Land Use and Stream Health in the Rivanna Basin, 2007-2009

By John Murphy
Science Advisor, StreamWatch
September 30, 2011

StreamWatch
P.O. Box 681
Charlottesville, VA 22901
www.streamwatch.org

ACKNOWLEDGMENTS

This report reflects the work of scores of individuals and thousands of person-hours. We extend our deep gratitude to the following individuals and organizations, without whose generosity and dedication this study would not have been possible.

StreamWatch Partners

Albemarle County / City of Charlottesville / Fluvanna County / The Nature Conservancy Rivanna Conservation Society / Rivanna River Basin Commission / Rivanna Water and Sewer Authority / Thomas Jefferson Planning District Commission / Thomas Jefferson Soil and Water Conservation District

Science Collaborators

For guidance with study design, assistance with modeling, and review of analytical methods, we extend our special thanks to Karen McGlathery and Todd Scanlon of University of Virginia’s Department of Environmental Sciences. For contributing research on stream sedimentation, we extend our special thanks to Christine May of James Madison University’s Department of Biology.

Technical Support

For development and management of GIS-based information about the Rivanna basin, we extend our special thanks to Chris Bruce of The Nature Conservancy, to Rick Odom, to Chesapeake Bay Funders Network, and to WorldView Solutions, Inc.

StreamWatch Technical Advisory Committee

For general guidance and support, and for review of text and analysis, we thank StreamWatch’s Technical Advisory Committee:

Samuel Austin, U.S. Geological Survey / Greg Harper, Albemarle County / David Hirschman, Center for Watershed Protection / John Kauffman, Virginia Department of Game and Inland Fisheries / Karen McGlathery, University of Virginia / Rick Odom, Ecologist, GIS specialist / Brian Richter, The Nature Conservancy

Todd Scanlon, University of Virginia / William Van Wart, Virginia Department of Environmental Quality

Volunteers and Interns

Our profound and heartfelt gratitude goes out to the many volunteers and interns who assisted with data collection and data management. We could not have completed this study without your hard work. Thank you!

Volunteers

Jennifer Alexander / Michael Baker / Dav Banks / Cameron Beers / Calvin Biesecker
Steve Botts / Kelly Bowman / Rachel Bush / Nora Byrd / David Carr / Tina Colom
Gus Colom / Cristina Cornell / Erin Cornell / Nancy Cornell / Aaron Cross / Vince Dish
Laura Dollard / Sharon Ellison / Terri Ellison / Brendan Ferreri-Hamberry / Jane Fisher
Nancy Ford / Ned Foss / Doug Fraser / Nancy Friend / Diane Frisbee / James Gano
Kathy Gerber / Nancy Gercke / Repp Glaettli / Helen Gordon / Sean Grzegorczyk
Shane Grzegorczyk / Deb Hackett / Elise Hackett / Ralph Hall / Shirley Halladay
Allen Hard / Bob Henricks / Tana Herndon / Joel Howard / John Ince / Stefan Jirka
Karen Joyner / Jim Kabat / Terri Keffert / Aidan Keith-Hynes / Bronwyn Keith-Hynes
Patrick Keith-Hynes / Frances Lee-Vandell / Vera Leone / Keggie Mallett
Ann McLeod-Lambert / Vicki Metcalf / Susan Meyer / Jill Meyer / Leslie Middleton
Janet Miller / Becky Minor / Maggie Murphy / Sarah Murphy / Rose Sgarlat Myers
Jim Nix / Marianne O'Brien / Cindy O'Connell / Killian O'Connell / James Peacock
Frank Persico / Art Petty / Kristin Pickering / Elena Prien / Patrick Punch
Anne Rasmussen / Nicola (Nicky) Roberts / Pat Schnatterly / Steve Schnatterly
Marjorie Siegel / Susan Sleight / Hugo Spaulding / Will Spaulding / Edward Strickler Jr.
Ida Swenson / Roger Temples / Pat Temples / Michelle Thompson / Rob Tilghman
Dorothy Tompkins / Rachel Vigour / John Walsh / Tom Walsh / Phyllis White
Frank Wilczek / Pat Wilczek / Steve Sylvan Willig / James Winsett / Laurel Woodworth

Interns

Aaron Bloch / Will Devault-Weaver / Kelsey Ducklow / Alissa Gador / Erin Gallagher
Benjamin Hines / Aryn Hoge / Margaret Jarosz / Sarah Kang / Katie Layman
Andrew Moore / Robert Noffsinger / Scott Osborne / Catherine Pham / Eleanor Preston
Peter Swigert / Brian Walton / Megan Wood

Funders

Albemarle County
Chesapeake Bay Restoration Fund
City of Charlottesville
Fluvanna County
J & E Berkley Foundation
Rivanna Water and Sewer Authority
The Nature Conservancy
Virginia Environmental Endowment

Contents

1) <u>Summaries</u>

1.1) Abstract.

We examined relationships between land use, stream habitat, and stream benthic macroinvertebrate condition (stream biological condition) in central Virginia's Rivanna River basin. Benthic macroinvertebrate condition was assessed at 51 sites per a slightly modified version of the Virginia Stream Condition Index protocol. Basin land use/land cover was classified at high resolution based on planimetrics and aerial imagery. Cattle population densities and grazed pasture were determined from aerial imagery. Across a set of 42 systems ranging from urban to nearly undisturbed conditions, watershed percent impervious cover predicted over 80% of variation in biological condition. When more highly urbanized systems were excluded from analysis, both forest cover and impervious cover emerged as distinctive, equally strong predictors of health, and together accounted for over 60% of biological condition variation. Noticeable biological degradation was associated with a very early stage of watershed disturbance; the healthiest benthic communities were found exclusively in basins with forest cover ≥ 99%. About 60% of the Rivanna basin is exurban (population density ranging from 40 to 160 per square mile; acres per dwelling ranging from 9 to 37 acres; impervious cover ranging from 1.2% to 3.1%). About half of studied exurban systems failed the Virginia aquatic life regulatory standard. Generally, the regulatory threshold was breached before systems reached 3% impervious cover. Cattle operations, quantified at the landscape scale, showed no correlation with biological condition. Streambed permeability was generally low, suggesting excess sedimentation. Several reach-scale habitat variables correlated weakly to moderately with biological condition, but were generally far less predictive of biological condition than was watershed land use/land cover. In rural, exurban, and suburban systems, riparian buffer condition explained some biological variation not captured by land use/land cover, suggesting that forested stream buffers can positively influence stream biology, but only within limits set by watershed land use/land cover. In rural and exurban systems, bank erosion and sediment deposition explained some biological variation not captured by land use/land cover.

1.2) Bulleted list of key findings.

- Most streams we studied failed Virginia's biological standard. This standard tells us whether streams support a variety of life forms. Streams with more life have better water quality, and can provide better services to humans. Such services include water supply, recreation, and aesthetic enjoyment.

- Stream health is closely related to land use. Rural landscapes with lots of forest have healthy streams. Urban areas have unhealthy streams. In between, health declines predictably as land use intensifies. The relationship is so strong that we can estimate stream health based on the amount of forest and development in the surrounding area.

- Unlike development and deforestation, cattle operations, quantified at the watershed scale, did not have a big impact on stream health. However, we did not study the effects of cattle located close to streams.

- Based on land use, we estimate that 70% of Rivanna streams fail the Virginia standard. Fortunately, only 5% to 10% of streams are severely degraded. Most streams sit near the pass/fail cusp and might meet the standard with better care.

- Most of the Rivanna basin is semi-rural (exurban). In this exurban landscape, forest cover averages about 70%, and there are about 17 acres for every house. This amount of disturbance may seem mild, yet more than half of exurban streams failed the biological standard.

- Rural and exurban streams decline rapidly with increased development or deforestation. In urban areas, stream health is already poor. Therefore, urban streams do not respond dramatically to additional development.

- Within 20 years, increased development in non-urban areas could reduce the number of healthy streams by about a third.

- Unstable banks and excess sediment appears to affect stream health in many Rivanna streams.

- Forested buffers alongside streams can protect and improve stream health.

2) Background

2.1) Overview: land use and stream health.

A substantial body of scientific literature documents relationships between land use and stream health (Allan 1997, Schueler 2009, Coles 2004, King 2010, Morse 2003, Ourso 2003). Conceptual models such as Center for Watershed Protection's Reformulated Impervious Cover Model provide useful frameworks for understanding the land use/stream health relationship in general terms (Schueler 2009). But this relationship varies across stream condition parameters (*e.g.* water quality, channel condition, biological integrity), and probably also varies across regions. Further, watershed management and conservation at the ground level often demands local data rather than generalist models.

Previous StreamWatch studies have illustrated strong relationships between land use/land cover and biological condition in the Rivanna basin (Murphy 2006, Murphy 2008). Those studies not only showed strong correlations between land use/land cover and biology, they also suggested that significant biological degradation commenced at fairly low levels of landscape disturbance. The current study draws from more extensive field data than previous studies, and utilizes land use/land cover data that is of far higher quality than that of earlier studies. The study examines empirical relationships between land use/land cover (LU/LC), channel and riparian conditions, and stream biological conditions as expressed by benthic macroinvertebrate multimetric index scores. With these newer, better, and more comprehensive data, we have been able to confirm that biological degradation in streams does indeed begin at the earliest stages of the landscape degradation continuum, and that Rivanna streams commonly fail Virginia's regulatory biological standard at levels of land disturbance commensurate with the basin's characteristically exurban landscape.

2.2) The Rivanna basin.

The Rivanna River drains 765-square miles of central Virginia's Jefferson country. The basin is about 70% forested and 3.2% impervious. Population centers such as the City of Charlottesville notwithstanding, the majority of the basin is exurban, with a mixture of residential and agricultural land uses. Agriculture—mostly cattle grazing—is only lightly to moderately intensive. Forestry is practiced mostly in the form of loblolly pine plantations and periodic harvesting of hardwoods.

For a detailed description of the basin's bedrock geology and soils, see Appendix C.

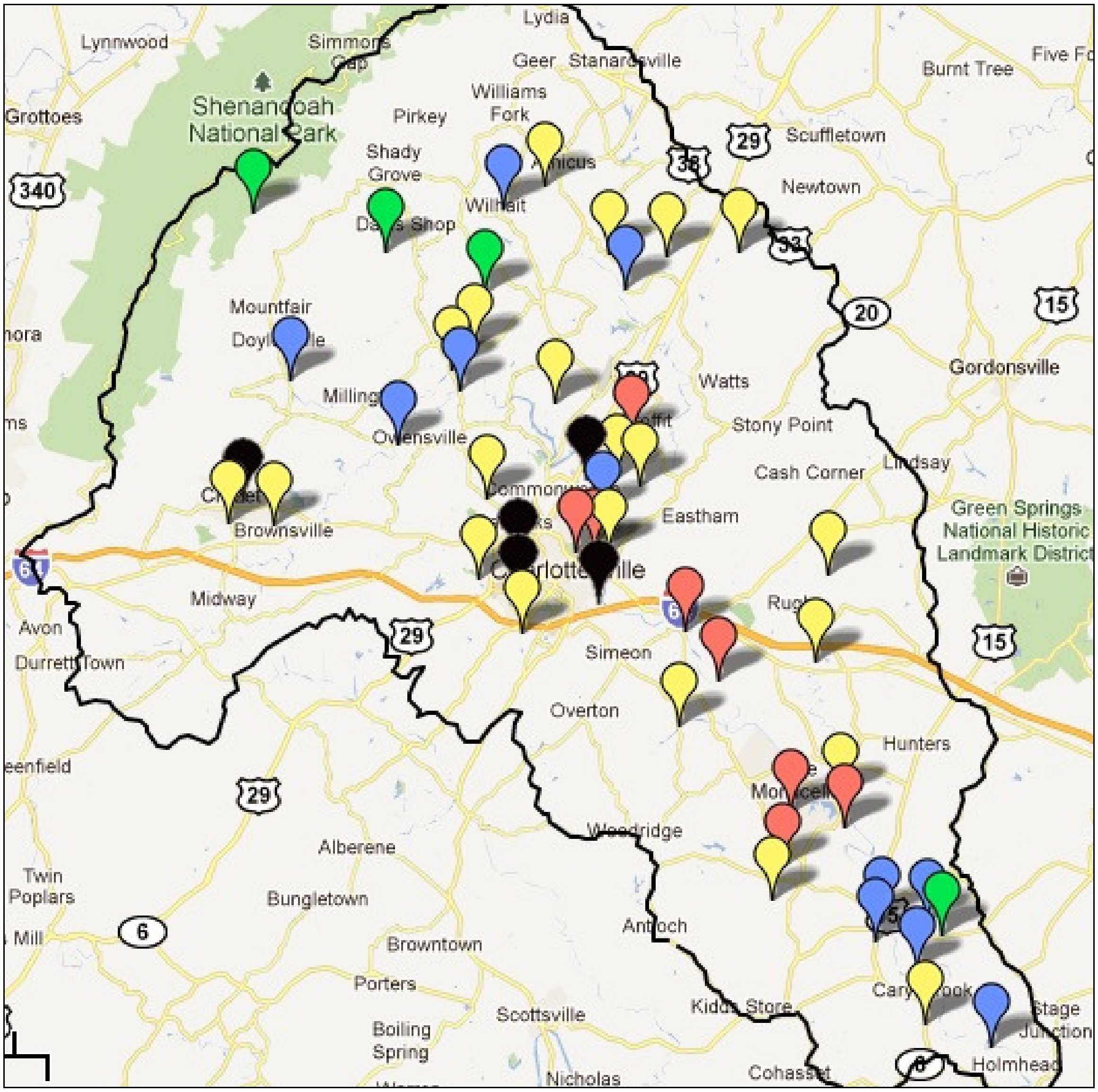
2.3) StreamWatch.

StreamWatch is a community-based monitoring program focused on the Rivanna Basin. We leverage volunteer labor to enhance data collection capacity for community partners ranging from the water and sewer authority to local governments to non-governmental organizations. This organizational model has helped to produce a robust, dense, benthic macroinvertebrate dataset that helps inform Rivanna basin watershed management and conservation. StreamWatch is professionally staffed and is committed to highest data quality standards. Our benthic macroinvertebrate protocol is subject to a Quality Assurance Project Plan approved by the Virginia Department of Environmental Quality (DEQ), and the DEQ uses StreamWatch data to list and de-list streams in its 305(b) reports.

2.4) Scope of this study.

The StreamWatch Land Use Study (LUS) was conceived to explore relationships between stream biological condition, reach-scale habitat conditions, and watershed-scale land use/land cover (LU/LC). The study was designed primarily to examine relationships between watershed scale LU/LC and stream biological condition, but we also explored possible links between landscape conditions (*e.g.* impervious cover) and reach-scale stream habitat conditions (*e.g.* sedimentation). The study was designed to provide information useful for land use planning, watershed management, and conservation. As such, the study focuses on human-mediated factors, and seeks to filter out the effects of natural variables as much as possible.

The study was not designed to trace causal links between environmental and biological conditions. Rather, we looked for empirical relationships, mostly in the form of correlations. Biological and habitat data were gathered at fifty-one sites (see map below). Watersheds were delineated for each site, and land use/land cover was analyzed for each watershed. Relationships among biological condition, habitat, and watershed land use/land cover were analyzed using a variety of statistical techniques. For more information on methods, see Appendix A.



Above: Icons show location and biological condition of study sites, with green indicating healthiest conditions, and black indicating poorest conditions.

2.5) Terminology.

- <u>IC: impervious cover</u> – expressed as the percentage of a given area (*e.g.* a watershed) that is covered by paved or unpaved roads, parking lots, sidewalks, rooftops, and railroads.
- <u>LU/LC: land use/land cover</u> – the terms land use and land cover have overlapping definitions. For instance, a pine plantation can be classified both as a land use (monoculture forestry) and a land cover (pine forest). For the purposes of our report, we chose to combine the terms.
- <u>Scales</u>:

  - Reach scale – the stream reach and riparian zone at and upstream of the sampling site. Depending on stream size, this area can extend up to 1,000 meters upstream of the site. Riparian zone width for our study is approximately 18 meters.
  - Watershed scale or landscape scale – the scale of the entire watershed draining to the sampling site. Areal extent varies from less than 1 square mile to more than 700 square miles.
- Reach-scale variables – include slope, riparian zone condition, channel alteration, and a category we call "channel conditions". Channel conditions include bank stability, frequency of riffles, and a subcategory we call "sediment-related variables, as shown below.

