\right)$$

S, Slope: Calculated similar to *previous version*, but uses updated DEM







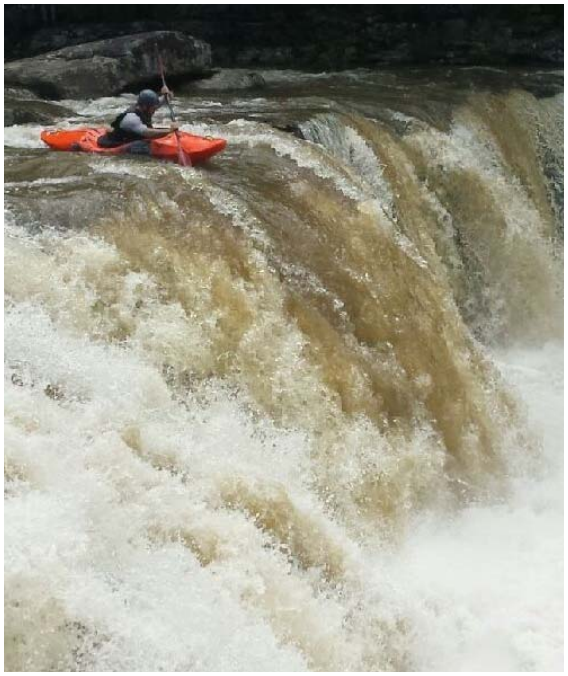


Travel time estimation

$$V_p = 0.308 + \left(0.0143 * \;\; D_a'^{0.919} \;\; \boxed{Q_a'^{-0.469}} \;\; S^{0.159} \;\; \frac{Q}{D_a}\right)$$

Q_a' Dimensionless streamflow index:

$$Q_a' = \frac{Q}{Q_a}$$



Q_a: mean annual streamflow

Q: event streamflow

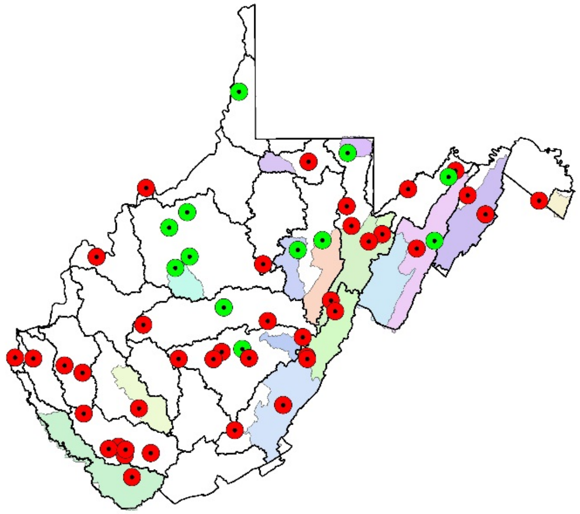
Q_a Mean annual streamflow

Easily determined for gauged watersheds given sufficiently long records (> 20 yrs.) ;

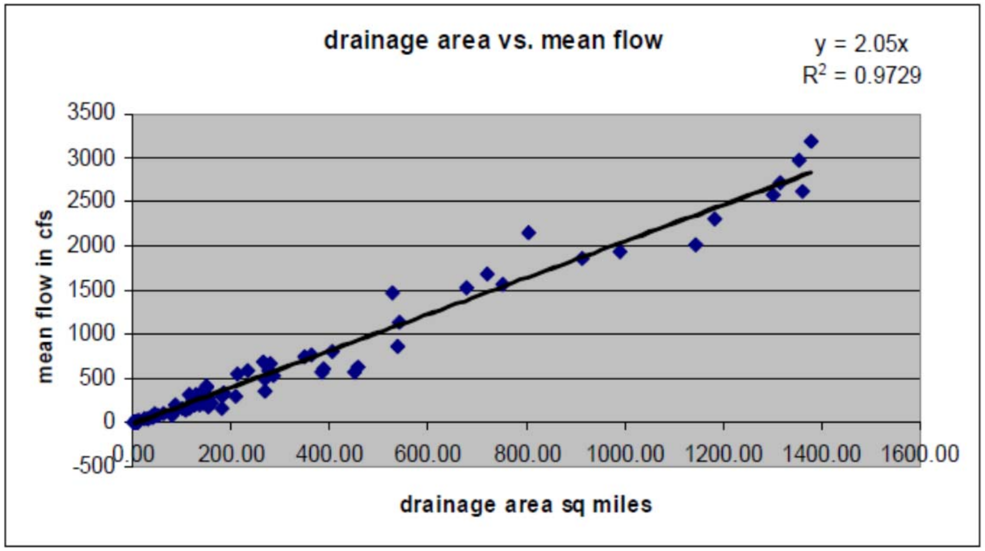
More difficult for ungauged watersheds;

Previous studies have used regression model *f* (drainage area);