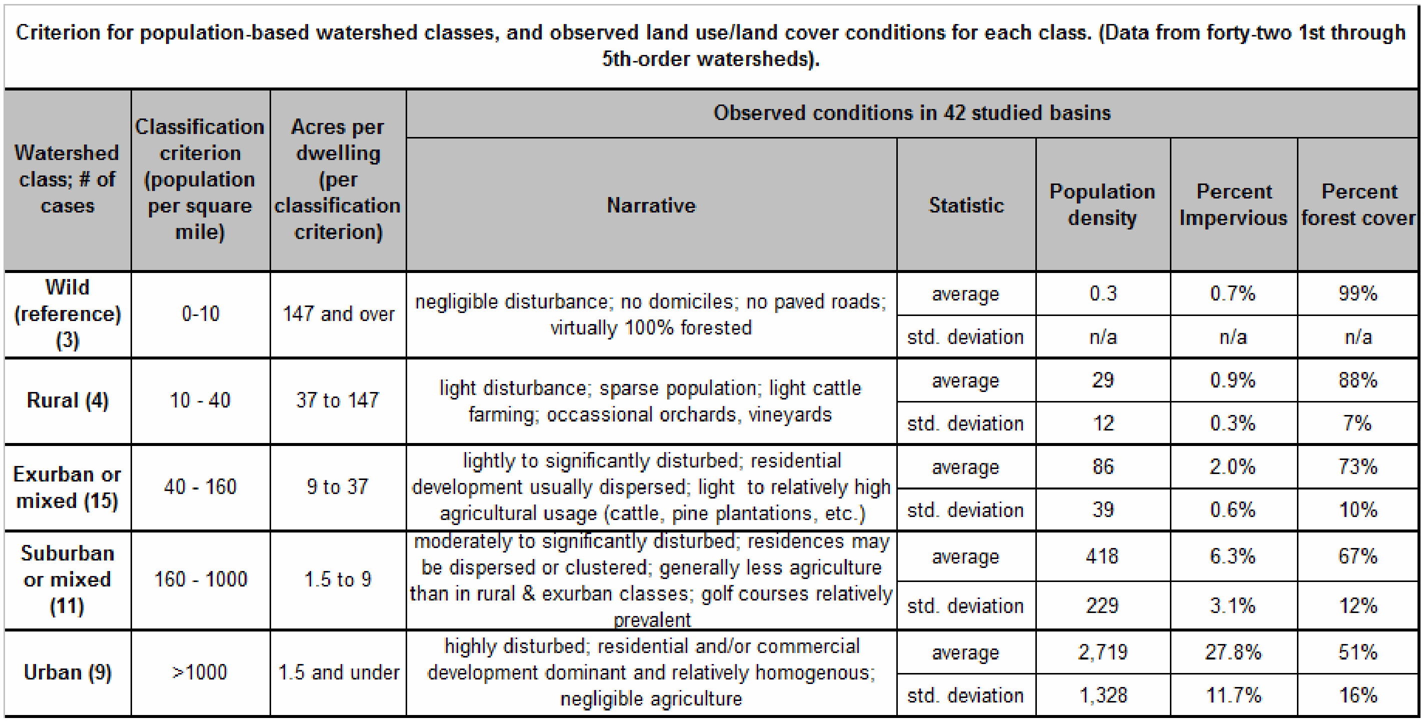
Reach-scale variables
- Channel alteration
- Riparian zone condition
- Slope
- Channel condition
  - Bank stability
  - Frequency of riffles
  - Substrate-related variables
    - Sediment deposition
    - Percent fine sand or clay
    - Percent cobble
    - Median particle size
    - Substrate fine sediment concentration
    - Sustrate permeability

- Stream order – Strahler stream order. Stream size increases with stream order.
- Stream biological condition – the diversity and stress tolerance profile of benthic communities. Biological conditions are expressed as either biological index scores or as health assessments derived from index scores (see sections 2.7 and 6.2). For ease of reading, we also use the terms "stream health", "health", "stream biology", and "biology" synonymously with "stream biological condition".
- System – the stream and its watershed. In our study, watersheds are defined by the location of data collection stations. That is, each field station defines a watershed that terminates at the station.
- Watershed order – Watershed managers use various systems to classify watersheds by size. In this report, watershed order refers to the stream order at the watershed terminus.

2.6) Watershed classifications.

As discussed in the findings section of this report, watershed impervious cover correlates strongly with stream biological condition. Population density follows impervious cover very closely (see section 3.1.6), and is therefore also a very strong predictor of biological condition. StreamWatch finds that classifications based on population density provide terminology that is more readily understood than impervious cover. For instance, a term such as "rural" is far more familiar than "approximately one percent impervious".

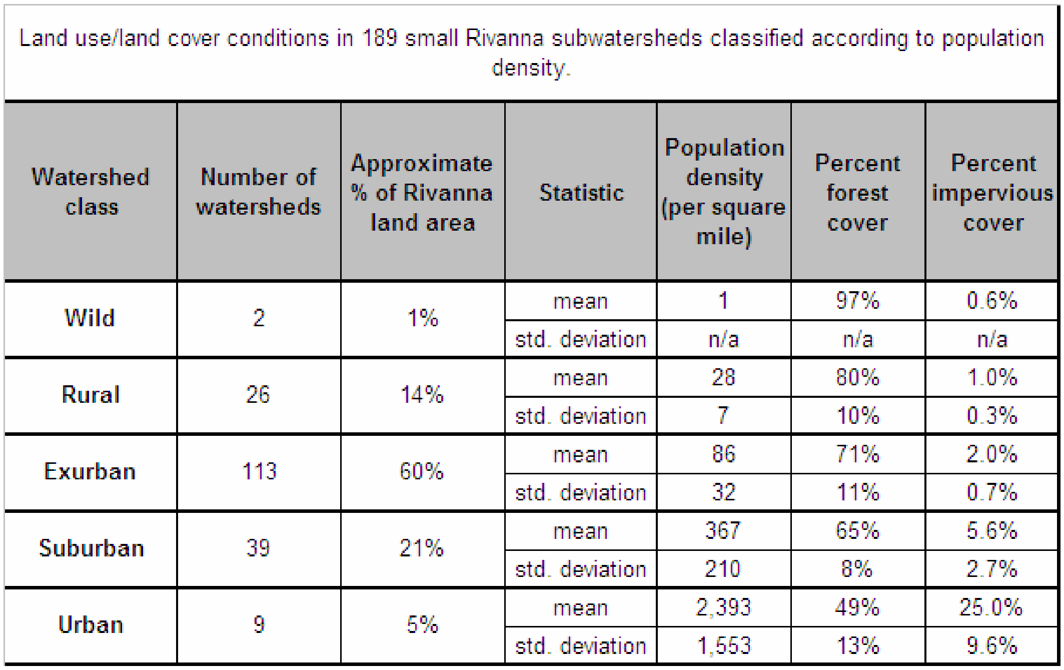
We classified watersheds into five land use intensity categories based on population density (see table below). The classification scheme is adapted from definitions developed by Theobald (Theobald 2004). The table also shows statistics describing observed LU/LC conditions in forty-two 1st though 5th-order systems. This set of forty-two systems is given particular focus in this study's analyses and modeling of relationships between watershed LU/LC and stream biological condition, for reasons explained in section 3.1.1. One of the statistics provided in the table is standard deviation. This statistic gives a sense of the "spread" of the data. About 70% of cases fall within the range indicated by the standard deviation.



Criterion for population-based watershed classes, and observed land use/land cover conditions for each class. (Data from forty-two 1st through 5th-order watersheds).

Watershed class; # of cases	Classification criterion (population per square mile)	Acres per dwelling (per classification criterion)	Observed conditions in 42 studied basins				
			Narrative	Statistic	Population density	Percent Impervious	Percent forest cover
Wild (reference) (3)	0-10	147 and over	negligible disturbance; no domiciles; no paved roads; virtually 100% forested	average	0.3	0.7%	99%
				std. deviation	n/a	n/a	n/a
Rural (4)	10 - 40	37 to 147	light disturbance; sparse population; light cattle farming; occassional orchards, vineyards	average	29	0.9%	88%
				std. deviation	12	0.3%	7%
Exurban or mixed (15)	40 - 160	9 to 37	lightly to significantly disturbed; residential development usually dispersed; light to relatively high agricultural usage (cattle, pine plantations, etc.)	average	86	2.0%	73%
				std. deviation	39	0.6%	10%
Suburban or mixed (11)	160 - 1000	1.5 to 9	moderately to significantly disturbed; residences may be dispersed or clustered; generally less agriculture than in rural & exurban classes; golf courses relatively prevalent	average	418	6.3%	67%
				std. deviation	229	3.1%	12%
Urban (9)	>1000	1.5 and under	highly disturbed; residential and/or commercial development dominant and relatively homogenous; negligible agriculture	average	2,719	27.8%	51%
				std. deviation	1,328	11.7%	16%

The following table provides similar statistics for the Rivanna overall (as opposed to just those systems which we studied). The data are drawn from 189 small watersheds with land area equal to or greater than 1 square mile. We culled the very smallest watersheds from this analysis because population estimates are subject to greater error in very small watersheds. Accounting for the exclusion of very small watersheds, the area analyzed covers 98% of the Rivanna basin.



Land use/land cover conditions in 189 small Rivanna subwatersheds classified according to population density.

Watershed class	Number of watersheds	Approximate % of Rivanna land area	Statistic	Population density (per square mile)	Percent forest cover	Percent impervious cover
Wild	2	1%	mean	1	97%	0.6%
			std. deviation	n/a	n/a	n/a
Rural	26	14%	mean	28	80%	1.0%
			std. deviation	7	10%	0.3%
Exurban	113	60%	mean	86	71%	2.0%
			std. deviation	32	11%	0.7%
Suburban	39	21%	mean	367	65%	5.6%
			std. deviation	210	8%	2.7%
Urban	9	5%	mean	2,393	49%	25.0%
			std. deviation	1,553	13%	9.6%

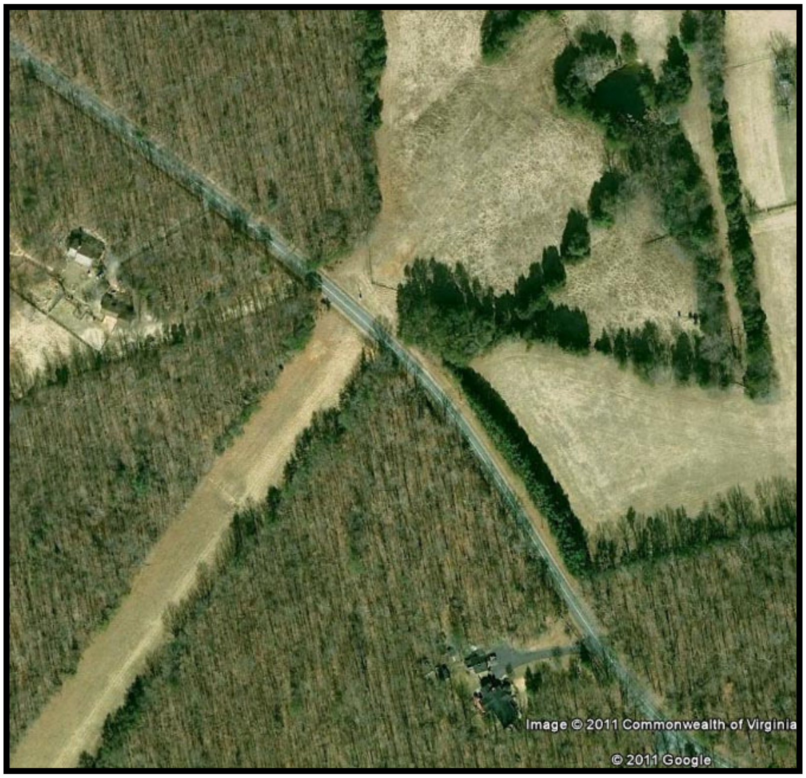
As shown above, the predominant land class in the Rivanna basin is exurban, accounting for sixty percent of the basin's land area. For this reason, our report focuses substantial attention on the exurban landscape as it relates to stream biological condition.

<u>Photographic examples of watershed types</u>.

Following are aerial photographs exemplifying each of the landscape classes described above. Each photo covers 40 acres (1/16th square mile), and shows the approximate average forest cover and housing density for the class.

Above: 40 acres of <u>wild</u> landscape. A small gravel road can be seen. Otherwise, the land is undisturbed.

Above: 40 acres of <u>rural</u> landscape. Average density in rural Rivanna is about 12 houses per square mile. Typical forest cover is about 80%.



Above: 40 acres of *<u>exurban</u>* *landscape. Average density in exurban Rivanna is about 37 houses per square mile. Typical forest cover is about 70%*

Above: 40 acres of *<u>suburban</u>* *landscape. Average density in suburban Rivanna is about 160 houses per square mile. Typical forest cover is about 65%.*

Above: 40 acres of urban landscape. Average density in urban Rivanna is about 1,040 houses per square mile. Typical forest cover is about 40%.

2.7) Measuring biological condition; StreamWatch assessment tiers; Virginia regulatory standard.

Using kick-nets with 1500 micron mesh, professional staff and volunteers collected an average of six benthic macroinvertebrate samples at each site over a period of two and a quarter years (spring 2007 through spring 2009). Target sample size was 200 specimens. Specimens were identified in the field and laboratory to the taxonomic level of family.

Biological index scores were calculated for each sample per the Virginia Department of Environmental Quality's Virginia Stream Condition Index protocol, an eight-metric index of biotic integrity that reflects diversity, stress tolerance, and other attributes of the benthic macroinvertebrate community (Barbour 1999). To learn more about how biological condition is scored via the Stream Condition Index, see the demonstration at the StreamWatch website: http://streamwatch.org/data-pop/streamwatch-scores.

Though StreamWatch's field collection protocol is somewhat different than Virginia DEQ's, the calculation of index scores is identical. Recognizing differences between field protocols, we call our version of the protocol the Adapted Stream Condition Index (ASCI). StreamWatch's procedures are subject to a Quality Assurance Project Plan approved by the Virginia DEQ. Virginia DEQ rates StreamWatch's biological data as "Level 3", meaning that the DEQ considers StreamWatch's data to be as reliable as its own data. The DEQ uses StreamWatch data to list and de-list streams on the Virginia impaired waters list (303[d] list).

This study's analyses and findings discuss biological condition in terms of both scores and assessments. Section 6.2 describes our methods for producing biological condition scores and assessments. The following table provides a reference for comparing scores, stream biological condition assessment tiers, and narrative descriptions of communities in different tiers.

Biological condition assessment tiers, associated index scores, and generalized descriptions of benthic macroinvertebrate communities associated with health tiers.

Biological condition assessment tier	Approximate range of biological index scores	Relationship to Virginia regulatory standard	Narrative description
Very good	70 and over	**meets Virgina standard**	Natural or nearly natural biological condition. The benthic macroinvertebrat community is diverse. Many types of organisms are present. The majority of the population is intolerant of human-caused stresses.
Good	60 - 70		Somewhat degraded. The community is diverse. Many types of organisms are present, but the number of types of sensitive organisms is somewhat reduced relative to the "very good" community. The majority of the population is intolerant of human-caused stresses.
Fair	40 - 60	**fails Virginia standard**	Moderately degraded. The community is fairly diverse. Many types of organisms are present, but the number of types of sensitive organisms is reduced relative to the "very good" community. The majority of the population is tolerant of human-caused stresses.
Poor	25 - 40		Substantially degraded. The community is clearly less diverse than "very good" communities. Fewer types of organisms are present, and the number of types of sensitive organisms is deeply reduced. The great majority of the population is tolerant of human-caused stresses.
Very poor	0 - 25		Severely degraded. The community contains very few types of organisms, virtually all of which are tolerant of human-caused stresses.

Per our data collection and computation, StreamWatch believes that those streams we assess as *very good* or *good* meet the Virginia aquatic life regulatory standard, and that streams assessed as *fair, poor,* or *very poor* fail the standard. Established by the Virginia DEQ, and pursuant to the federal Clean Water Act, the Virginia aquatic life standard is designed to identify whether or not water bodies support "the propagation and growth of a balanced, indigenous population of aquatic life" (State Water Control Board, 2011).

As discussed in section 6.2, the Virginia DEQ considers StreamWatch's data to be as reliable as its own data, and uses StreamWatch data to place streams on or remove streams from the Virginia impaired waters list (303[d] list).

As described in section 6.2, the process of assigning sites to an assessment tier involves several factors including but not limited to average biological index score. Because average score is not the sole factor by which assessments are derived, actual average scores for sites assigned to a given tier can deviate slightly from the ranges listed in the table above.

2.8) Why bugs?

StreamWatch determines the biological condition of streams by sampling and analyzing stream benthic macroinvertebrate communities. The organisms comprising these communities, including insects, crustaceans, snails, and worms, are variously responsive to environmental stresses and changes. By analyzing the presence, absence, and relative abundance of different types of macroinvertebrates, we discern a community profile that reflects water quality and other aspects of stream condition (Barbour 1999, Karr 1999).

Because the benthic community profile is a function of multiple environmental factors occurring over time, benthic monitoring can detect changes that other monitoring methods cannot. For example, most water monitoring in Virginia consists of periodic collection of water samples for laboratory chemical and bacterial analyses. This produces a snapshot of water quality at a particular moment in time, but often fails to detect intermittent stressors such as polluted urban stormwater runoff, or the effects of habitat changes such as sedimentation. Intermittent stressors and habitat changes can have longterm effects on biological condition, and benthic monitoring can reveal these effects (U.S. EPA 2002).

StreamWatch uses the benthic macroinvertebrate monitoring method because it is the most effective and sensitive way to gauge overall stream health. In the words of James Karr and Ellen Chu:

> *"Whether you think running water is for drinking, fishing, washing, flushing, shipping, irrigating, generating electricity or making money in countless ways, keeping tabs on the water's biology makes sense. If we fail to protect the biology of our waters, we will not protect human uses of that water. When rivers no longer support living things, they will no longer support human affairs."*
>
> *"Degradation of water resources begins in upland areas of a watershed, or catchment, as human activity alters plant cover. These changes, combined with alterations of stream corridors, in turn modify the quality of water flowing in the stream channel as well as the structure and dynamics of the channel and its adjacent riparian environments. Biological evaluations focus on living systems, not chemical criteria, as integrators of such riverine change. In contrast, exclusive reliance on chemical criteria assumes that water resource declines have been caused by chemical contamination alone."*
>
> *"When compared with strictly chemical assessments, those using biological criteria typically double the proportion of stream miles that violate state or federal water quality standards or designated uses".*
>
> --from *Restoring Life in Running Waters: Better Biological Monitoring* by James Karr and Ellen Chu. Island Press. 1999.