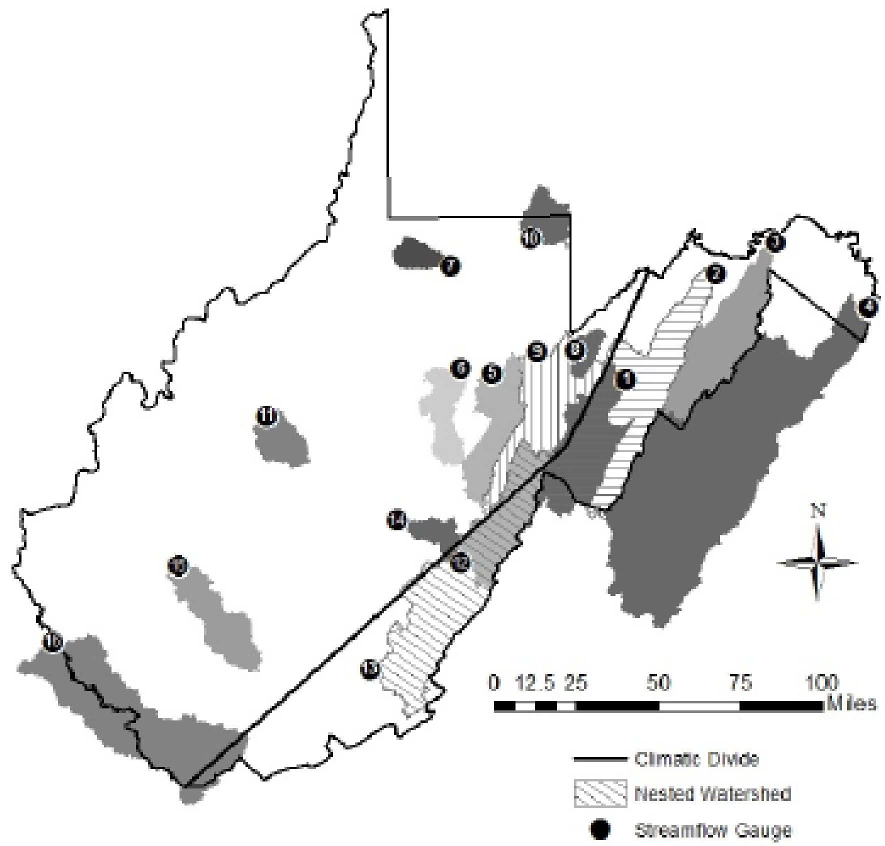
Big Sandy Creek USGS Streamflow station



USGS streamflow stations in WV

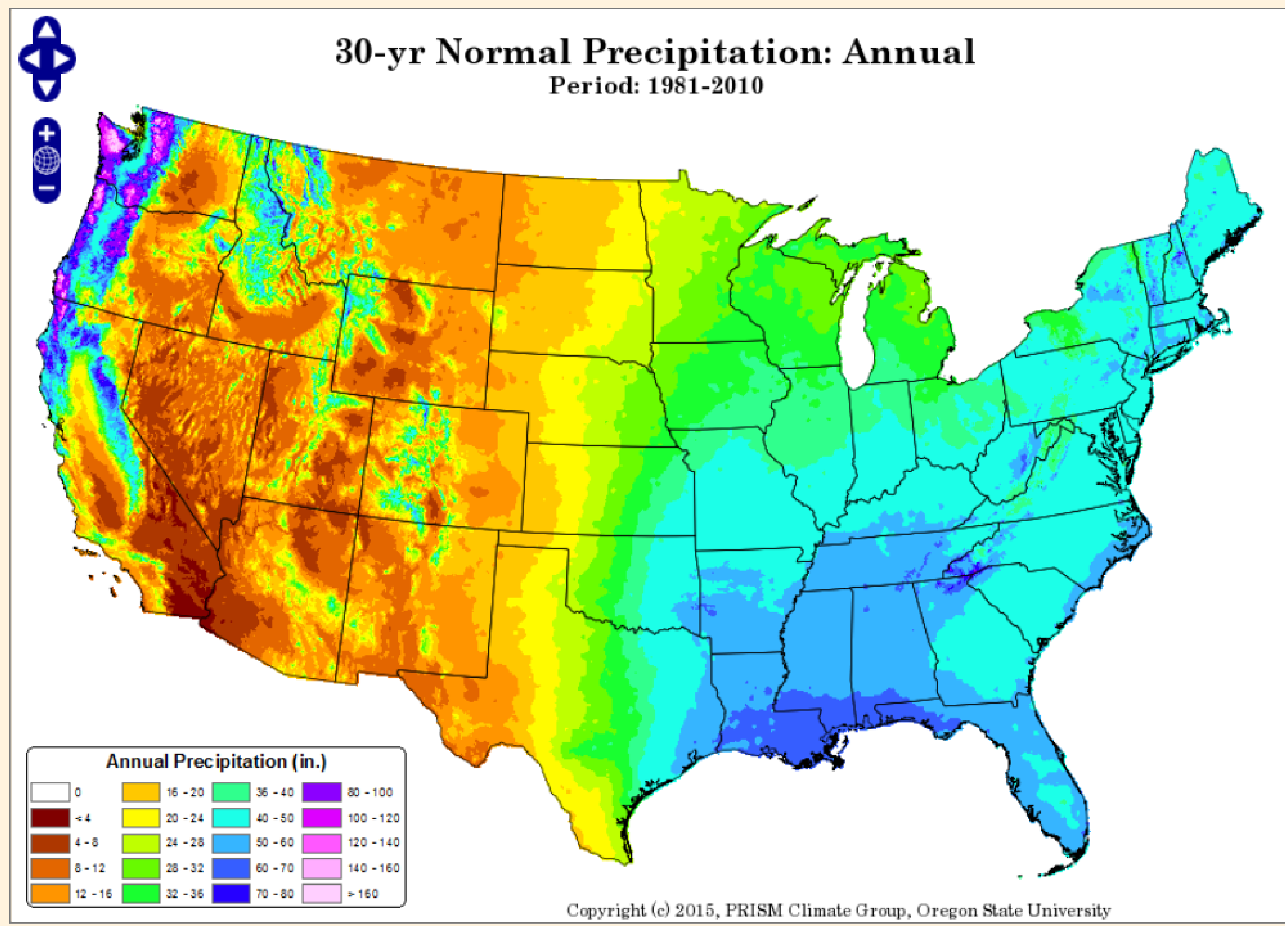


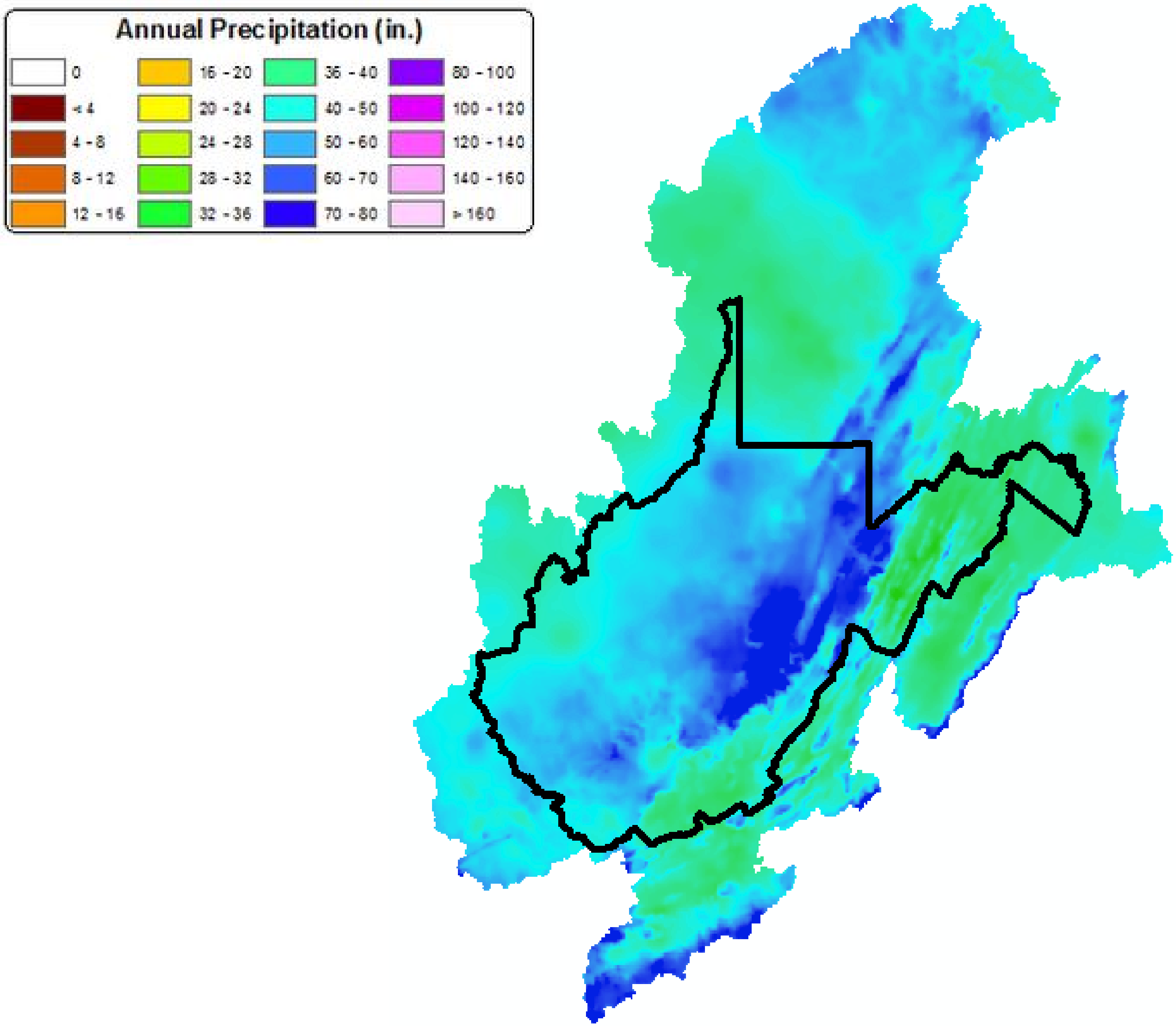
7. Tables and Figures



1	South Branch Potomac River near Petersburg	9	Cheat River near Parsons
2	South Branch Potomac River near Springfield	10	Big Sandy Creek at Rockville
3	Cacapon River near Great Cacapon	11	West Fork Little Kanawha River at Rocksdale
4	Shenandoah River at Millville	12	Greenbrier River at Buckeye
5	Tygart Valley River at Belington	13	Greenbrier River at Alderson
6	Buckhannon River at Hall	14	Williams River at Dyer
7	Buffalo Creek at Barrackville	15	Big Coal River at Ashford
8	Blackwater River at Davis	16	Tug Fork at Kermit

Figure 1. Locations of the 16 study watersheds throughout West Virginia.

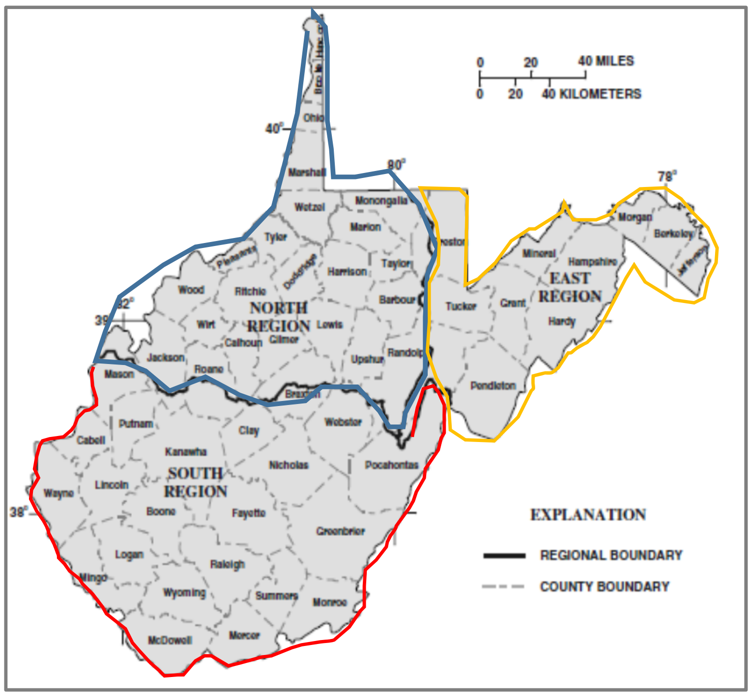

30-yr Normal Precipitation: Annual
Period: 1981-2010
Annual Precipitation (in.)
0
< 4
4 - 8
8 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 100
100 - 120
120 - 140
140 - 160
> 160
Copyright (c) 2015, PRISM Climate Group, Oregon State University


Annual Precipitation (in.)
0
< 4
4 - 8
8 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 100
100 - 120
120 - 140
140 - 160
> 160

Travel time estimation

Updated version uses Q/P relationship from regional modeled outputs

- Limited by the free flowing upstream contributing area above a USGS gauge site with records that match the precipitation data



Region	Watersheds	USGS #	P-Q Regression Model	R^2	Q/P
North	Big Sandy	3070500	y = 0.9691x - 503.69	0.888	0.57
North	Blackwater	3066000	y = 0.9512x - 496.25	0.9	0.6
North	Buckhannon	3053500	y = 0.9529x - 564.02	0.92	0.55
North	Buff Ck	3061500	y = 0.8272x - 507.36	0.855	0.4
North	Cheat	3069500	y = 1.015x - 539.03	0.939	0.63
North	Tygart Val	3051000	y = 0.9669x - 546.51	0.929	0.55
North	William	3186500	y = 0.8876x - 417.14	0.83	0.61
South	GB Ald	3183500	y = 0.9696x - 546.61	0.888	0.46
South	GB Buck	3182500	y = 0.9459x - 566.26	0.888	0.48
South	Big Coal	3198500	y = 0.7698x - 464.09	0.84	0.38
South	TugKermit	3214500	y = 0.6861x - 393.82	0.787	0.28
East	SB Pot Peters	1606500	y = 1.7037x - 992.39	0.76	0.73
East	SB Pot Spring	1608500	y = 0.8094x - 425.27	0.797	0.35
East	ShenMillville	1636500	y = 0.6684x - 344.43	0.688	0.31

Travel time estimation

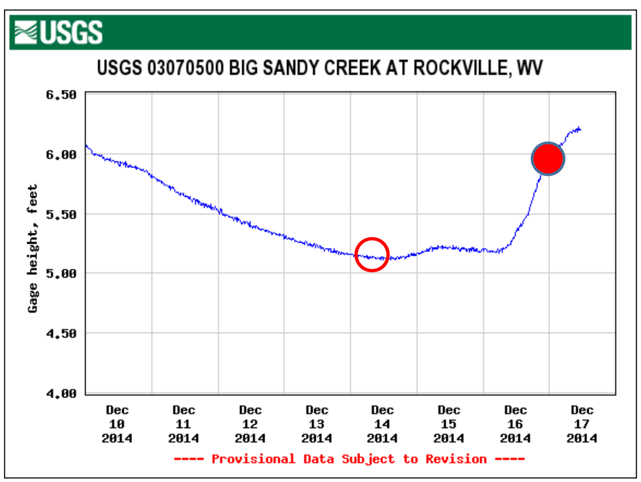
Determining Q event streamflow

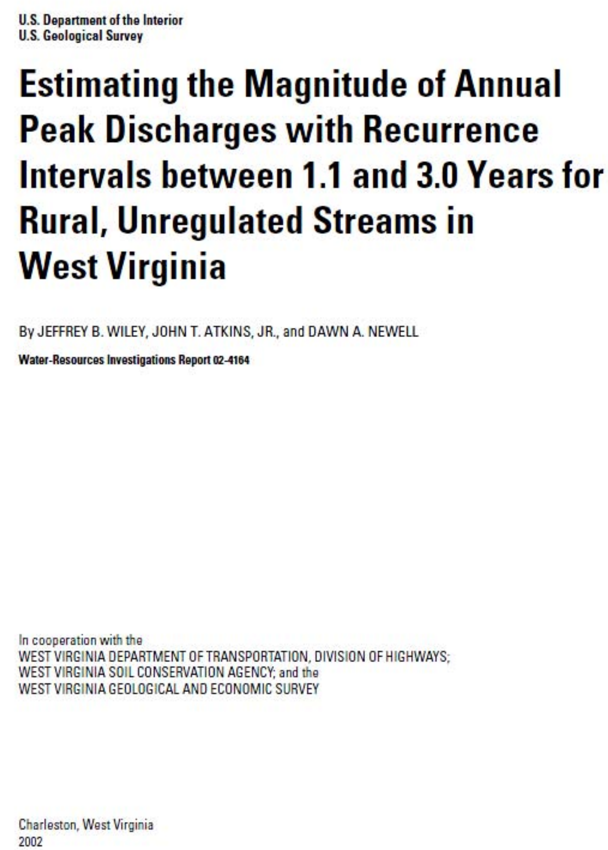
$$Q'_a = \frac{Q}{Q_a}$$

Previous ZCC version used bankfull flow calculated as 90% of annual flow

Updated version uses annual peakflow streamflows from *Wiley et al., 2002*

- Used to represent a range of flow conditions from 1.1 to 3-yr recurrence storms.