3) <u>Findings</u>

3.1) Relationships between stream biological condition and watershed land use/land cover.

3.1.1) Across the full range data, spanning reference to urban systems, biological condition correlates more strongly with impervious cover than with other land use/land cover variables.

We tested for correlations between biological condition at sites and land use/land cover parameters in site-defined watersheds. Three study sites with known point source impacts were excluded from the test. After controlling for natural variables (elevation, watershed size, and stream slope) we found highly robust correlations between stream health and each of three land use/land cover parameters – percent forest cover, percent impervious cover, and population density (see table below). We also reversed the procedure by testing for correlations between biological condition and natural variables while controlling for land use. No significant relationships between health and natural factors were found.

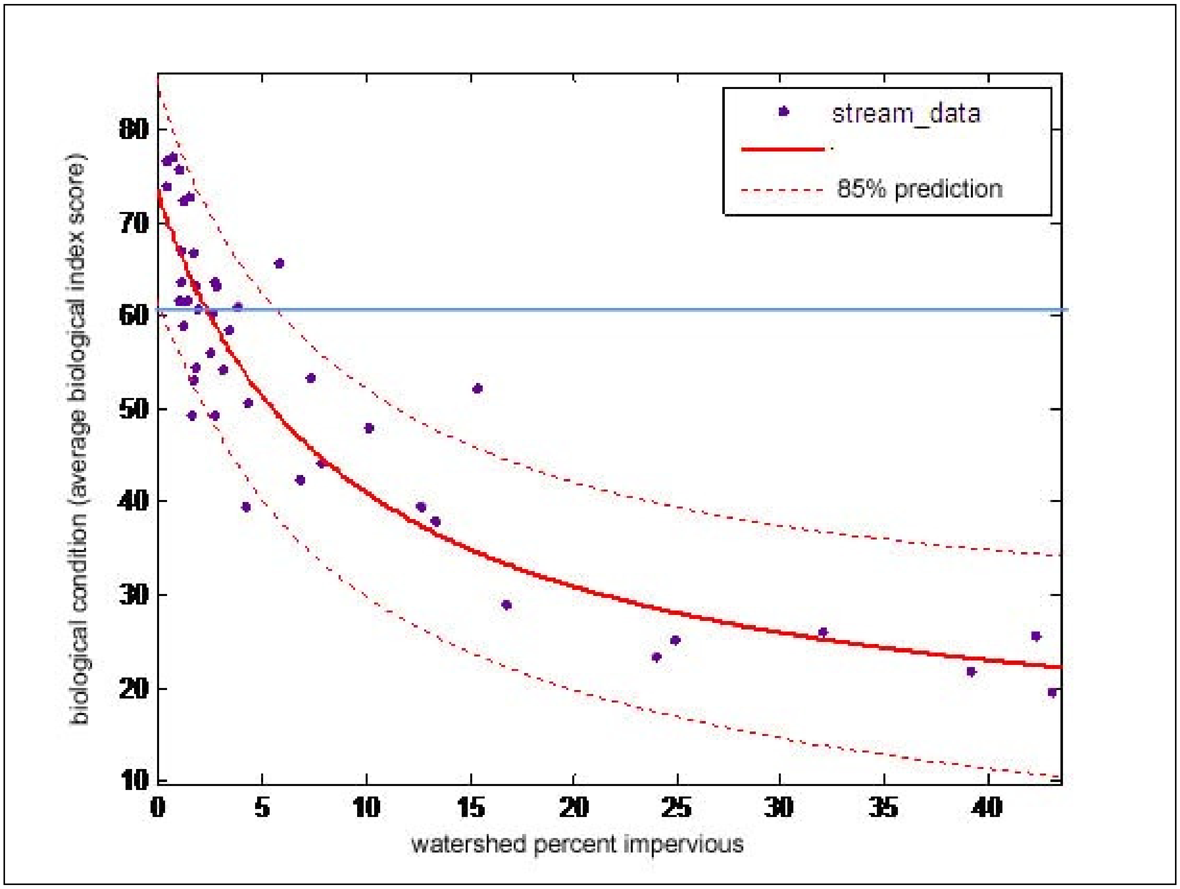
Correlations between stream biological condition (average biological index score) and watershed land use/land cover. Forty-two 1st through 5th-order systems. (3 sites with known point source impacts were excluded).

		Watershed cattle density (per square mile)	**Watershed percent forest cover**	**(ln) Watershed percent impervious cover**	**(ln) Population density**
Partial correlations, controlling for the following natural factors: elevation, watershed size, stream water surface slope	Correlation coefficient	0.07	0.72	-0.88	-0.73
	Significance (2-tailed)	0.69	0.000	0.000	0.000
Spearman correlations. No controls for natural factors.	Correlation coefficient	0.25	0.76	0.86	0.86
	Significance (2-tailed)	0.118	0.000	0.000	0.000

The dataset referenced in the above table comprises 42 stream/watershed systems ranging from 1st through 5th order and from virtually undisturbed (reference) to severely disturbed (dense urban). We will call this dataset the “all streams” set. Sites on the mainstem Rivanna River were excluded because we wanted to use the “all streams” dataset to explore relationships among landscape scale factors, reach-scale factors and stream biological condition. Previous StreamWatch studies indicate that many reach-scale factors have negligible influence on the relatively large Rivanna mainstem. Also excluded from “all streams” were three sites with known point source impacts.

As noted, forest cover, impervious cover, and population density all correlate strongly with health. However, when accounting for natural factors, IC emerges as the strongest correlate. Cattle population density does not correlate with stream biological condition in this dataset.

The health/IC relationship is illustrated below in the form of a scatterplot and rectangular hyperbola fit line.

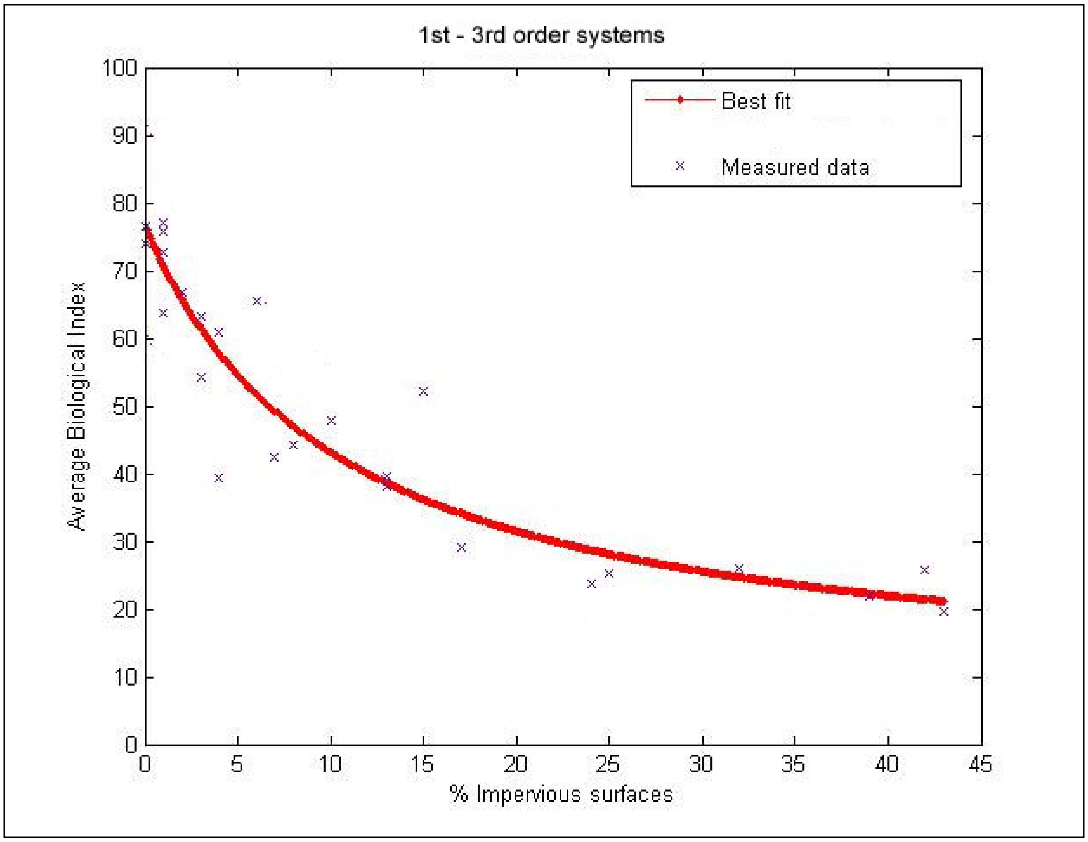


Above: Rectangular hyperbolic curve fit to biological condition and watershed percent impervious cover. Forty-two 1st through 5th order systems, 0.4% to 43% IC. R-square=0.81, p<0.001. Horizontal blue line approximates the Virginia biological standard.

The Center for Watershed Protection's impervious cover conceptual model is limited to 1st to 3rd-order systems. In our study, we find the IC/stream biology relationship in 4th and 5th-order systems generally conforms to the same patterns as 1st to 3rd-order systems, though the correlation is not as strong (see discussion below in Section 3.1.1.1). When appropriate, however, we will conduct parallel analyses on a dataset restricted to 1st through 3rd order systems. The table below gives correlation statistics for health/ LU/LC relationships in this restricted dataset. Below the table is a scatterplot graph for the smaller streams.

Correlations between stream biological condition (average biological index score) and watershed land use/land cover. Twenty-five 1st through 3rd-order systems.

		Watershed cattle density (per square mile)	Watershed percent forest cover	(ln) Watershed percent impervious cover	(ln) Population density
Partial correlations, controlling for the following natural factors: elevation, watershed size, stream water surface slope	Correlation coefficient	0.2	0.76	-0.91	-0.79
	Significance (2-tailed)	0.42	0.000	0.000	0.000
Spearman correlations. No controls for natural factors.	Correlation coefficient	0.21	0.76	0.94	0.92
	Significance (2-tailed)	0.327	0.000	0.000	0.000



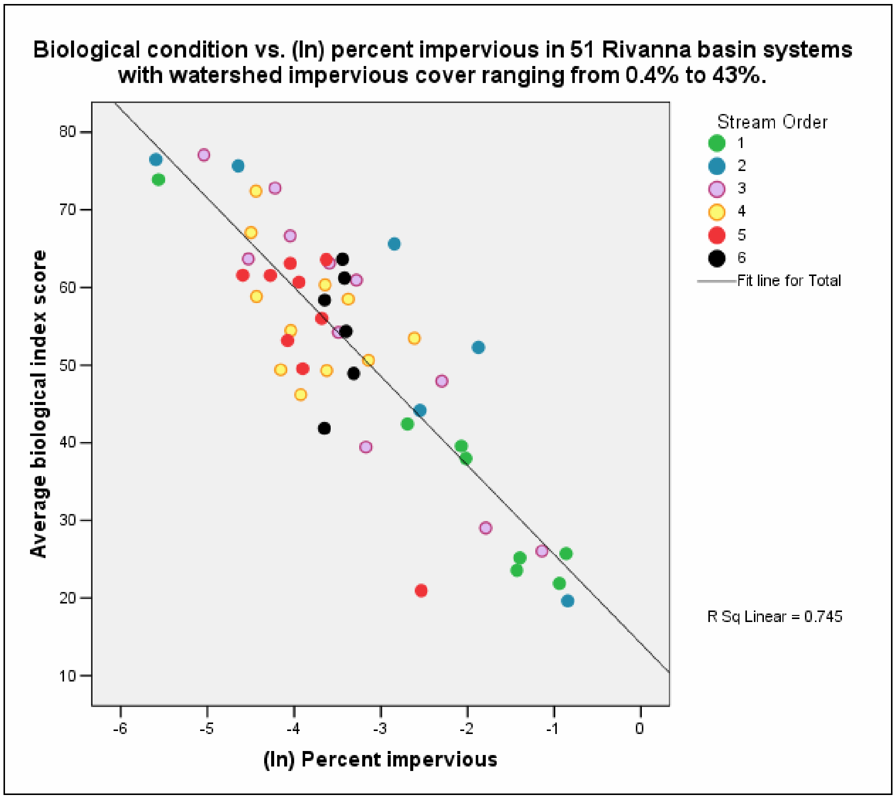
Above: Rectangular hyperbolic curve fit to biological condition and watershed percent impervious data. Twenty five 1st to 3rd-order systems, 0.4% to 43% IC. R-square=0.89, p<0.001.

We note that the health / LU/LC correlations in 1st through 3rd order systems follow a pattern very similar to all streams. Forest cover, impervious cover, and population correlate strongly with health; cattle density does not. We observe that the health/ LU/LC correlations and the model R-square values are stronger for smaller streams than for all streams.

We also observe in both sets considerable scatter in the range of data representing systems with about 1.5% to 10% IC. As noted, our study's 4th and 5th-order systems fall entirely within this range, therefore the "all streams" dataset exhibits higher variance.

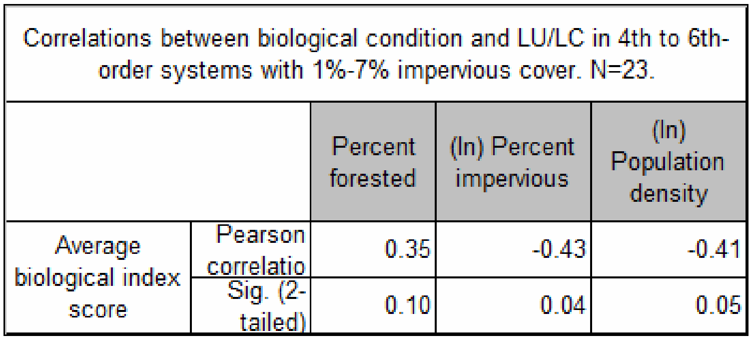
3.1.1.1) Land use/land cover and biology were more strongly related in smaller streams than in larger streams.

In this study, biology in 4th through 6th-order systems correlated significantly with LU/LC, though not as strongly as it did in 1st through 3rd-order systems. The plot below shows that the relationship between biological condition and impervious cover in larger streams was generally consistent with the relationship observed for smaller streams, but was not as tight.



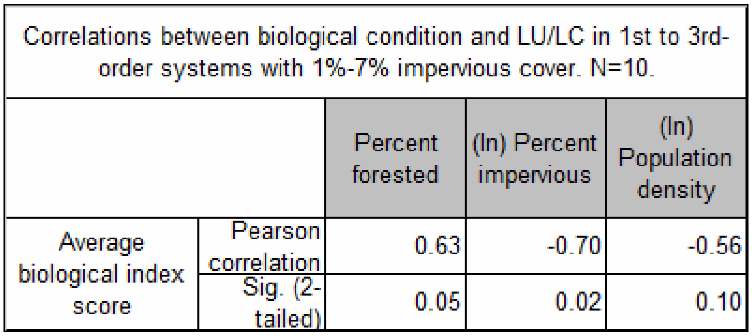
An obvious outlier is the low-scoring 5th-order stream with relatively moderate IC. This is our monitoring station on Moores Creek. Impervious cover is unevenly distributed in the Moores Creek basin; urbanization is concentrated at the lower (downstream) end of the watershed. Our station is located in the urban portion of the system. Additionally, the station is situated about 1,000 yards downstream of the Moores Creek wastewater treatment plant. Either or both of these factors appear to be depressing biological condition to much lower level than predicted by watershed-wide average percent impervious cover.

In the 4th through 6th-order systems we studied, IC ranged from 1% to 7% IC. Excluding three systems with known point-source impacts, the relationships between average biological index score and IC in twenty-three larger systems was significant but not strong (Pearson *r*=0.43, p=0.04). In ten 1st through 3rd order systems with the same range of IC values, the correlation was stronger (Pearson *r*=0.70, p=0.02). (See tables below).



Correlations between biological condition and LU/LC in 4th to 6th-order systems with 1%-7% impervious cover. N=23.

		Percent forested	(ln) Percent impervious	(ln) Population density
Average biological index score	Pearson correlatio	0.35	-0.43	-0.41
	Sig. (2-tailed)	0.10	0.04	0.05

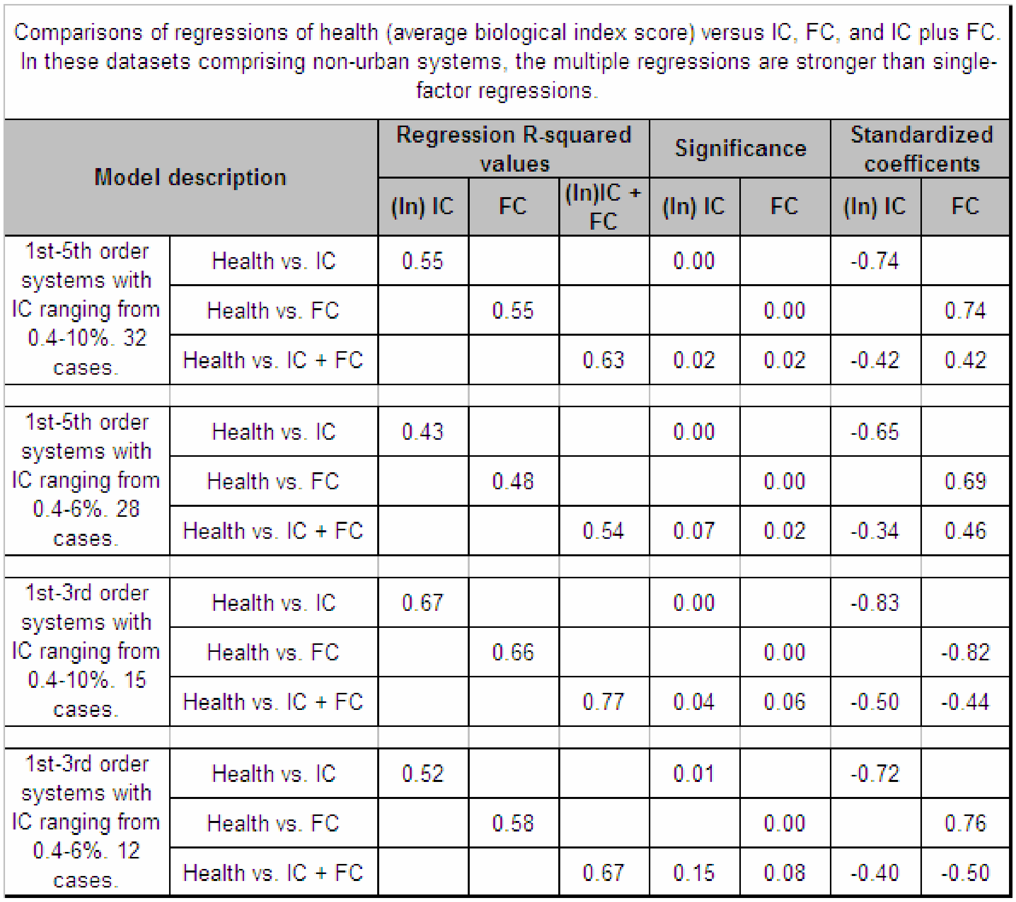


Correlations between biological condition and LU/LC in 1st to 3rd-order systems with 1%-7% impervious cover. N=10.

		Percent forested	(ln) Percent impervious	(ln) Population density
Average biological index score	Pearson correlation	0.63	-0.70	-0.56
	Sig. (2-tailed)	0.05	0.02	0.10

3.1.2) In non-urban systems, forest cover and impervious cover together predict stream biological condition better than impervious cover alone.

Though IC is the strongest predictor of stream biological condition across our study's full range of LU/LC conditions, when we focus on less urbanized systems, forest cover (FC) becomes as or even more important than IC. Though IC and FC co-vary moderately in our datasets, the two variables are sufficiently independent of one another to each operate as distinct, statistically significant variables in a multiple regression models, and the multiple regression models are significantly better predictors of biological condition than models based on either IC or FC alone. This is demonstrated in the table below, where the qualities of single-factor and multiple regression models are compared for four subsets of our data.



Comparisons of regressions of health (average biological index score) versus IC, FC, and IC plus FC. In these datasets comprising non-urban systems, the multiple regressions are stronger than single-factor regressions.

Model description		Regression R-squared values			Significance		Standardized coefficents	
		(In) IC	FC	(In)IC + FC	(In) IC	FC	(In) IC	FC
1st-5th order systems with IC ranging from 0.4-10%. 32 cases.	Health vs. IC	0.55			0.00		-0.74	
	Health vs. FC		0.55			0.00		0.74
	Health vs. IC + FC			0.63	0.02	0.02	-0.42	0.42
1st-5th order systems with IC ranging from 0.4-6%. 28 cases.	Health vs. IC	0.43			0.00		-0.65	
	Health vs. FC		0.48			0.00		0.69
	Health vs. IC + FC			0.54	0.07	0.02	-0.34	0.46
1st-3rd order systems with IC ranging from 0.4-10%. 15 cases.	Health vs. IC	0.67			0.00		-0.83	
	Health vs. FC		0.66			0.00		-0.82
	Health vs. IC + FC			0.77	0.04	0.06	-0.50	-0.44
1st-3rd order systems with IC ranging from 0.4-6%. 12 cases.	Health vs. IC	0.52			0.01		-0.72	
	Health vs. FC		0.58			0.00		0.76
	Health vs. IC + FC			0.67	0.15	0.08	-0.40	-0.50

In each dataset, the multiple regression is significantly superior. However, in only one of the multiple regression models do both IC and FC have statistical significance of less than 0.05, probably because this regression is applied to the largest dataset. This set comprises 1^{st} to 5^{th}-order systems with IC ranging from 0.4 to 10%. The iterative process reflected in the above table was also employed in datasets that included systems with greater than 10% IC, but forest cover was much less significant. The selected model is described as follows:

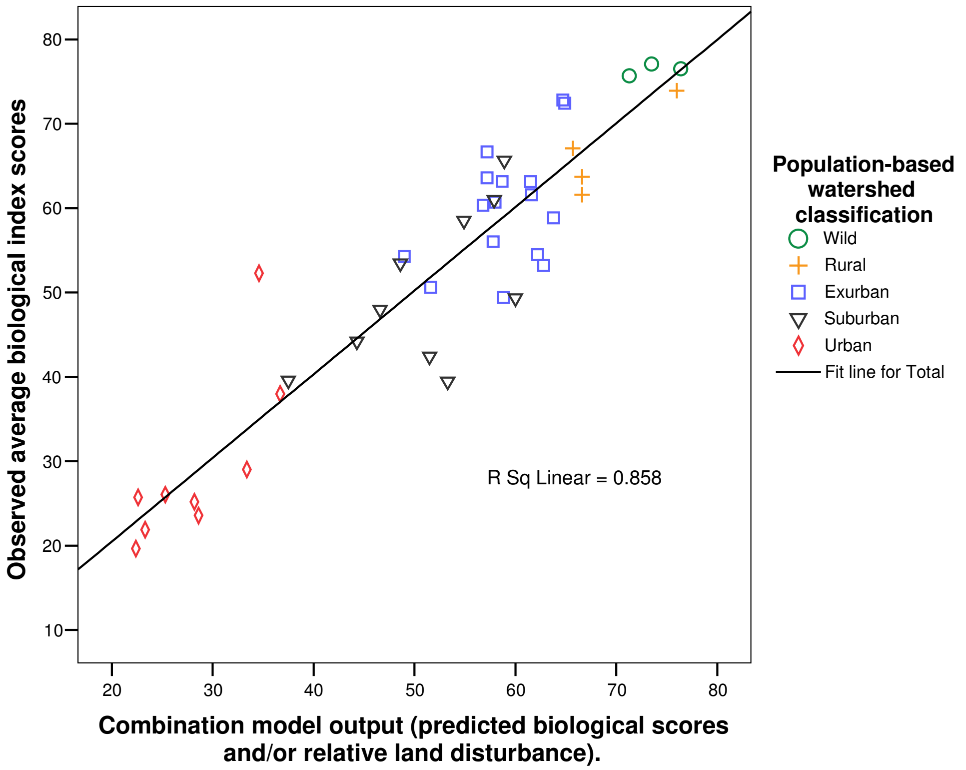
$$\textit{Average bio index score} = 16.4 + (31.0 \times \textit{percent FC}) + (-5.2 \times \textit{natural log IC})$$

The model's R-square value is 0.63, and each of the independent variables correlate with biological condition with p-values of 0.02.

A major objective of this study is to determine the risk of stream degradation associated with landscape disturbance. Since the majority of the Rivanna basin is non-urban, and because both forest cover and impervious cover are significant and independently operative factors in non-urban systems, it is quite important to incorporate both factors in our risk analysis.

A model that combines the best *rectangular hyperbola health/IC model* and the *multiple regression health/FC+IC model* provides a better risk assessment tool than either model alone. For this combination model, we employ the rectangular hyperbola algorithm for systems with greater than 10% IC, and we employ the multiple regression algorithm for systems with 10% or less IC. The outcome of this approach is illustrated in the scatterplot below. Note that inasmuch as the model is a function driven by land use factors, its outputs can be regarded as indices of relative land disturbance (in addition to predictions of stream biological condition).

Actual average biological index scores versus scores predicted by combination model. The model is based on watershed impervious cover and forest cover. The model's outputs, therefore, can be viewed either as predictions of biological condition or as indices of land disturbance.



The combination model's R-square is 0.86, which compares favorably to the R-square for the rectangular hyperbola model (0.81). While this may seem a rather small improvement, it is important to note that the gains of the combination model are realized chiefly in tighter predictions for non-urban systems with 10% or less IC. Within this large and important subset, the goodness of fit is substantially improved: for the combination model, predicted values correspond to actual values with an R-square of 0.63, compared with an R-square of 0.49 for the rectangular hyperbola model.

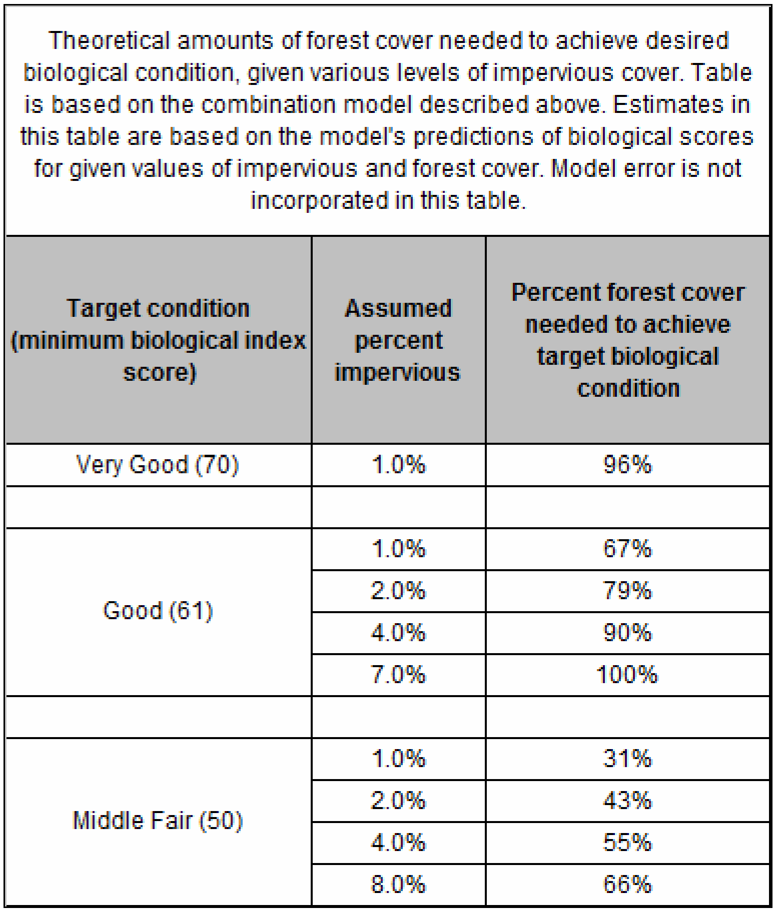
The average value for the combination model's eighty-five percent confidence interval for any given individual datum is 18.6 (the range is 18.4 to 19.3). In other words, the model predicts biological condition with precision of about ± 9.3 points with about 85% reliability. The model can be usefully applied to estimate the likely range of biological condition values for Rivanna basin streams based on known impervious cover and forest cover. We illustrate those estimations in the form of a map (see section 3.1.5). The model can also be used to predict the effect of future land use changes (section 3.1.6).

We stress again the importance of including both forest cover and impervious cover in our model because: a) the majority of the Rivanna basin is non-urban, and b) both forest cover and impervious cover are significant and independently operative factors in non-urban systems. In addition, it should also be noted that in our dataset FC and IC co-vary moderately. However, our dataset misrepresents the Rivanna landscape in this respect. In

208 Rivanna small watersheds with under 10% IC, IC and FC co-vary only minimally. If IC and FC predict biological condition independently in our sample dataset, there is good reason to believe they operate even more independently in the "total population" of non-urban Rivanna subwatersheds.

Using the model for planning and conservation

The above-described model can be applied by watershed planners and managers to predict the biological condition of streams in watersheds subject to various land use scenarios. For instance, in a small watershed where significant land use change is expected (*e.g.* the development of large housing tract), the model can be used to predict or plan for changes in stream biological condition. Conversely, the model can be used to estimate levels of IC and FC required to achieve stream health targets. The table below gives examples of estimated ranges of impervious cover and forest cover associated with various stream biological condition targets.

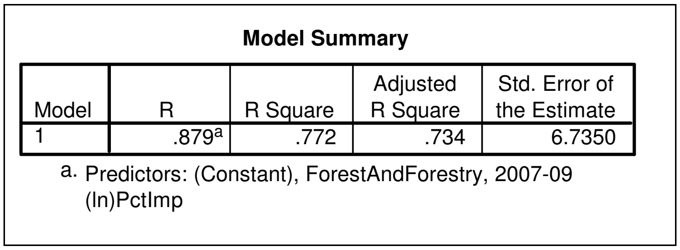


Theoretical amounts of forest cover needed to achieve desired biological condition, given various levels of impervious cover. Table is based on the combination model described above. Estimates in this table are based on the model's predictions of biological scores for given values of impervious and forest cover. Model error is not incorporated in this table.

Target condition (minimum biological index score)	Assumed percent impervious	Percent forest cover needed to achieve target biological condition
Very Good (70)	1.0%	96%
Good (61)	1.0%	67%
	2.0%	79%
	4.0%	90%
	7.0%	100%
Middle Fair (50)	1.0%	31%
	2.0%	43%
	4.0%	55%
	8.0%	66%

1st-3rd order watersheds

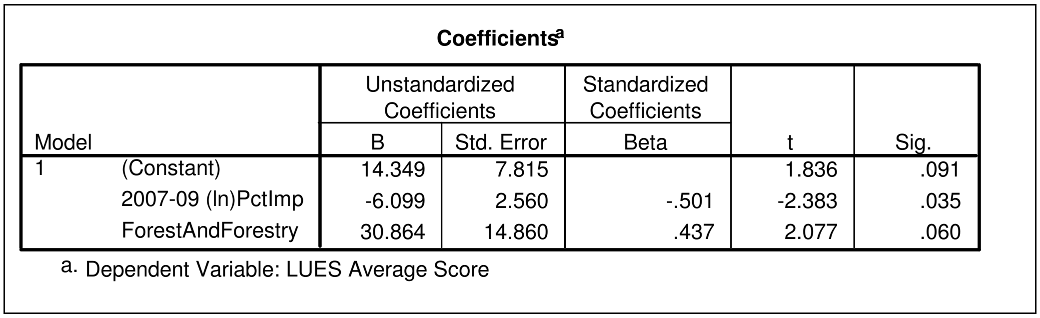
As discussed in Section 3.1.1.1, we assume that 4th and 5th order systems behave in ways consistent with the Center for Watershed Protection's Revised Impervious Cover Model. The Center for Watershed Protection recommends that its model should be applied only to 1st through 3rd order systems. Since our assumption regarding larger systems runs contrary to this recommendation, we provide the following parallel model of the relationship between IC+FC and biological condition in a dataset that excludes 4th and 5th order systems.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.879[a]	.772	.734	6.7350

a. Predictors: (Constant), ForestAndForestry, 2007-09 (ln)PctImp



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	14.349	7.815		1.836	.091
	2007-09 (ln)PctImp	-6.099	2.560	-.501	-2.383	.035
	ForestAndForestry	30.864	14.860	.437	2.077	.060

a. Dependent Variable: LUES Average Score

The data subset from which this model is derived is about half the size as the model based on 1st-5th order systems. But, because fewer systems in this set occupy the high scatter zone, this model's R-square is stronger. Within this subset, IC is a slightly stronger predictor than FC. Minor differences nothwithstanding, this model is more similar to the first model than it is dissimilar.

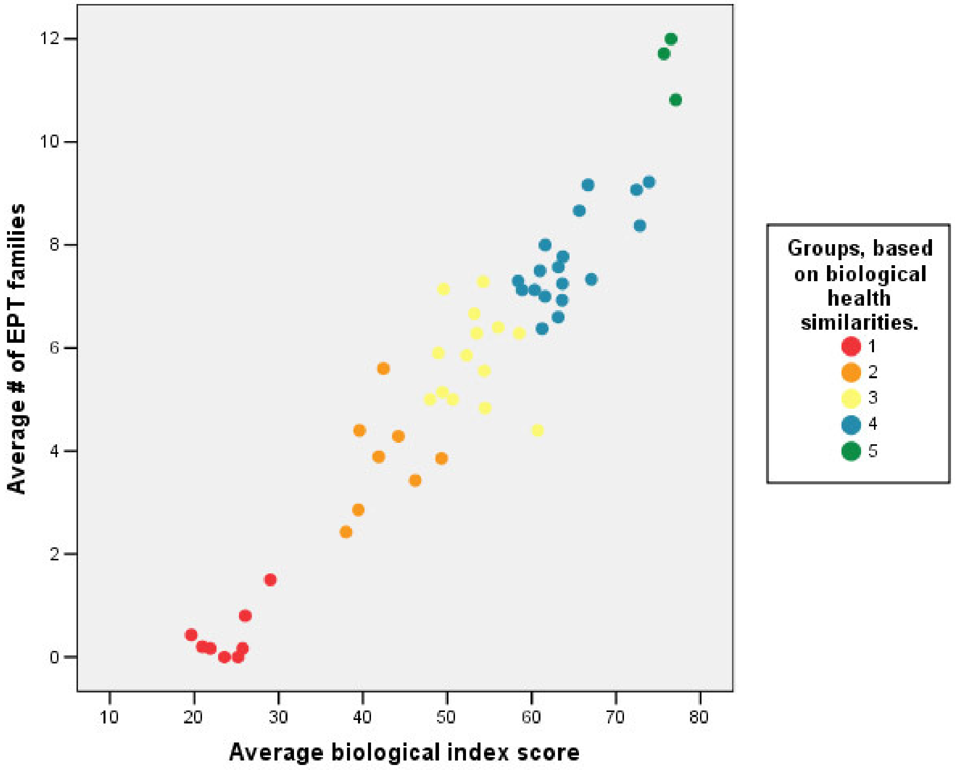
3.1.3) Degradation begins very early in the watershed disturbance continuum. Our healthiest benthic communities were found exclusively in basins with forest cover ≥ 99%.