U.S. Department of the Interior
U.S. Geological Survey

Estimating the Magnitude of Annual Peak Discharges with Recurrence Intervals between 1.1 and 3.0 Years for Rural, Unregulated Streams in West Virginia

By JEFFREY B. WILEY, JOHN T. ATKINS, JR., and DAWN A. NEWELL

Water-Resources Investigations Report 02-4164

In cooperation with the
WEST VIRGINIA DEPARTMENT OF TRANSPORTATION, DIVISION OF HIGHWAYS;
WEST VIRGINIA SOIL CONSERVATION AGENCY; and the
WEST VIRGINIA GEOLOGICAL AND ECONOMIC SURVEY

Charleston, West Virginia
2002

Travel time estimation

Determining Q event streamflow

$$Q'_a = \frac{Q}{Q_a}$$

U.S. Department of the Interior
U.S. Geological Survey

Estimating the Magnitude of Annual Peak Discharges with Recurrence ...ls between 1.1 and 3.0 Years for Unregulated Streams in ...irginia

...LEY, JOHN T. ATKINS, JR., and DAWN A. NEWELL

...estigations Report 02-4164

Table 1. Equations and regression statistics determined in the regional regression analysis of peak discharges

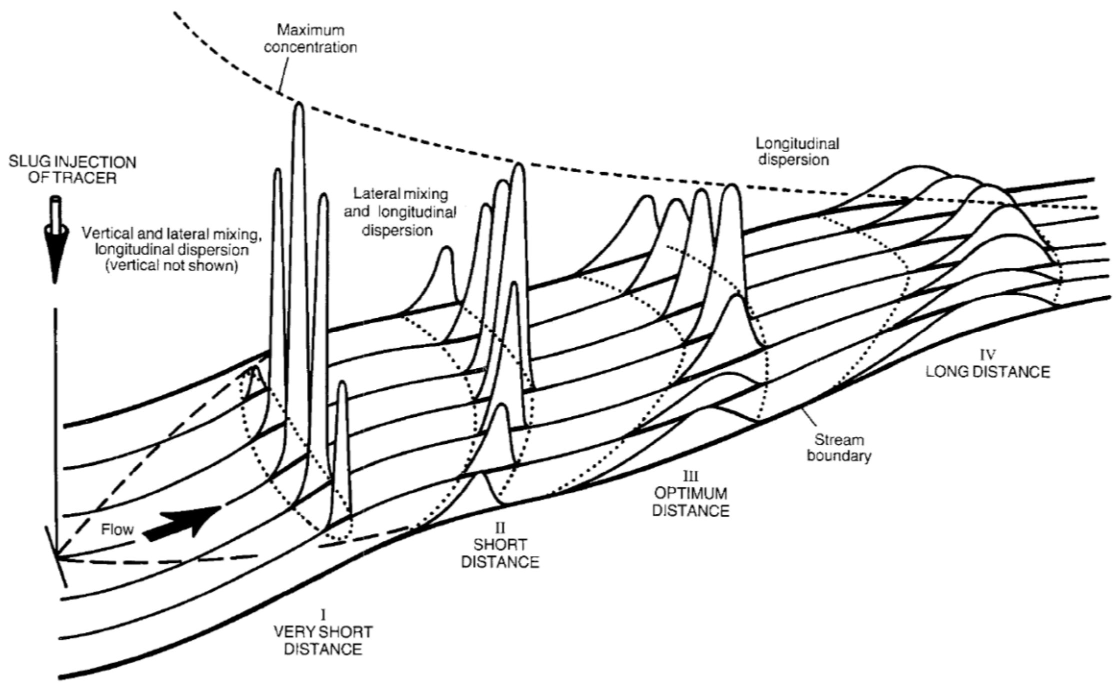
[Q(n) is the discharge in cubic feet per second for the (n)-year recurrence interval; A is the drainage area in square miles]

Regression equation	Standard error of the model, in percent	Average standard error of sampling, in percent	Average prediction error, in percent	Equivalent years of record	Number of streamflow stations	Range of drainage area in square miles
East Region						
Q(1.1) = 31.7 A $^{0.834}$	51.1	10.1	52.4	1.3		
Q(1.2) = 37.9 A $^{0.8}$						
Q(1.3) = 42.6 A $^{0.8}$						
Q(1.4) = 46.5 A $^{0.8}$						
Q(1.5) = 49.9 A $^{0.8}$						
Q(1.6) = 53.0 A $^{0.8}$						
Q(1.7) = 55.8 A $^{0.8}$						
Q(1.8) = 58.4 A $^{0.8}$						
Q(1.9) = 60.9 A $^{0.8}$						
Q(2) = 62.6 A $^{0.842}$						
Q(2.5) = 72.9 A $^{0.8}$						
Q(3) = 80.2 A $^{0.843}$						
North Region						
Q(1.1) = 57.7 A $^{0.789}$	30.8	7.6	31.8	2.6		
Q(1.2) = 73.2 A $^{0.771}$						
Q(1.3) = 85.3 A $^{0.759}$						
Q(1.4) = 95.5 A $^{0.751}$						
Q(1.5) = 105 A $^{0.744}$						
Q(1.6) = 113 A $^{0.738}$						
Q(1.7) = 120 A $^{0.733}$						
Q(1.8) = 127 A $^{0.728}$						
Q(1.9) = 134 A $^{0.725}$						
Q(2) = 138 A $^{0.724}$						
Q(2.5) = 166 A $^{0.708}$						
Q(3) = 188 A $^{0.698}$						
South Region						
Q(1.1) = 46.9 A $^{0.804}$	47.4	8.0	48.3	1.1		
Q(1.2) = 56.9 A $^{0.799}$	44.0	7.6	44.8	1.3		
Q(1.3) = 64.4 A $^{0.795}$	42.3	7.6	43.1	1.4		
Q(1.4) = 70.5 A $^{0.792}$	41.1	7.6	41.9	1.4		
Q(1.5) = 75.8 A $^{0.790}$	40.3	7.3	41.1	1.5		
Q(1.6) = 80.6 A $^{0.789}$	39.7	7.3	40.5	1.5	100	0.10–8,371
Q(1.7) = 84.8 A $^{0.787}$	39.2	7.3	40.0	1.5		
Q(1.8) = 88.8 A $^{0.786}$	38.8	7.3	39.6	1.6		
Q(1.9) = 92.4 A $^{0.785}$	38.5	7.3	39.3	1.6		
Q(2) = 95.4 A $^{0.785}$	38.4	7.3	39.2	1.6		
Q(2.5) = 110 A $^{0.781}$	37.6	7.3	38.4	1.7		
Q(3) = 121 A $^{0.778}$	37.2	6.9	38.0	1.7		