As discussed in above, the negative correlation between land use intensity and stream biological condition is tremendously strong. In this section, we demonstrate not only that the land/stream biology relationship is strong, but also that degradation begins at very early stages of watershed disturbance.

Using hierarchical cluster analysis in SPSS, we classified invertebrate communities from 51 sites based on 2 biological attributes: average biological index score, and the average number of EPT families per sample (families within classes ephemeroptera, plecoptera, and trichoptera – not including hydropsychid caddisflies). Average biological index score reflects general biological health (see Section 6.2). EPT families are one of the eight metrics used to calculate the index score. The EPT metric is more sensitive than the overall index to biological changes at the "better" end of the spectrum. EPT organisms are sensitive, require good to excellent habitat and water quality, and are often the first organisms to disappear in response to environmental stress. By examining the number of EPT taxa *and* the index score, we can discern which streams are the "best of the best".

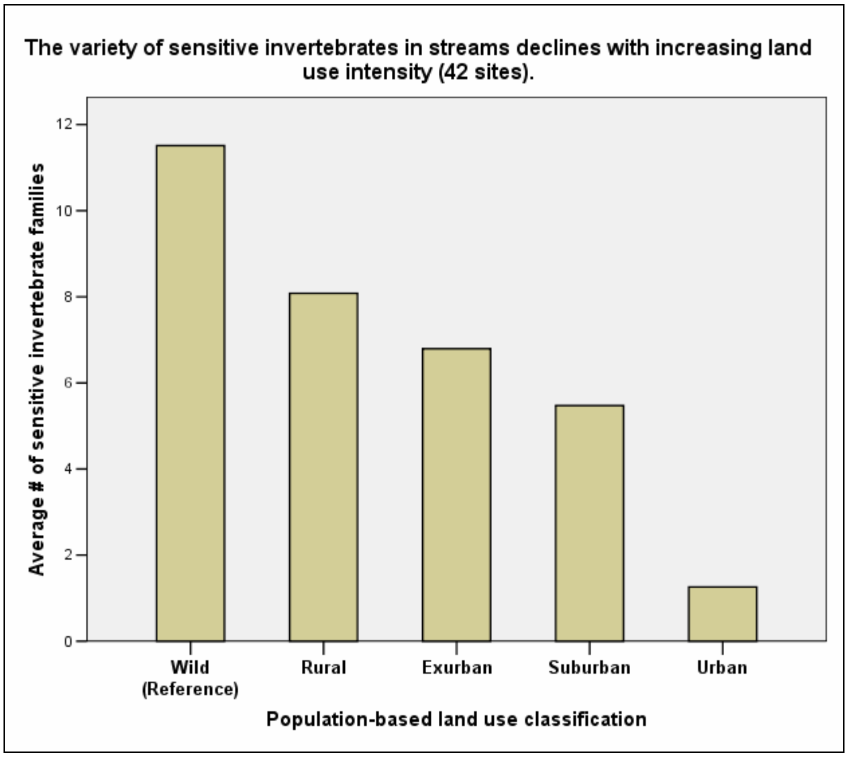
To run the analysis, values for both variables were standardized across the 51 cases so that each variable weighed equally in the classification process. We used the complete linkage (furthest neighbor) method to maximize within-cluster homogeneity. Exploration of clusters thus generated suggested four or five statistically distinctive groups. In either set of groupings, a cluster emerged that was comprised of three sites with distinctively excellent health, as shown in the plot below.

Of 51 study sites, three sites (green, upper right) had distinctively excellent biology, with a combination of both high biological index scores and high numbers of sensitive taxa. This level of health was found exclusively in streams draining reference watersheds (fully forested, no domiciles, no paved roads).



Our data suggest that biological condition declines rapidly with the onset of landscape disturbance. This rapid degradation is reflected in the steep slope of the fit line in the graph in Section 3.1.1, with biological condition falling quite sharply while impervious cover increases only modestly. Rapid degradation is further illustrated by the groups identified via the above-described hierarchical cluster analysis. In the plot above, the green dots to the upper right represent benthic communities whose diversity and robustness place them in a statistically distinctive "class of their own." Not coincidentally, we encounter these healthiest communities exclusively in our study's 3 reference-condition systems—streams draining watersheds with more than 99% forest cover, no paved roads, and no domiciles. As soon as we move into disturbed watersheds—even modestly disturbed watersheds—we encounter a different and noticeably degraded biological profile.

This degradation can also be expressed simply in terms of the number of sensitive taxa found in respective watershed classes. As shown in the chart below, there is a distinctive difference between average sensitive taxa richness in undisturbed reference systems (11 sensitive taxa) and lightly distrubed rural systems (8 sensitive taxa).



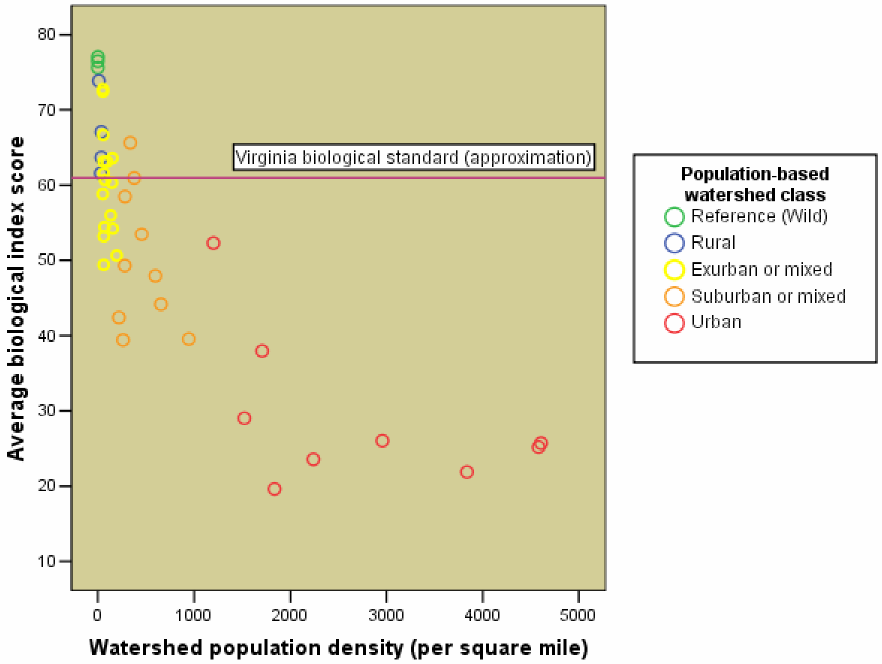
3.1.4) Failure to meet the Virginia aquatic life regulatory standard becomes common at the exurban stage of the land use continuum. Most of the Rivanna basin is exurban.

In reference systems with minimal land disturbance (population density less than ~10/square mile, IC less than ~1%), biological condition is predictably excellent. In dense urban systems with heavy land disturbance (population density greater than ~2,000/square mile, IC greater than ~20%), biological condition is predictably poor or very poor. Between these extremes, biological condition generally varies from poor to good, and is somewhat less predictable. As discussed in Section 3.1.2, the predictability of biological condition in non-urban streams is improved when forest cover is considered as an additional factor. But even with the inclusion of forest cover, biological condition scores for systems with similar degrees of disturbance can vary by about 19 points. As we will see, this variation has important implications for conservation and management.

To explore the relationship between land use and stream biological condition in the context of Virginia's regulatory standard, we focused on the 42-case set of streams and watersheds that excluded the mainstem Rivanna River and sites with known point-source impacts. For the sake of public discussion, and as described in Section 2.6, we classified systems into five land use intensity categories based on population.

As shown in the graph below, biological condition in exurban systems generally ranges from fair to good. This range straddles the Virginia regulatory standard. In other words, failure to meet the regulatory standard becomes common at the exurban level of land use intensity. All urban systems and nearly all suburban systems failed the standard.

Stream biological health and watershed population density in 42 1st-5th order systems. Note that the tendency to fail the Virginia biological standard becomes common at the exurban stage of development intensity.



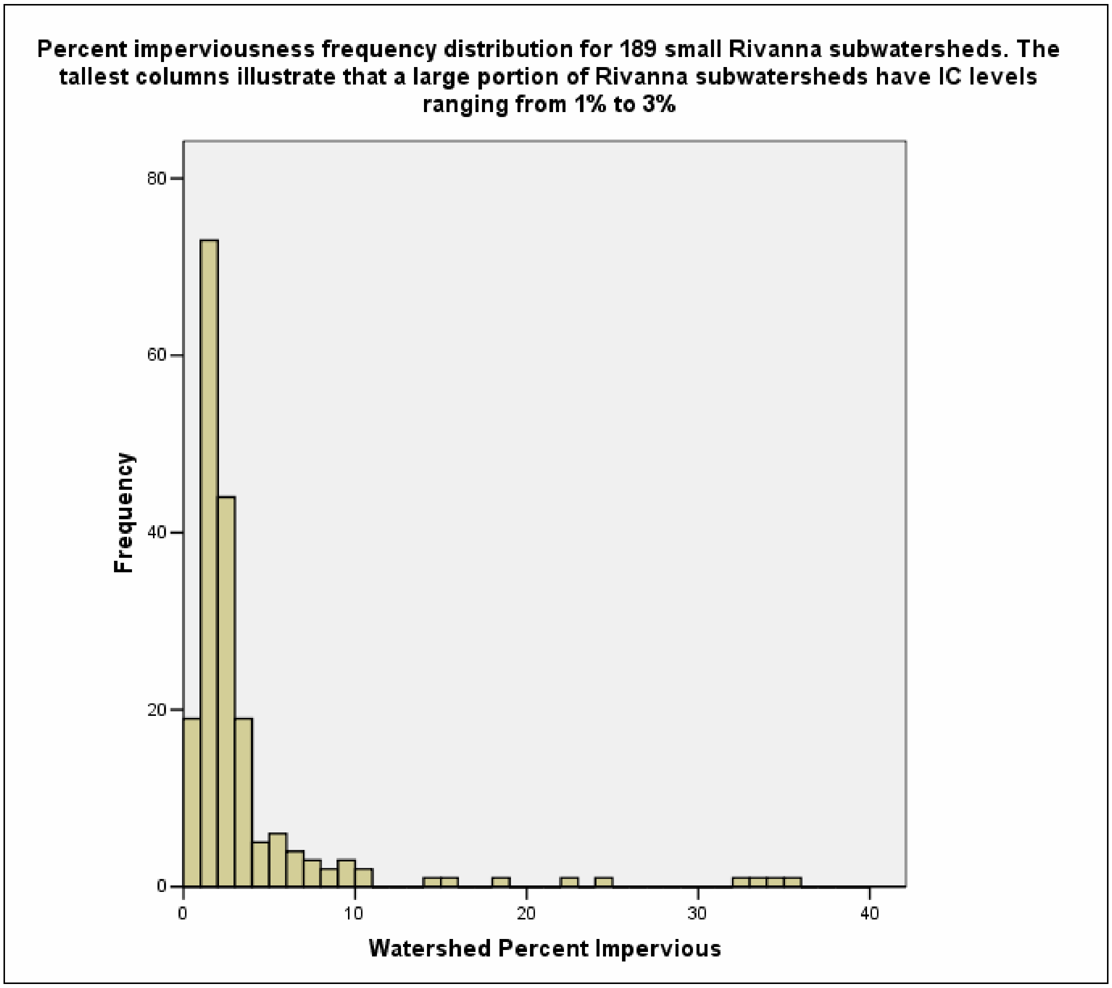
Land use in the Rivanna exurban landscape is by no means homogenous, but it is nevertheless instructive to note that the average acreage per dwelling in our study's exurban systems was 24 acres. In many parts of the basin, exurbia is characterized by residences, often on large lots, interspersed with grazed pasture, hayfields, forest, and the occasional vineyard or orchard. Impervious cover in Rivanna exurbia ranges from roughly one to four percent, and forest cover ranges from roughly 45% to 85%. Given a fairly light agricultural footprint, it may seem surprising that over half the systems fitting this profile were sufficiently degraded to warrant 303(d) listing.

It is particularly important to note the biological condition variance in exurban systems because a) the variance straddles the regulatory standard, and b) the exurban segment of the land use intensity spectrum is characteristic of most of the Rivanna landscape. (We classify about 60% of Rivanna basin subwatersheds as exurban, based on population density.) These observations suggest that most of the Rivanna landscape harbors streams that are on the cusp of passing or failing the standard.

As we will discuss in Section 3.3, bank stability, sedimentation, and riparian buffer conditions appear to help explain some of the variance in biological condition not accounted for by forest cover and impervious cover. Still, there is much yet to learn about risk factors in the Rivanna's exurban systems. From an optimistic perspective, it is heartening to note that a great portion of the Rivanna basin is on the cusp. There seems reason to hope that practical management measures could tip the scale, and that with care, many of the Rivanna basin's impaired streams could attain "good" biological condition and meet the Virginia standard.

Our findings are noteworthy also in the context of the Center for Watershed Protection's Revised Impervious Cover Model (Schueler et al, 2009). This model can be (mis)interpreted to infer that systems with less than 20-25% IC generally support regulatory standards. Carefully examined, the model does make room for regulatory failure at lower levels of IC. The model's authors note that metrics based on benthic communities are particularly responsive to increasing IC. Data from the Rivanna basin support this view. Along with other workers, we find that biological condition begins to degrade at the earliest stages of watershed disturbance (Coles 2004, King 2010, Morse 2003, Ourso 2003). In general, the regulatory threshold is breached at less than 3% IC in the Rivanna systems we studied (see graph in Section 3.1.1). We do not interpret this finding to mean that IC is the sole landscape-scale cause of biological degradation in the Rivanna's moderately disturbed exurban landscape. Nevertheless, given the justifiable currency of the Revised Impervious Cover Model, we think it important to say that our findings argue for a conservative, cautionary interpretation of the model when it comes to benthic thresholds. In our study, failure of the aquatic life standard generally occurred at about one level of magnitude lower than 20-25% IC, and all systems with 20% or more IC were substantially or severely degraded.

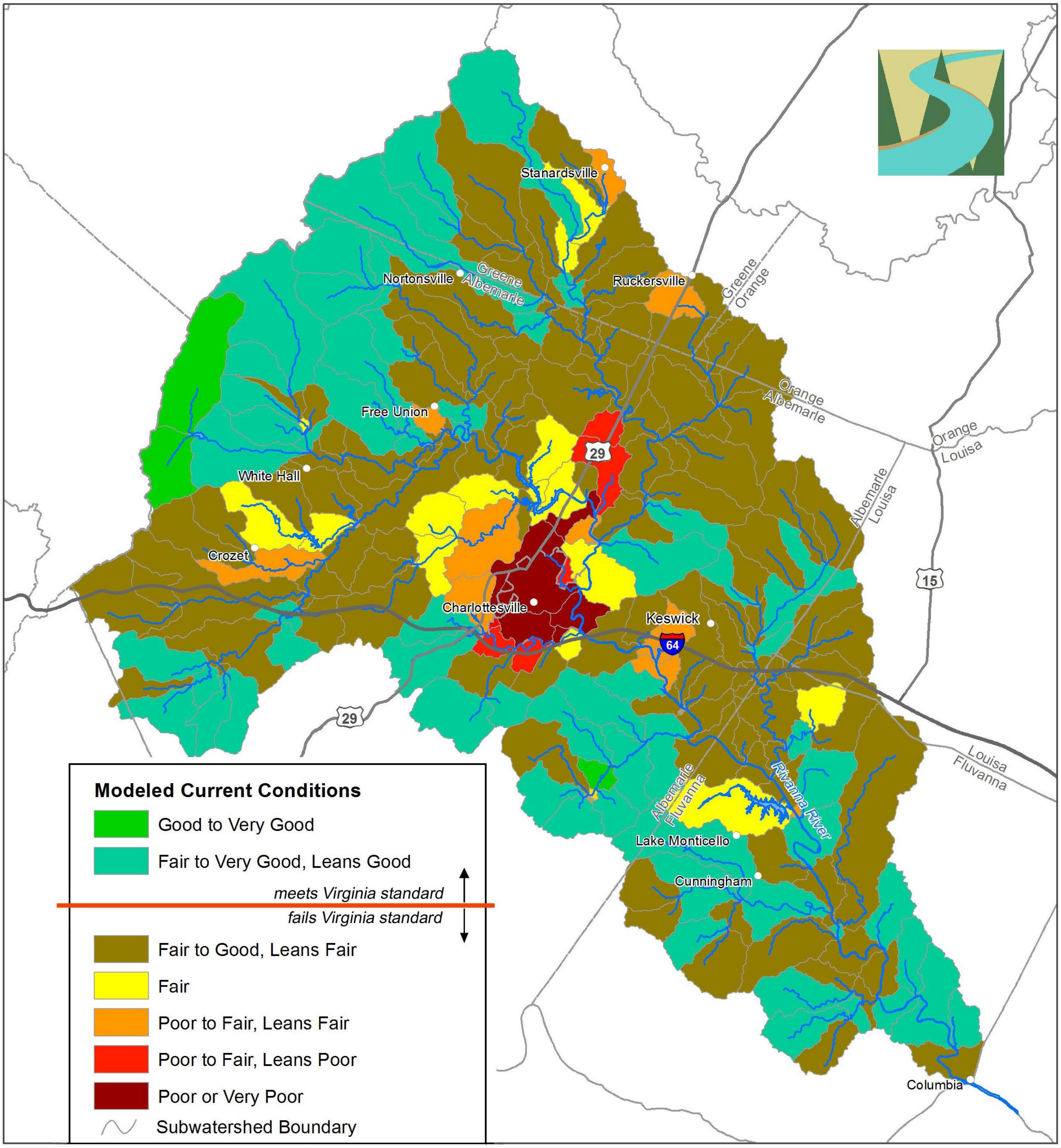
The figure below shows that about 65% of Rivanna basin subwatersheds have impervious cover ranging from 1% to 3%.