Travel time estimation

$$V_{mp} = 0.82 + \left(0.02 * \ D_a'^{0.919} \ \ Q_a'^{-0.469} \ \ S^{0.159} \ \ \frac{Q}{D_a}\right)$$

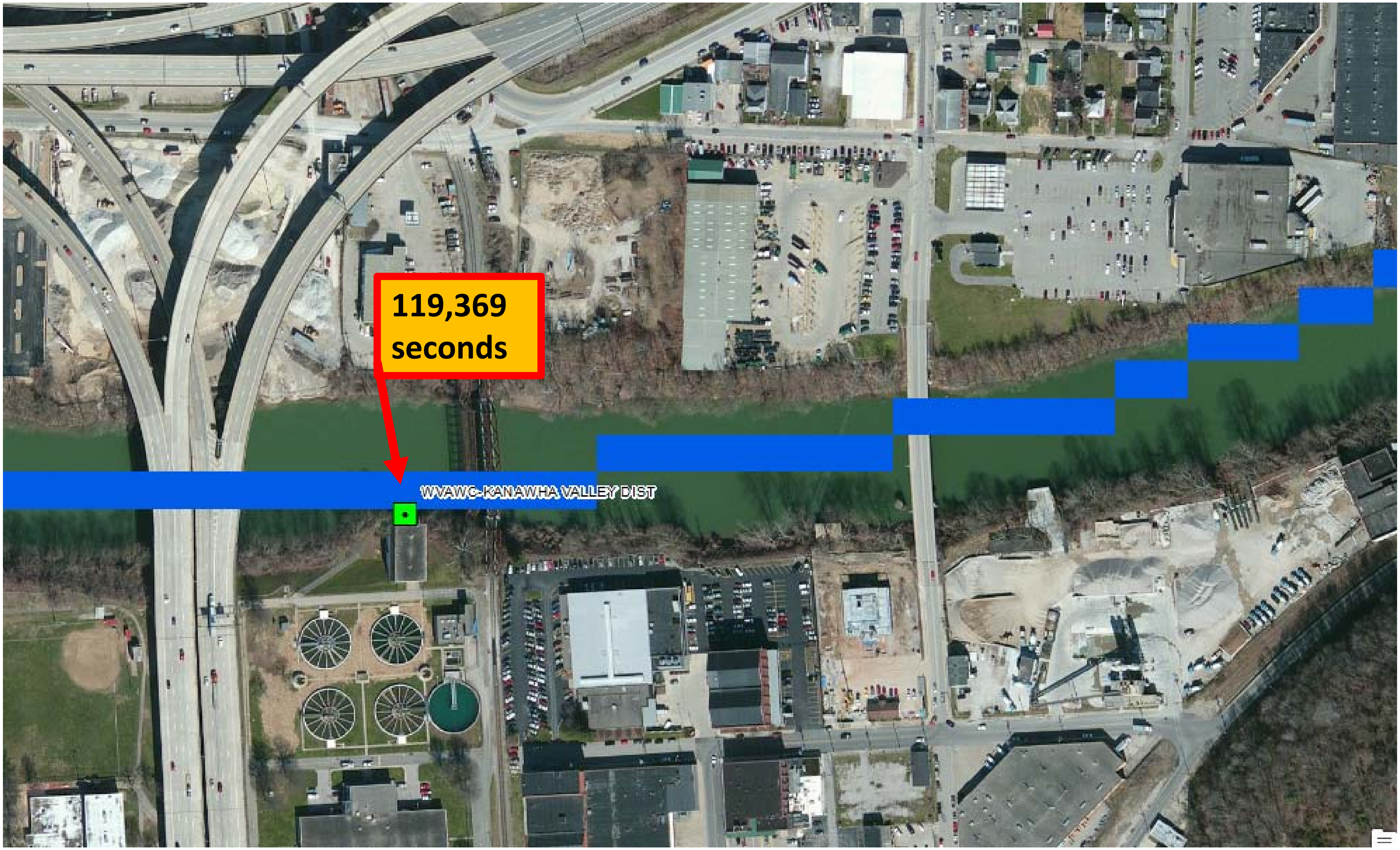
$V_{mp} =$ Maximum probable velocity

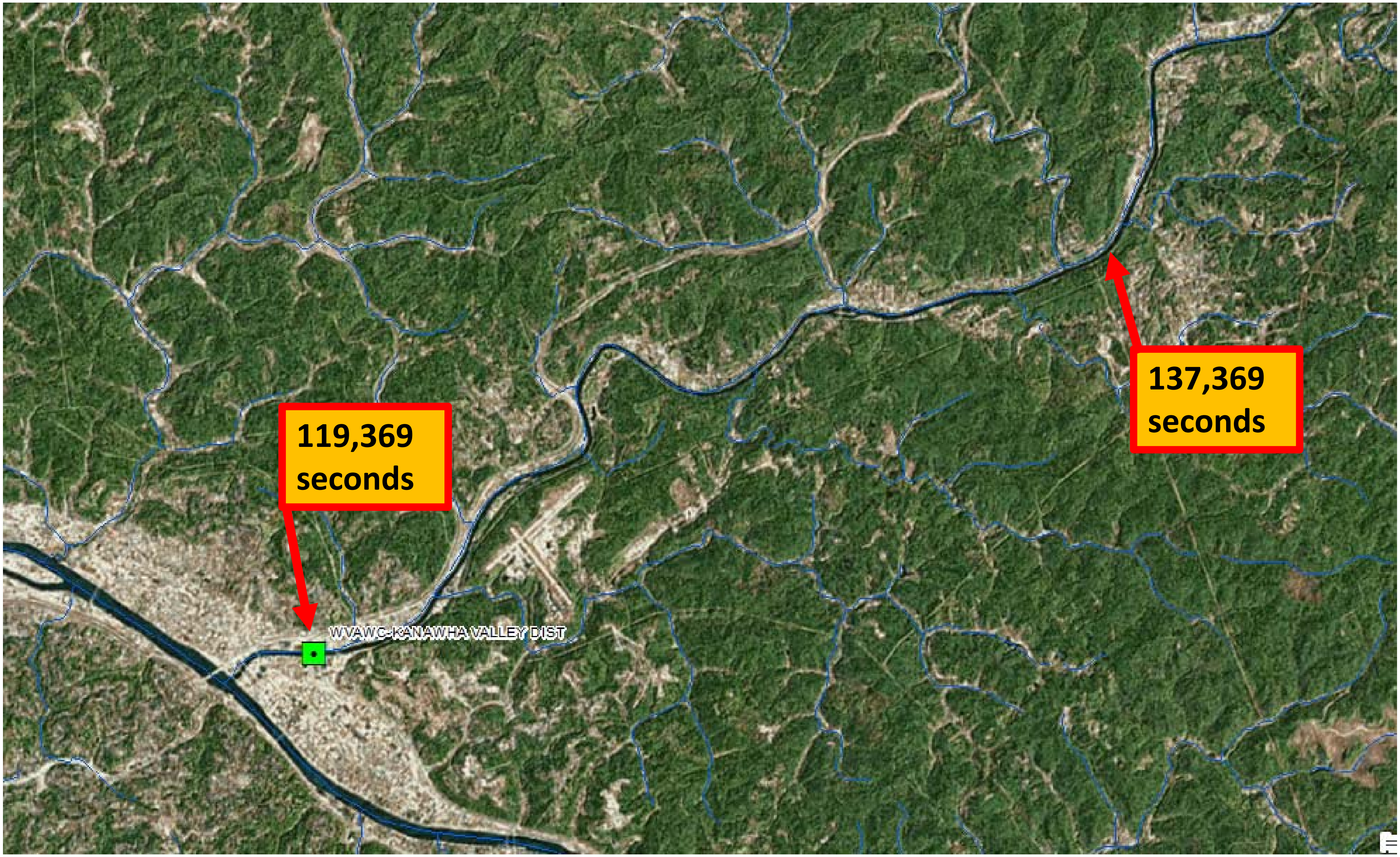


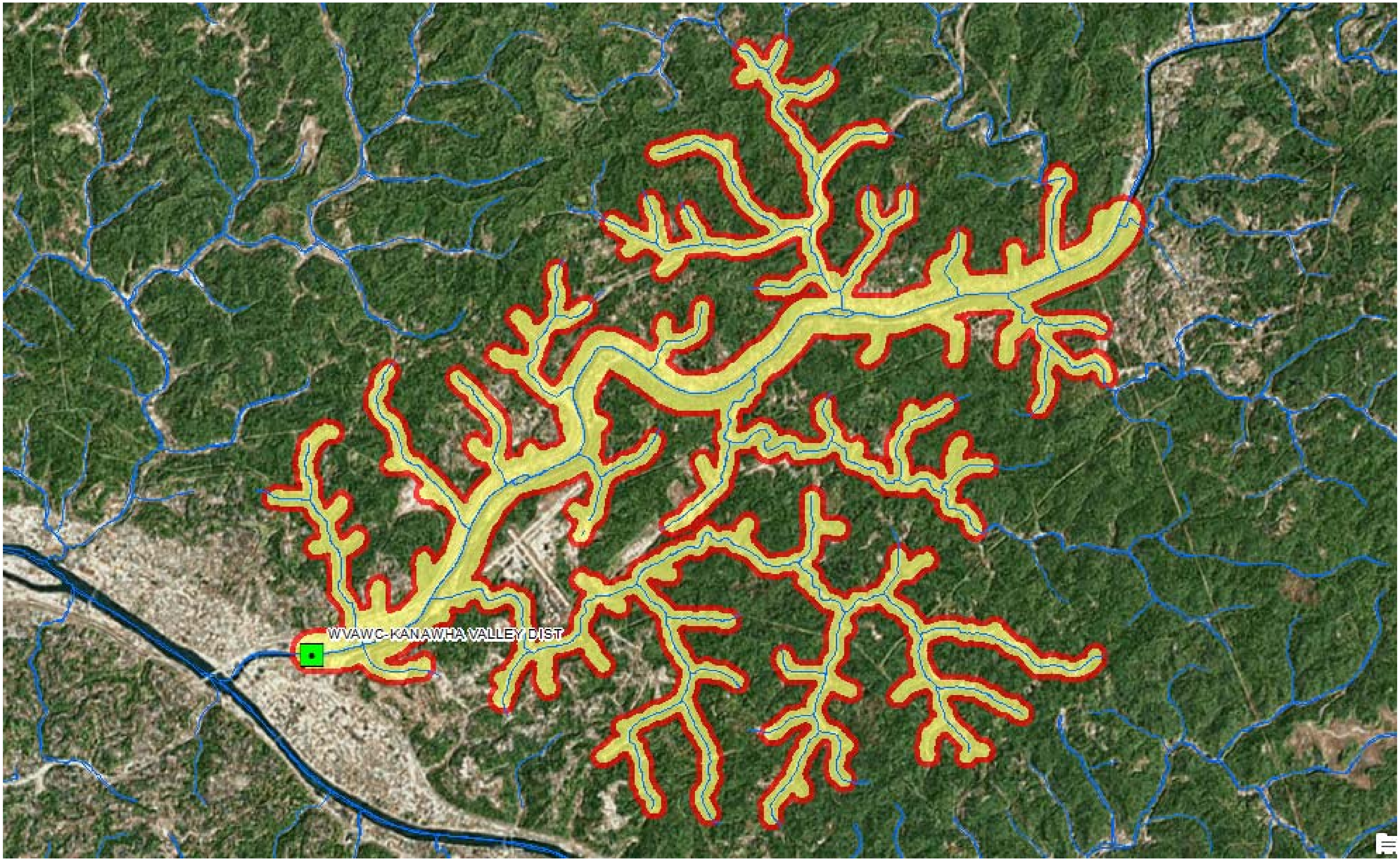
Kilpatrick & Wilson, 1982

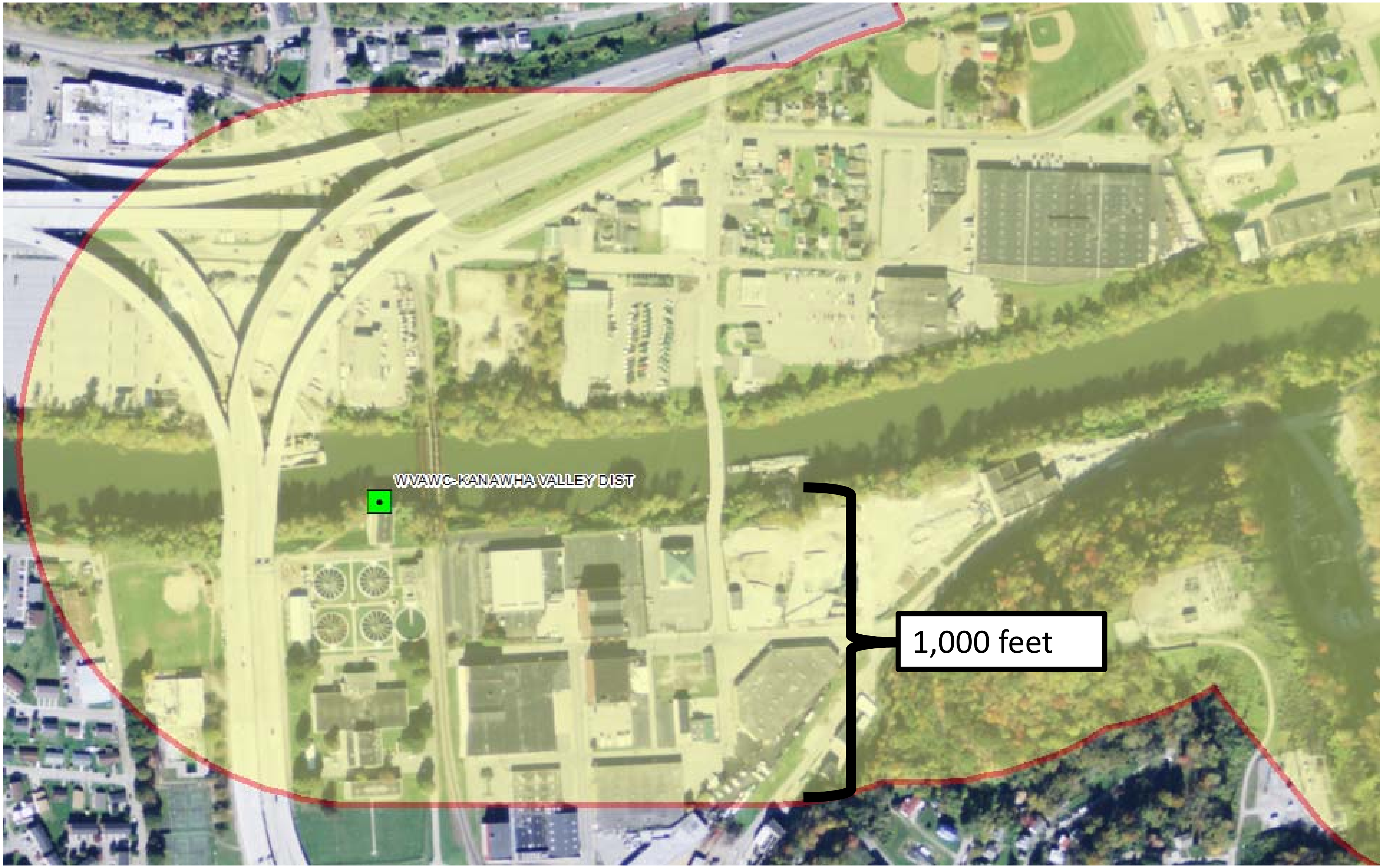

WVAWC-KANAWHA VALLEY DIST


WVAWC-KANAWHA VALLEY DIST

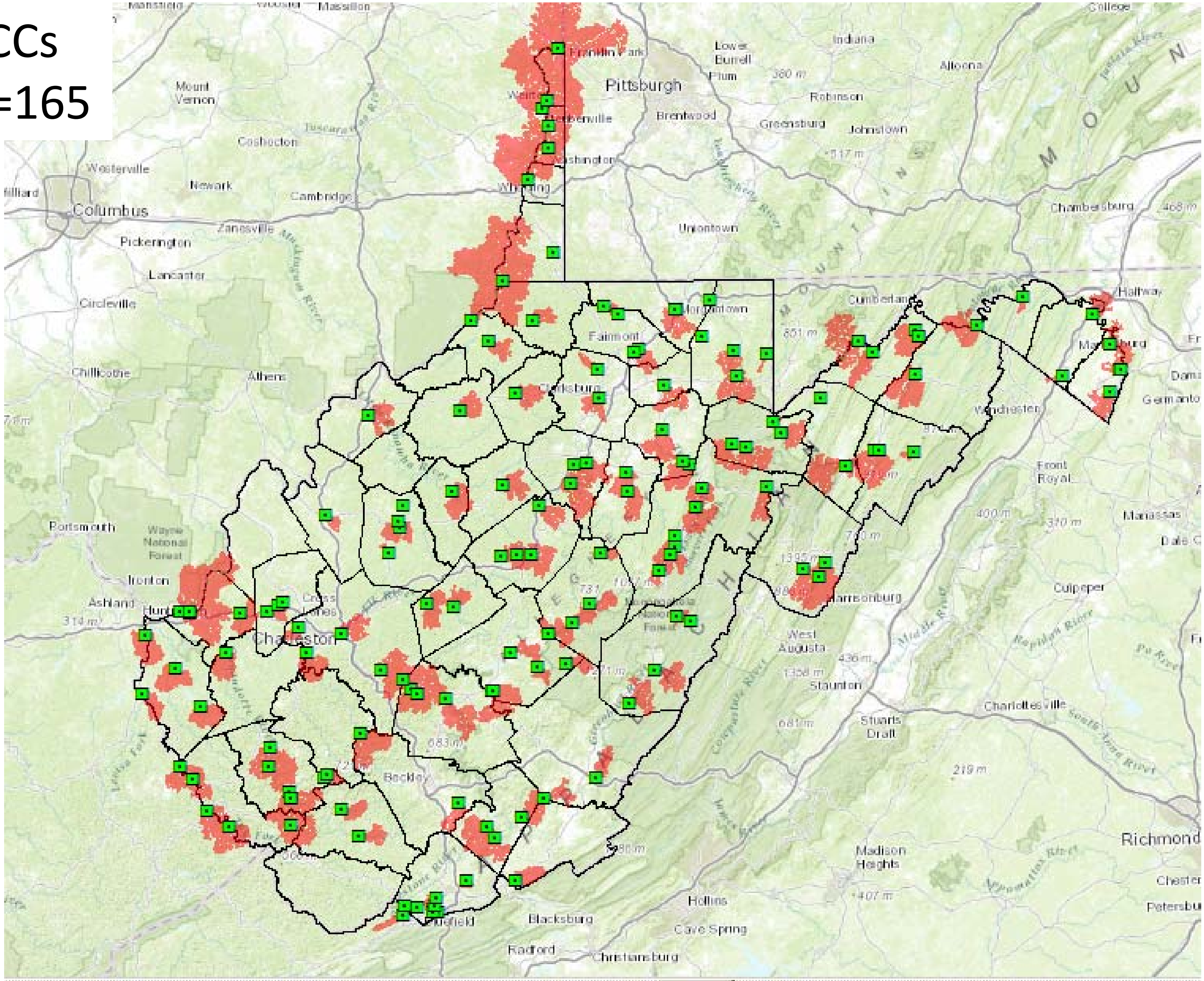

119,369 seconds
WVAWC-KANAWHA VALLEY DIST


119,369
seconds
137,369
seconds
WVAWC-KANAWHA VALLEY DIST


WVAWC-KANAWHA VALLEY DIST

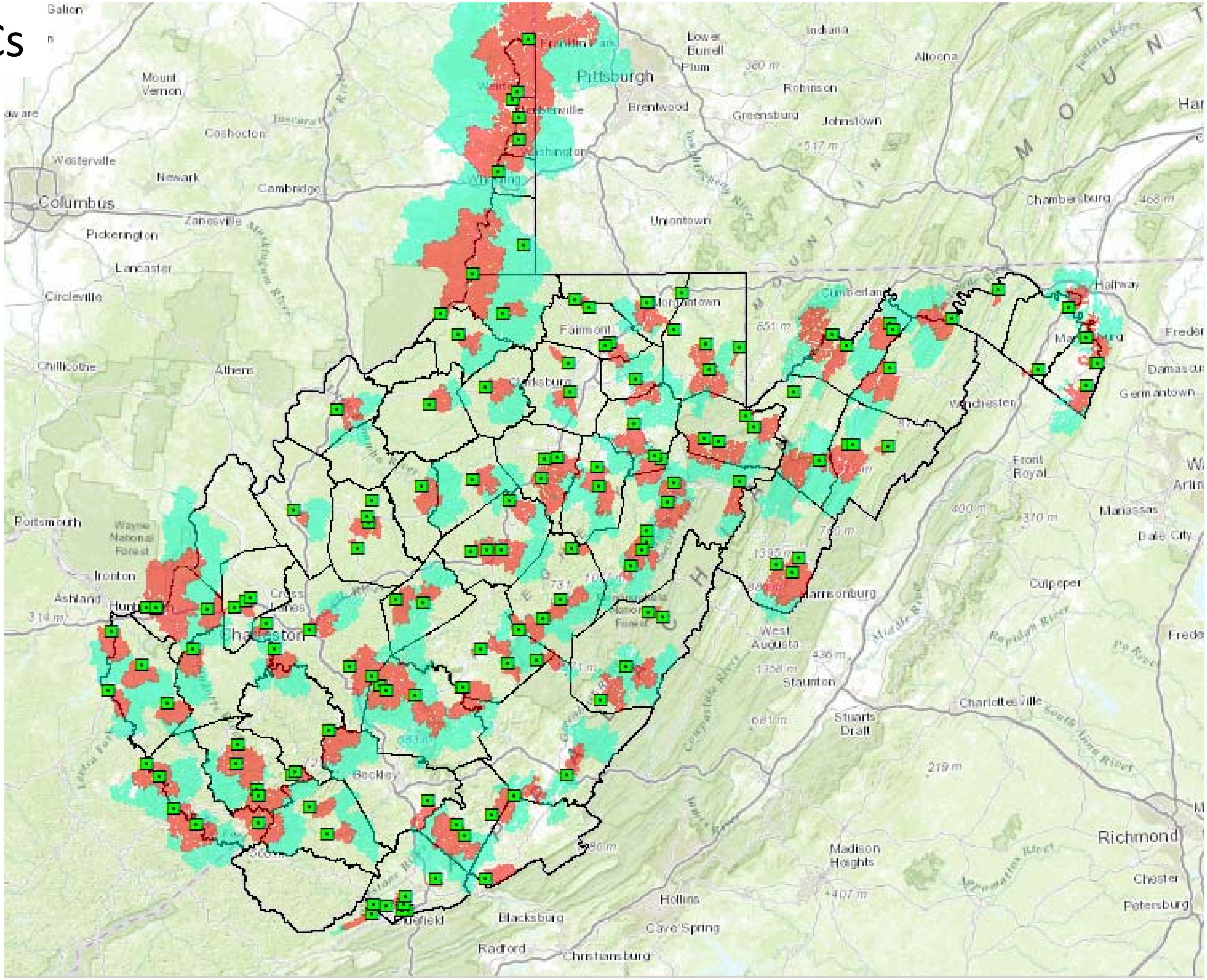

WVAWC-KANAWHA VALLEY DIST
1,000 feet

ZCCs
n=165



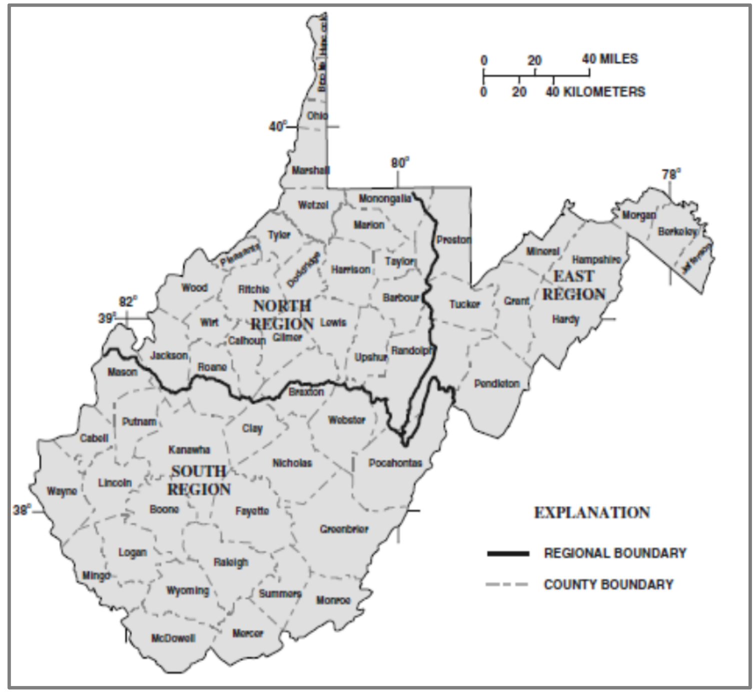
Pittsburgh
Franklin Park
Weirton
Steubenville
Washington
Wheeling
Lower Burrell
Plum
Indiana
Altoona
Robinson
Brentwood
Greensburg
Johnstown
Uniontown
Chambersburg
Cumberland
Hagerstown
Halfway
Martinsburg
Winchester
Front Royal
Manassas
Culpeper
Harrisonburg
Staunton
West Augusta
Stuarts Draft
Charlottesville
Madison Heights
Richmond
Chester
Petersburg