Above: A majority of the basin's watersheds have between 1% and 3% impervious cover. The histogram is based on 189 small watersheds with land area exceeding 1 square mile. The dataset covers 98% of the basin's land area.

3.1.5) Based on impervious cover and forest cover, we estimate that most small streams in the Rivanna basin do not meet the Virginia biological standard.

Using recent land use/land cover data to feed the combination model described in Section 3.1.2, we can calculate the probable current biological condition in streams draining small Rivanna subwatersheds. The results of this application are shown in the map below.

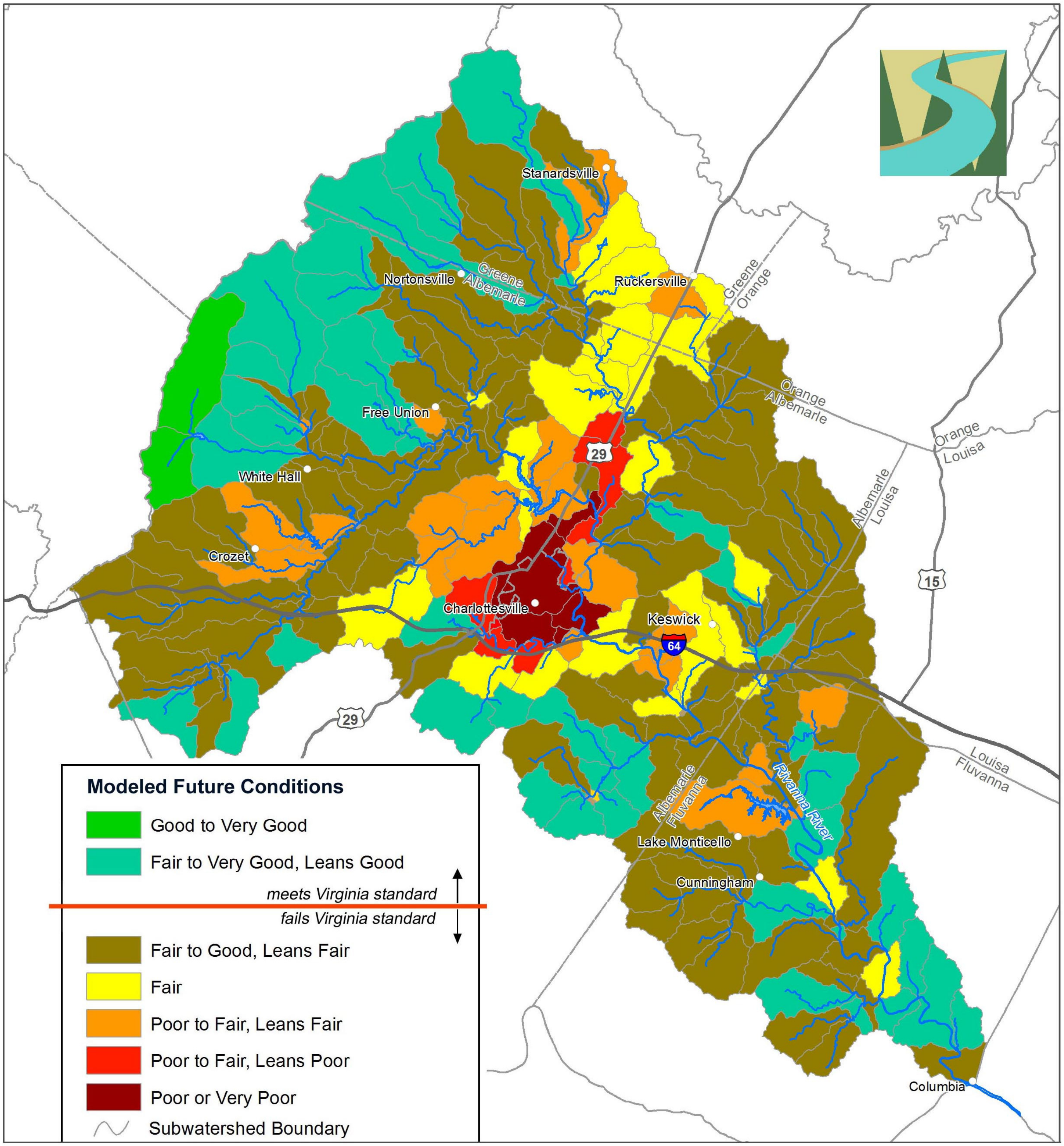


Above: Modeled current health of streams in small Rivanna watersheds.

As illustrated in the map, we estimate that only about 30% of systems meet the Virginia regulatory standard (teal or green shading), and that about 70% of systems fail the standard (brown shading or worse). Fortunately, most of the failing systems are moderately rather than severely degraded. Only about 6% of systems are likely to be in “poor” health (see table in Section 3.1.6 below).

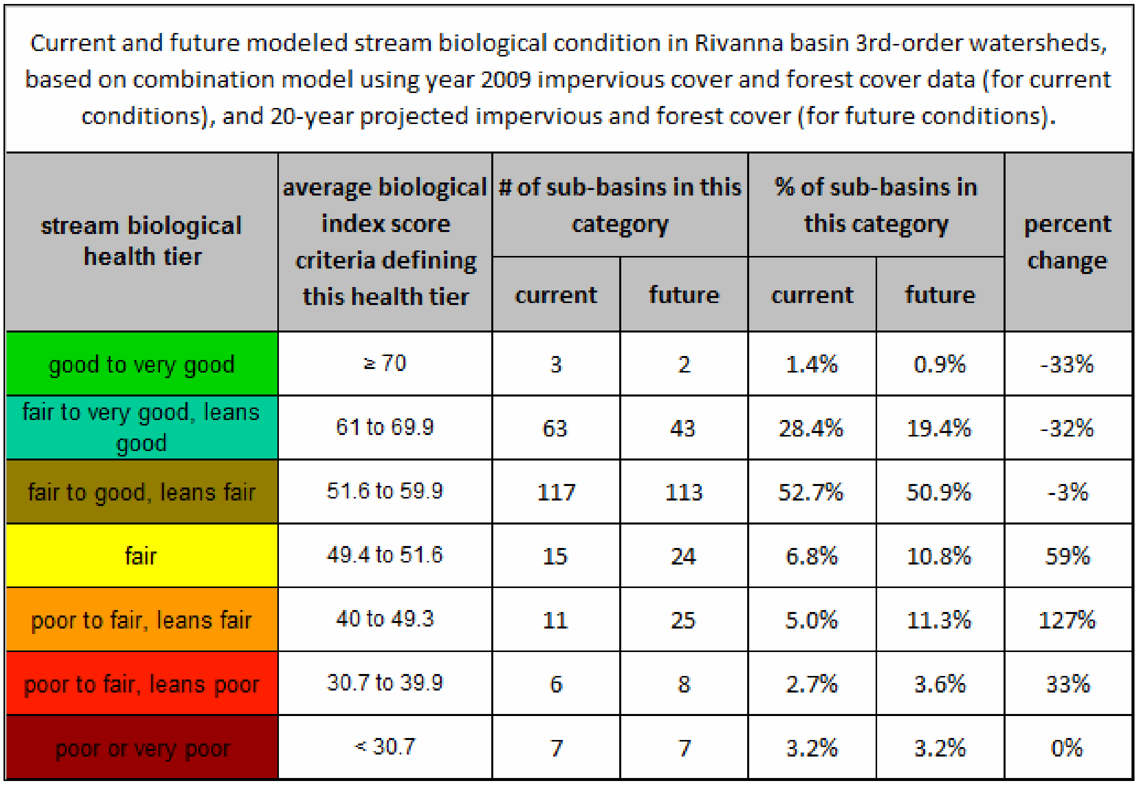
3.1.6) Potential effects of future land use change.

The model used to generate the map in Section 3.1.5 above can be applied to future scenarios in order to predict the possible effects of land use change. We created a scenario whereby impervious cover in the Rivanna basin's non-urban subwatersheds was increased by an average of thirty-three percent—from the current average of 2.6% impervious per subwatershed to a future average of 3.4%. Forest cover was decreased slightly. This change corresponds to a 50% increase in the population of the non-urban areas, which would occur in about 20 years assuming population growth rates reported in the 2010 Census. We assumed little change in urban watersheds with current population of 1,000 or more people per square mile. We also assume no growth in watersheds situated primarily in Shenandoah National Park. The scenario is a speculation conducted for the purpose of generating conversation about the effects of land use change. The scenario uses very simple assumptions, and we recognize that future change may unfold quite differently than in our scenario. For instance, it is unlikely that the spatial distribution of future population-driven IC change will occur as formulaically as it does in our scenario. The speculative map is shown below.



Above: Modeled stream health in 20 years, based on speculative scenario (see text).

In our 20-year scenario, with impervious cover increasing by an average of 33% in most of the basin, we estimate that the number of systems meeting the Virginia biological standard would decline by about one-third (from 66 to 45). The table below provides further comparisons between modeled current conditions and modeled future conditions.

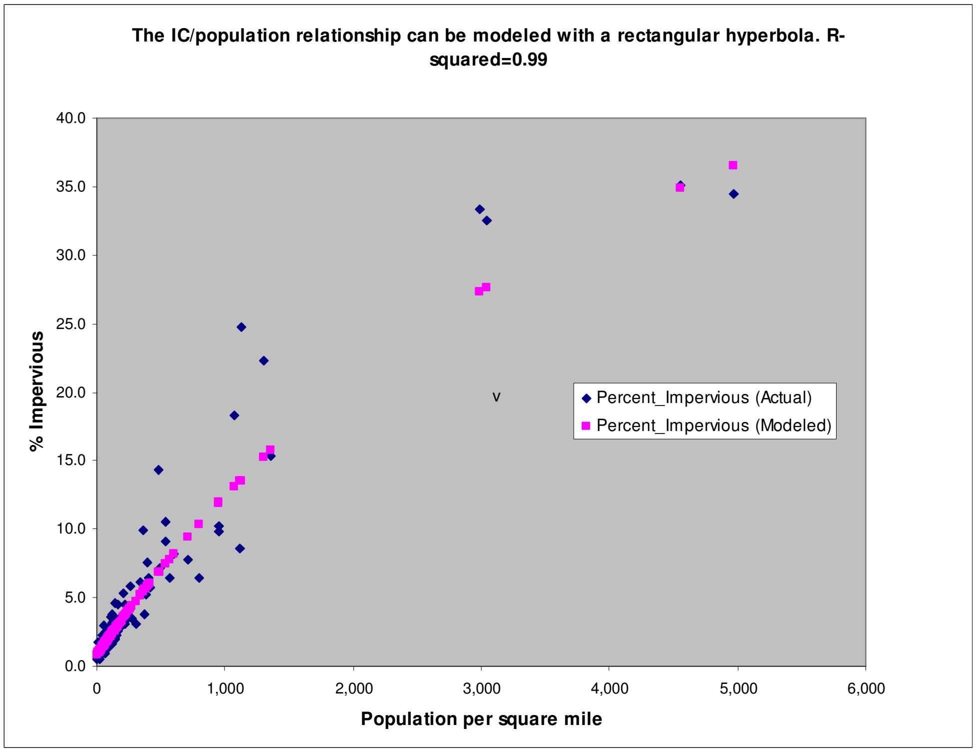


Current and future modeled stream biological condition in Rivanna basin 3rd-order watersheds, based on combination model using year 2009 impervious cover and forest cover data (for current conditions), and 20-year projected impervious and forest cover (for future conditions).

stream biological health tier	average biological index score criteria defining this health tier	# of sub-basins in this category		% of sub-basins in this category		percent change
		current	future	current	future	
good to very good	≥ 70	3	2	1.4%	0.9%	-33%
fair to very good, leans good	61 to 69.9	63	43	28.4%	19.4%	-32%
fair to good, leans fair	51.6 to 59.9	117	113	52.7%	50.9%	-3%
fair	49.4 to 51.6	15	24	6.8%	10.8%	59%
poor to fair, leans fair	40 to 49.3	11	25	5.0%	11.3%	127%
poor to fair, leans poor	30.7 to 39.9	6	8	2.7%	3.6%	33%
poor or very poor	< 30.7	7	7	3.2%	3.2%	0%

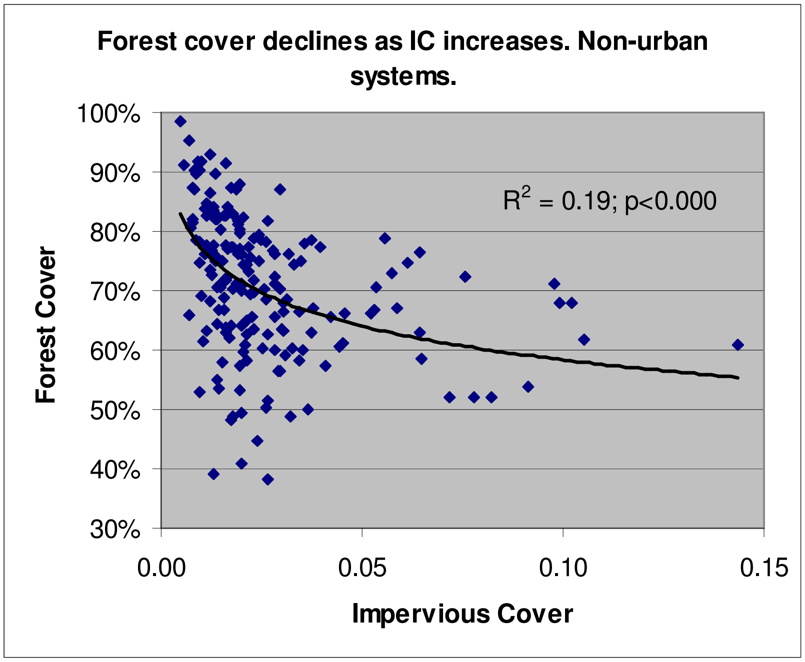
Method for estimating 20-year land cover changes

As mentioned above, we assume a population increase of 50% over 20 years. We distribute this increase according to current spatial distribution of population. That is, each watershed's current population is increased by fifty percent. Population density and impervious cover are closely related, and can be modeled as shown in the plot below.

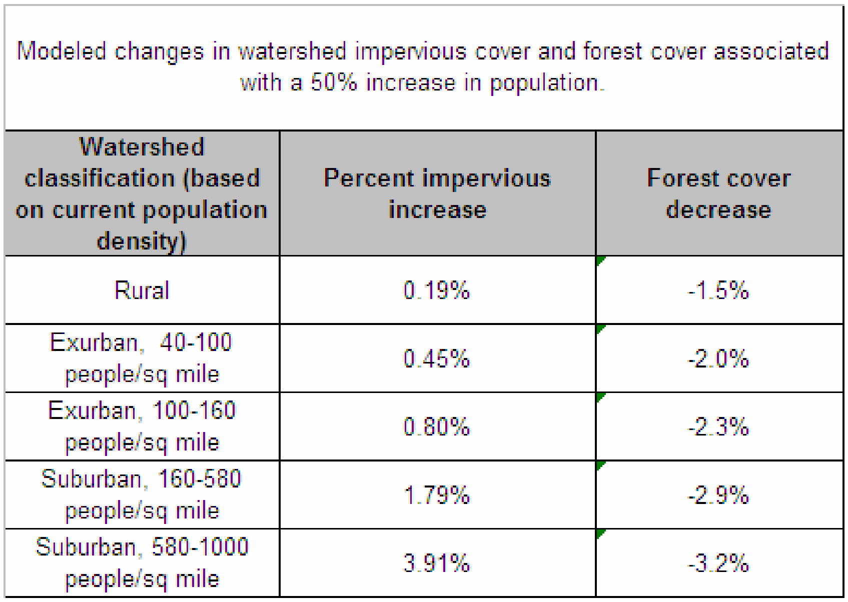


The R-square of the model is very strong, but the error is nevertheless significant in the context we are working in. The model's estimates of IC can err by 1% IC or more (*i.e.* the model can predict 2% IC when actual IC is 1%). Given our finding that non-urban streams are quite sensitive to IC changes, we should not base the future conditions scenario *directly* on the population/IC model. If we did, some systems would improve nonsensically (because of model error), while others would degrade too much. Instead, we computed an *average* projected IC increase for each watershed class, and added that value to the current IC for each watershed.

There is a weak but statistically very significant relationship between IC and FC in the Rivanna, as represented below. We adjusted future forest cover based on this model.



The projected land cover changes to watersheds in each of several population-based classes are shown below.

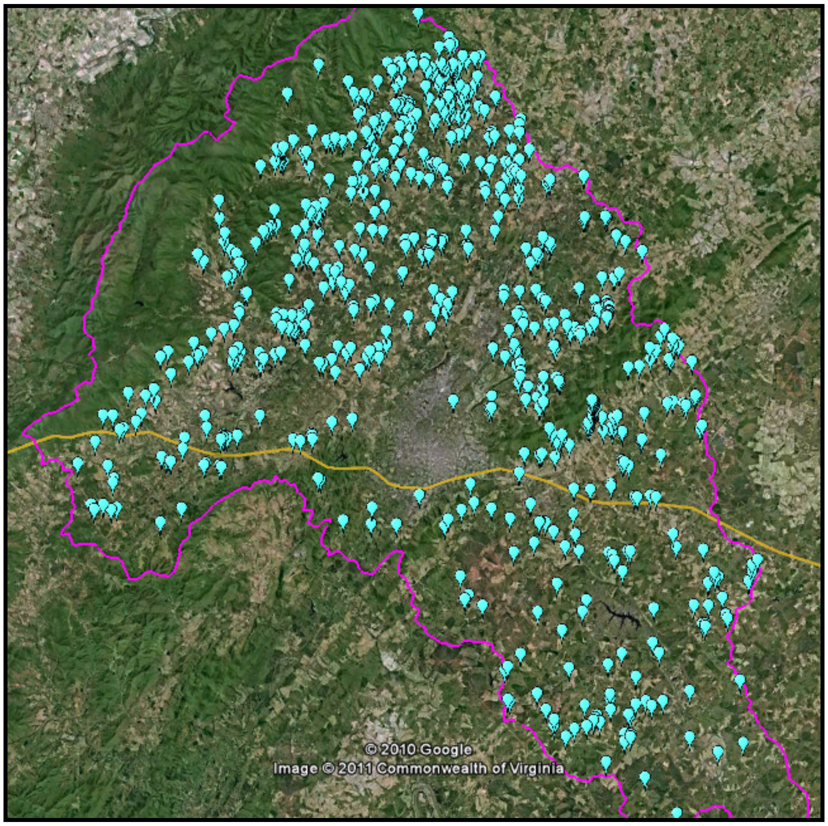


Modeled changes in watershed impervious cover and forest cover associated with a 50% increase in population.

Watershed classification (based on current population density)	Percent impervious increase	Forest cover decrease
Rural	0.19%	-1.5%
Exurban, 40-100 people/sq mile	0.45%	-2.0%
Exurban, 100-160 people/sq mile	0.80%	-2.3%
Suburban, 160-580 people/sq mile	1.79%	-2.9%
Suburban, 580-1000 people/sq mile	3.91%	-3.2%

3.2) We found no relationship between stream biological condition and cattle operations quantified at the watershed scale.

We tested for correlations between cattle grazing and stream biological condition in subsets of data that excluded urban streams and sites on the relatively large Rivanna River mainstem (see correlation matrix in Appendix B). In 1st through 5th-order systems, and also in most subsets limited to smaller streams, watershed cattle population showed little or no correlations with biological condition. By way of comparison, IC and FC were consistently strong or moderate correlates. In two subsets limited to systems with 0.4 to 4% IC, cattle density did correlate with health. However, in these instances cattle co-varied strongly with FC, and IC and FC were stronger predictors. We could not tease out cattle effects in these datasets because of data normality issues. We explored four customized datasets in which we randomly deleted cases to achieve normal distributions of cattle data. In each of these trials, correlations between cattle density and biological condition faded entirely, while IC and FC remained strong factors.



Above: Icons show locations of herds or small groups of cattle.

We conducted similar tests to explore for correlations between grazed pasture (as a percent of watershed area) and biological condition. No significant relationships were found.

We can not infer that Rivanna basin cattle operations have no impact on stream biological condition. However, our data show no detectable relationship between cattle and benthic health *at the landscape scale*. Assuming our data are valid measures of relative intensity of cattle operations, our study suggests that cattle are generally not a significant factor in the biological health of most Rivanna basin streams. We note that our study did not examine reach-scale impacts. That is, we did not situate our sampling sites near cow pastures or otherwise try to detect cattle effects at stream locations near cattle operations. We also note that Rivanna cattle operations may be generally less intensive than in some other areas of Virginia and the mid-Atlantic region.

3.3) Relationships between stream biology and reach-scale environmental variables.

3.3.1) Bank stability, sediment deposition, and related channel variables correlated with biological condition, particularly in exurban and rural streams.

An overview of the relationships among biological condition, watershed-scale land use, and reach-scale conditions is given in the matrix of Spearman correlations in Appendix B. Note that Spearman correlation coefficients and p-values will differ from Pearson correlations, and that both Spearman and Pearson correlations are applied in our analyses, depending on setting and purpose. (Pearson correlations are best with normal data distributions and linear relationships. The normal distribution generally follows the classic bell curve. Spearman correlations, on the other hand, can reveal or suggest linear or non-linear relationships among variables that are not necessarily normally distributed.) In the correlation matrix, correlations possessing significance of p=0.05 or better are highlighted in grey, and correlations possessing very strong significance (p=0.001 or better) are highlighted in purple. Significance, in statistics speak, is a measure of likelihood that the correlation is a product of random chance. The lower the number, the more likely the relationship is *not* a product of chance.

The matrix is arranged such that correlations can be examined in each of various subsets of our data. The reason we examine subsets along with the total dataset is because the relative importance of ecological factors can vary according to system attributes. For instance, we parse datasets according to land use intensity because our data strongly suggest that streams in heavily urbanized watersheds show little response to incremental increases in watershed impervious surface, while rural streams respond dramatically to the same amount of impervious surface increase. Urban streams may also respond (or not respond) to reach-scale factors differently than do non-urban streams.

We parse data according to stream order because other studies suggest that 1st through 3rd-order systems are responsive to impervious cover, while larger systems are not (Schueler 2009. As discussed in Section 3.1.1.1 above, the data in our study suggest that larger streams do respond to IC and other indicators of landscape disturbance, though less robustly than smaller streams.

A scan of the correlation matrix shows that biological condition (labeled “average bio score”) correlates more consistently and strongly with watershed LU/LC than with any other environmental variable. (In the matrix, the LU/LC factor is labeled “landscape factors (combo model output)”. This variable consists of the output of the model described in Section 3.1.2, and can be understood as an index of watershed land use intensity derived from percent forest cover and percent impervious cover.)

The variable with the next greatest amount of consistency of correlation with biological condition is riparian zone condition. We will discuss the riparian zone in Section 3.3.3.

A number of channel variables including bank stability, frequency of riffles, and substrate-related variables correlated with biological condition, particularly in non-urban streams, and most particularly in rural and exurban streams. Slope correlates with biological condition in non-urban streams.

Though correlations between biology and channel conditions are generally fairly weak, they are statistically robust. Clearly, in the systems we studied, biological condition is significantly associated with various conditions in the channel. Even though LU/LC predicts biology more powerfully than reach-scale conditions, common sense tells us that landscape-scale conditions are not directly felt by stream organisms. Rather, landscape alterations precipitate a cascade of changes that ultimately alter the flow regime, water quality, and physical habitat experienced by stream organisms at the scale of the habitat they occupy through their lifecycles. Of course, this framework of cause and effect is not all-encompassing or absolute. Sometimes, for instance, habitat disturbance within a reach is related to spatially proximate conditions or events (*e.g.* road crossings, cattle wallows, riparian forest clearance, etc.).

The observation that watershed LU/LC is a stronger predictor of biology than channel conditions makes intuitive sense inasmuch as the effects of landscape alteration are distributed over multiple processes and features in the stream, and no single habitat factor within the reach will have as much influence on biology as the sum of all factors. Seen from another angle, many habitat conditions in the reach are integrated at the scale of the watershed. Our study, however, does not shed clear light on the relationships between LU/LC and channel conditions. Nor does our study capture all of the factors that influence biology. What our study does show clearly is that land use/land cover at the scale of the watershed usually predicts biological condition far more powerfully than any single local-scale factor we studied, and more powerfully than any combination of local-scale factors. In addition to tremendously strong statistical evidence, the dominant role of watershed-scale LU/LC in predicting biological condition is evident by example: Even though our data suggest generally that reach-scale attributes such as bank stability and substrate can affect biology, we find examples in our reference systems of biologically healthy streams with fairly unstable banks and/or excessive sedimentation. In these systems, complete forestation and the lack of impervious surfaces throughout the watershed appear to trump habitat deficiencies in the reach.

As noted above, in the datasets comprising 1st through 5th-order streams, we observe correlations between biology and a number of channel variables. We also observe that these correlations strengthen as the dataset becomes less urbanized. The relationships are strongest in the dataset limited to twenty-five systems with 0.4% to 4% IC. These comprise our wild (reference), rural, and exurban systems, as well as three systems classified as suburban. In the remainder of the discussion we focus on this set, not only because it best reveals relationships between channel conditions and biology, but also because it, like the Rivanna basin, is dominated by exurban systems.

The matrix below focuses on the strongest correlations among biology, LU/LC (combo model output), residuals of the LU/LC→biology model, and channel conditions in the subject dataset.

Pearson correlations among biological condition, channel conditions, watershed land use intensity, and residuals of land use/biological condition model. 1st through 5th-order systems with IC ranging from 0.4% to 4%.

		LUES Average Score	Combo model residuals	Combo model output	LN__ Slope	Frequency of Riffles	Bank Stability	Sediment Deposition	% Fine Sand/ Clay
LUES Average Score	Pearson Correlation	1	.594**	.716**	.723**	.594**	.649**	.509*	-.510*
	Sig. (2-tailed)		.002	.000	.000	.002	.001	.011	.011
	N	25	25	25	25	24	24	24	24
Combo model residuals	Pearson Correlation	.594**	1	-.136	.370	.509*	.431*	.365	-.250
	Sig. (2-tailed)	.002		.517	.068	.011	.035	.079	.238
	N	25	25	25	25	24	24	24	24
Combo model output	Pearson Correlation	.716**	-.136	1	.569**	.260	.398	.288	-.395
	Sig. (2-tailed)	.000	.517		.003	.219	.054	.172	.056
	N	25	25	25	25	24	24	24	24
LN__Slope	Pearson Correlation	.723**	.370	.569**	1	.620**	.556**	.603**	-.570**
	Sig. (2-tailed)	.000	.068	.003		.001	.005	.002	.004
	N	25	25	25	25	24	24	24	24
Frequency of Riffles	Pearson Correlation	.594**	.509*	.260	.620**	1	.799**	.729**	-.756**
	Sig. (2-tailed)	.002	.011	.219	.001		.000	.000	.000
	N	24	24	24	24	24	24	24	24
Bank Stability	Pearson Correlation	.649**	.431*	.398	.556**	.799**	1	.517**	-.594**
	Sig. (2-tailed)	.001	.035	.054	.005	.000		.010	.002
	N	24	24	24	24	24	24	24	24
Sediment Deposition	Pearson Correlation	.509*	.365	.288	.603**	.729**	.517**	1	-.810**
	Sig. (2-tailed)	.011	.079	.172	.002	.000	.010		.000
	N	24	24	24	24	24	24	24	24
% Fine Sand/Clay	Pearson Correlation	-.510*	-.250	-.395	-.570**	-.756**	-.594**	-.810**	1
	Sig. (2-tailed)	.011	.238	.056	.004	.000	.002	.000	
	N	24	24	24	24	24	24	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Above: Pearson correlations among biological condition, channel conditions, watershed land use intensity, and residuals of land use/biological condition model. Wild, rural, and exurban 1st through 5th-order systems with IC ranging from 0.4% to 4%.

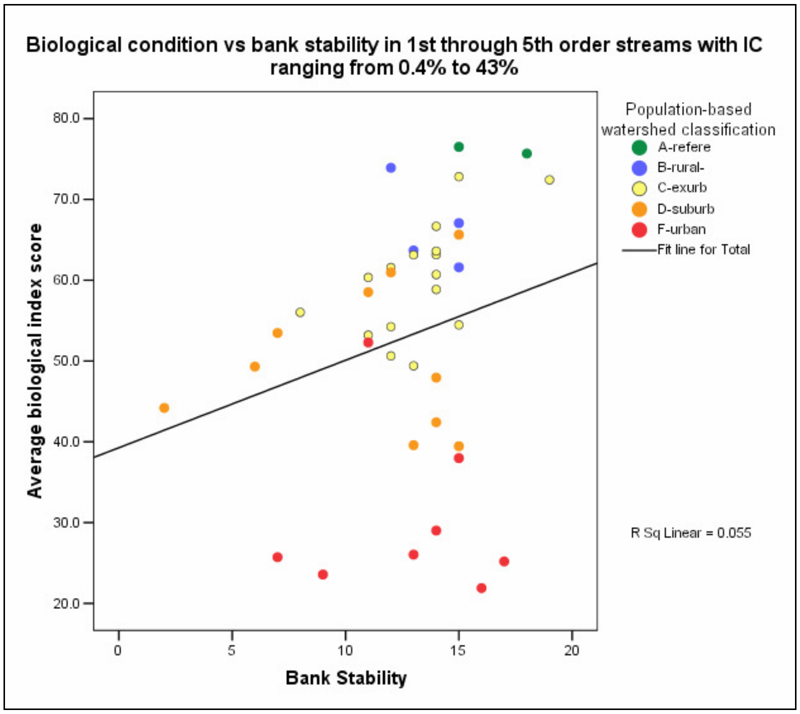
As shown above, riffle frequency, bank stability, sediment deposition, percent fines, and slope all correlate significantly with biological condition. They also correlate with one another. Sediment deposition and percent fines are so highly correlated that they may be regarded as a single factor. The same can be said for bank stability and frequency of riffles. Overall, the data reflect what we know from common sense: flatter streams tend to harbor finer substrate, and are more prone to sediment deposition than steeper streams. The data also suggest a relationship that is less obvious to the casual observer: flatter streams appear to have a higher risk of bank erosion.

Most of the channel factors do not appear to correlate significantly with LU/LC (bank stability may be an exception). Slope, however, is moderately correlated with LU/LC, probably reflecting a tendency toward greater land use intensity in less mountainous landscapes. Two or three channel factors—frequency of riffles, bank stability, and (marginally) sediment deposition—correlate with residuals of the combination model, suggesting a potential effect on biological condition that is not captured by the LU/LC→biology model (but only within systems with this range of land use intensity). Frequency of riffle data are abnormally distributed, and, to be statistically strict, the Pearson correlations between riffle frequency and other variables should be interpreted cautiously.

Percent fines data is also abnormally distributed. Percent fines and riffle frequency data cannot be usefully transformed, and cannot be examined in multiple regression contexts. We observe simply that these variables exhibit moderate correlation with biological condition and stream slope.

Bank stability

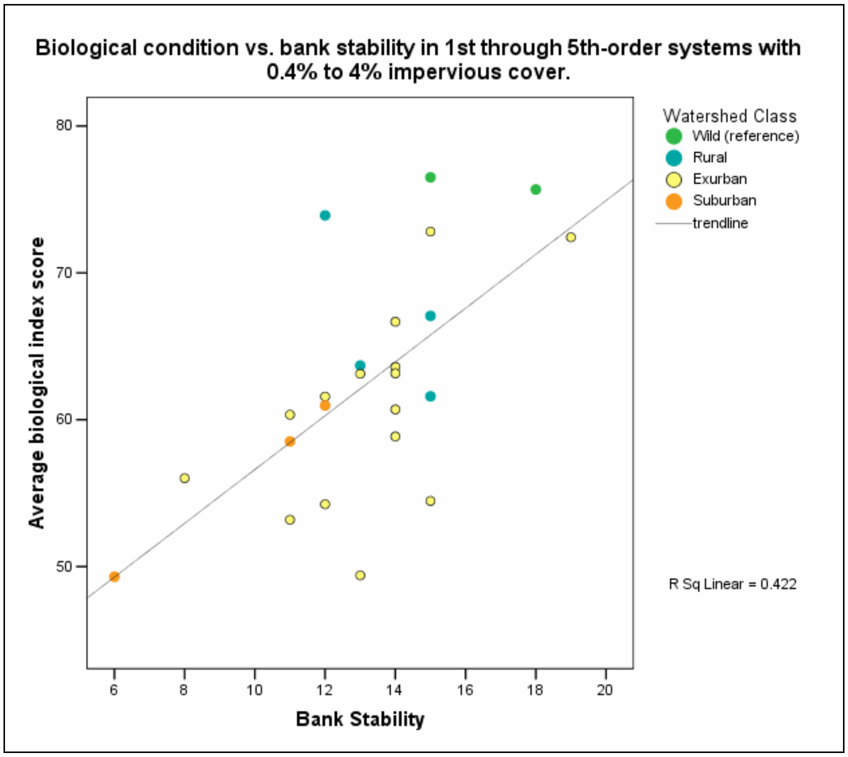
As mentioned, channel conditions relate more strongly to biology in subsets that exclude urban systems. The figures below illustrate why this is so. We focus on the relationship between biological condition and bank stability, while noting that other variables tend to follow similar patterns as the data becomes "de-urbanized".