Hollins
Blacksburg
Cave Spring
Radford
Christiansburg
Bluefield
Beckley
Charleston
Cross Lanes
Huntington
Ashland
Ironton
Portsmouth
Wayne National Forest
Chillicothe
Athens
Circleville
Lancaster
Pickerington
Columbus
Westerville
Newark
Zanesville
Cambridge
Coshocton
Mount Vernon
Mansfield
Massillon
Fairmont
Morgantown
Clarksburg
Germanton

ZPCs



Limitations

- Three streamflow regions
- Doesn't consider dispersion plume for specific chemicals
- Maximum velocity equation is very conservative
- Lack of calibration or validation at this time



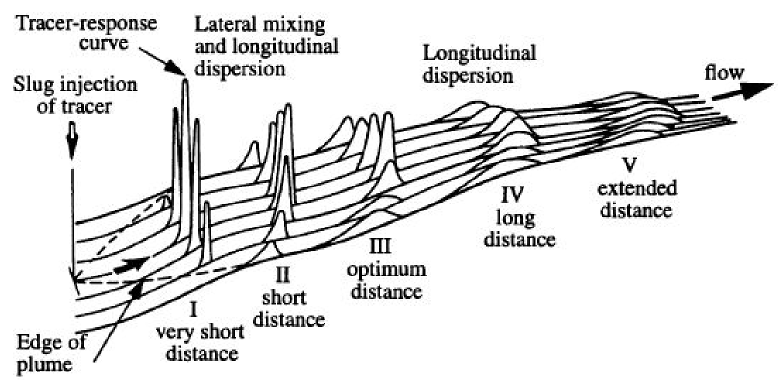


Figure 1. Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center, slug injection of tracer. (Modified from Kilpatrick, 1993, p. 2.)

Why the 2001 and 2015 ZCC differences?

- 100K streams versus 24k streams
- One stream flow equation versus three regional ones
- Bankfull flow of 90% of high flow versus statistical occurrence of 90% flow
- 30m elevation data versus 1 and 3m elevation data to provide drainage area and stream gradient
- Buffers from stream centerline versus stream banks