The scatterplot above reveals a cluster of urban sites in which biological condition is depressed and does not respond to better stream bank stability. The cluster is composed of urban systems with population density greater than 1,200 people per square mile. Most of the other reach-scale variables tend to exhibit similar patterns in which these same urban sites form an outlying cluster.

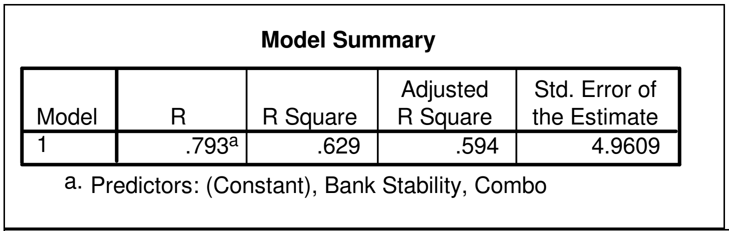
We cannot be sure of the reasons bank stability and most other reach-scale variables seem relatively unrelated to biology in these urban systems. We can speculate that perhaps these systems have exceeded a disturbance threshold whereby the influences of channel and substrate attributes are overwhelmed by other stressors such as extreme flashiness or polluted runoff from yards, streets, and parking lots.

Set A3 excludes the above-described cluster of urban systems, as well as all other urban systems and most suburban systems. The scatterplot below illustrates the noticeably stronger association between biology and bank stability in this subset. Again, as indicated in the correlation matrix, other channel variables' relationships with biology are also tightened in this predominantly rural and exurban subset.



In the streams we studied, the average bank stability score was 12.75. Scores range from 0 (worst) to 20 (best) and reflect stability in terms of percentage of stream bank area that is eroding. An average score of 12.75 means that in the 40 streams we surveyed, 20-25% of stream bank surfaces were visibly unstable or actively eroding.

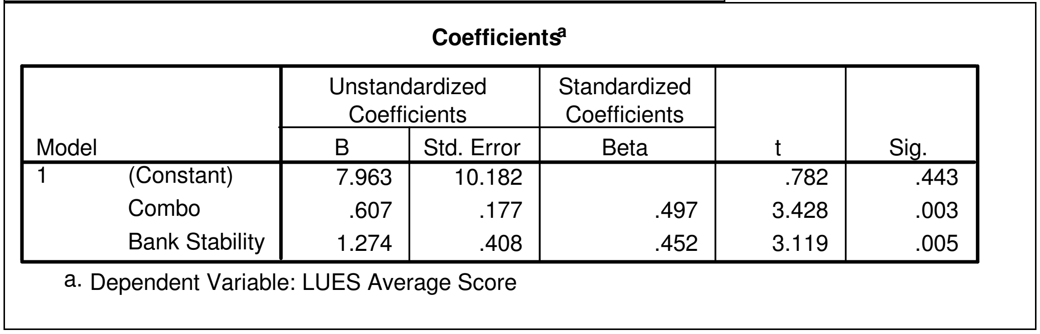
The model below suggests that bank stability and land use intensity (combo model output) are about equally strong predictors of biology in this subset, and that bank stability explains a significant amount of biological condition variation *not* explained by LU/LC.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.793[a]	.629	.594	4.9609

a. Predictors: (Constant), Bank Stability, Combo



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.963	10.182		.782	.443
	Combo	.607	.177	.497	3.428	.003
	Bank Stability	1.274	.408	.452	3.119	.005

a. Dependent Variable: LUES Average Score

Slope could arguably be added to the above model as a third independent variable, but its significance is marginal when controlling for LU/LC and bank stability. On its own, or when controlling only for LU/LC, slope significantly correlates with biology. Our data are inconclusive with respect to the relative amount of influence each of LU/LC, slope, and bank stability exert on biology.

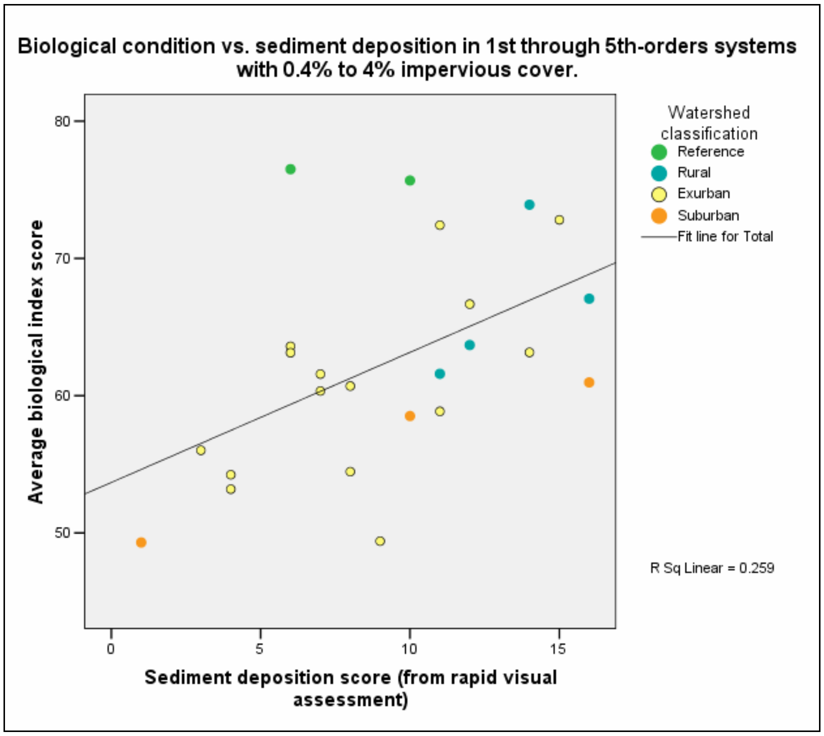
Slope

As to slope's relative importance through the entire range of our data: A scan of the matrix in Appendix B shows that slope is a moderate correlate of biological condition in only two subsets (Sets A2 and A3), while LU/LC is a strong or moderate correlate through the entire dataset (Set A1) and in every subset. Even in subsets that are quite small—with only about 10 cases— LU/LC is a powerful predictor of biology.

Sets A2 and A3 are important exceptions. These sets are comprised largely of rural and exurban systems—most typical of the Rivanna basin. In these systems, slope correlates significantly with LU/LC, channel conditions, and biological condition. A rigorous understanding of the process interactions among LU/LC, slope, channel conditions and biological condition would be of value, but is beyond the scope of this report. However, we can say our data strongly suggest that whatever role slope may play, it is constrained within limits set by LU/LC.

Sediment deposition

A scatterplot showing the relationship between biological condition and sediment deposition is shown below.



Above: Sediment deposition and biological condition were significantly correlated in the subset of systems with 0.4% to 4% IC (R-squared=0.26, p=0.01).

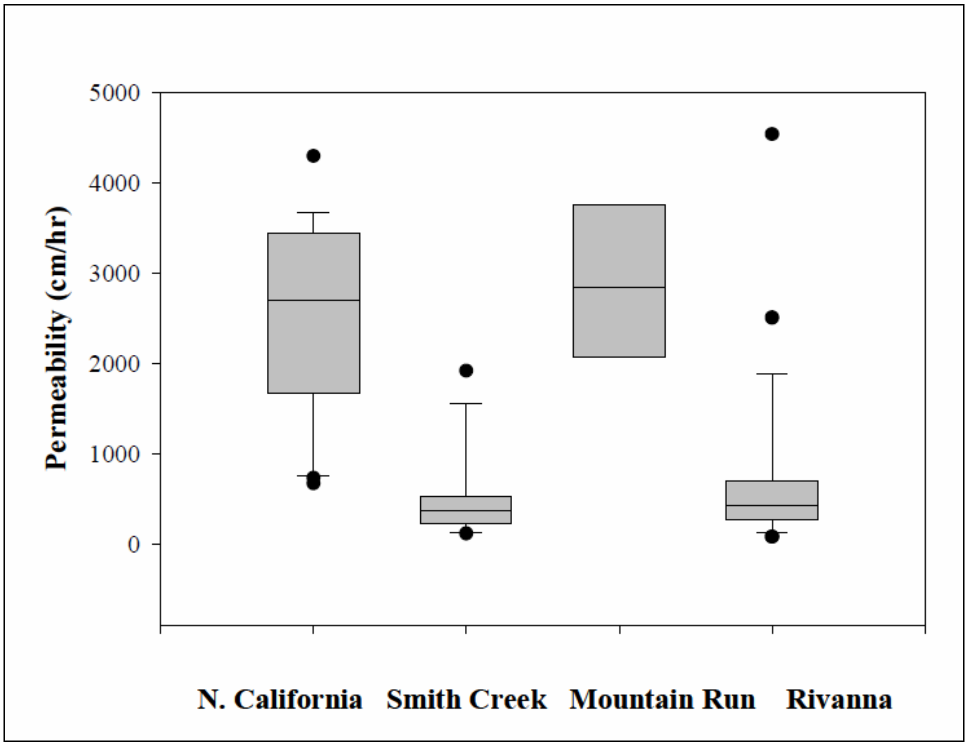
The model below suggests that sediment deposition is a statistically significant predictor of biology in this dataset, and explains some biological condition variation *not* explained by LU/LC. However, when controlling for slope, sediment deposition does not correlate with biological condition, suggesting that slope may be controlling sediment deposition and other factors, and that the aggregated biological effects of slope-mediated channel factors may be greater than the effect of sediment deposition alone.

3.3.2) Streambed permeability and substrate sediment concentration.

StreamWatch acknowledges Dr. Christine May of James Madison University's Department of Biology for contributing the field work and most of the analyses for this segment of our study.

3.3.2.1) Streambed permeability was generally low.

Streambed permeability in tributaries to the Rivanna River was generally low. For comparison, the chart below presents data from other studies of permeability that have been conducted by Dr. Christine May, Department of Biology at James Madison University.



Northern California streams used in this comparison are impacted by timber harvest and forest roads (data published in Cover et al. 2008). The Shenandoah Valley stream used in this comparison is Smith Creek, which is heavily impacted by agriculture and listed as impaired on Virginia's Section 303(d) Total Maximum Daily Load Priority List due to violations of the State's Water Quality Standards for fecal coliform bacteria and benthic impairment due to excessive sedimentation (Virginia Department of Environmental Quality 2004). Mountain Run drains the west side of the Blue Ridge Mountains along the foothills of the Shenandoah Valley (McHugh 2009). This stream is minimally impacted by agriculture and has mature forest buffers and forested headwaters. In general, permeability values in the Rivanna basin are comparable to the samples collected at Smith Creek, suggesting excessive sedimentation and impairment.

3.3.2.2) Streambed permeability and substrate sediment concentration did not strongly correlate with biological condition.

Permeability values observed in this study of the Rivanna basin were highly variable within and among streams. Within each stream, one riffle was sampled, and within this riffle permeability was measured at three separate placements of the sampling instrument (see Section 6.7 for methods). For data gathered at each instrument location, the variability was very low (average coefficient of variation 9%), indicating high precision of the sampling method. However, variability among instrument locations within the same riffle was often high, indicating that streambed conditions were very patchy (average coefficient of variation 68%). Because of the high within-stream variation, comparisons among streams will have low statistical power. This will make it difficult to detect relationships between permeability and other ecological variables, and it will make it difficult to detect changes through time. It is possible that modifications to the protocol could overcome this difficulty in future studies.

Usually, when data variance is high, data distribution is skewed and the number of samples is low (as with our permeability data), median values are considered to be a better statistical representation than average values. However, due to the variance described above, statistical relationships between permeability and other ecological variables are somewhat tenuous, so in the spirit of thorough exploration we will consider both the median and the average of the three permeability values gathered at each site. We will consider two datasets. Set 1 consists of all 25 sites at which permeability data were gathered. This set includes 3 heavily urbanized systems and 1 suburban system. Set 2, a subset of Set 1, comprises 21 primarily rural and exurban systems. For this second subset, systems with more than 10% watershed IC were excluded. The 10% cutoff was used so that this analysis would parallel the analyses applied to other stream habitat variables. The result of applying this cutoff was that the systems populating Set 2 have watershed IC ranging from 0.4% to 3.8%. (By chance, no permeability data were collected in systems with IC ranging from 4% to 10%).

The table below, built from Set 1, shows Pearson correlations among biological condition, substrate-related variables (median and average permeability; average sediment concentration; percent fines and percent cobble from Wolman pebble counts; sediment deposition score from rapid visual assessment) and watershed land use/land cover variables (percent impervious; output of combination model driven by percent impervious and percent forest cover (see Section 3.1.2 for explanation of combination model)).

Pearson correlations among biological condition, substrate-related variables, and watershed land use/land cover variables in 25 Rivanna basin streams.

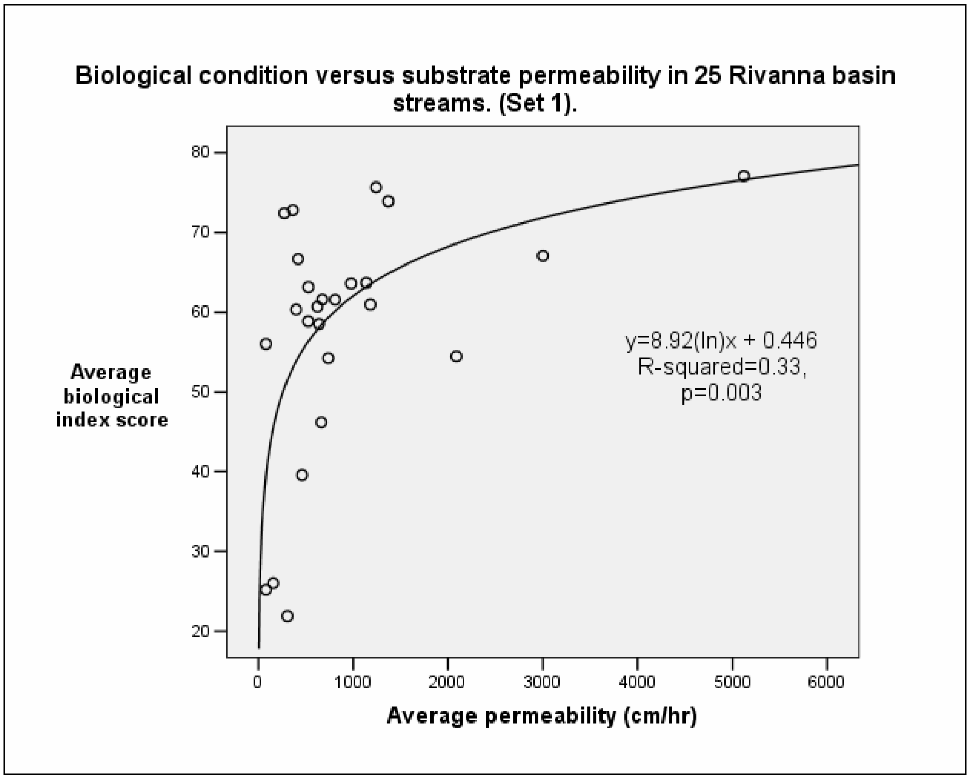
		Avg Bio Index Score	LN_ Avg Permeability	LN_ Median Permeability	Avg Sediment Concentration	LN_ Percent Fines	LN_ Percent Cobble	Sediment Deposition (rapid visual)	LN_ Percent Impervious	Combo Model Output (IC and FC)
Avg Bio Index Score	Pearson Correlation	1	.572**	.430*	-.420*	-.257	.253	.446*	-.921**	.935**
	Sig. (2-tailed)		.003	.032	.036	.226	.233	.029	.000	.000
LN_Avg Permeability	Pearson Correlation	.572**	1	.869**	-.595**	-.430*	.524**	.406*	-.608**	.624**
	Sig. (2-tailed)	.003		.000	.002	.036	.009	.049	.001	.001
LN_Median Permeability	Pearson Correlation	.430*	.869**	1	-.584**	-.448*	.451*	.391	-.453*	.443*
	Sig. (2-tailed)	.032	.000		.002	.028	.027	.059	.023	.026
Avg Sediment Concentration	Pearson Correlation	-.420*	-.595**	-.584**	1	.210	-.311	-.260	.443*	-.458*
	Sig. (2-tailed)	.036	.002	.002		.324	.139	.219	.027	.021
LN_Percent Fines	Pearson Correlation	-.257	-.430*	-.448*	.210	1	-.556**	-.633**	.372	-.366
	Sig. (2-tailed)	.226	.036	.028	.324		.005	.001	.073	.078
LN_Percent Cobble	Pearson Correlation	.253	.524**	.451*	-.311	-.556**	1	.755**	-.182	.210
	Sig. (2-tailed)	.233	.009	.027	.139	.005		.000	.395	.324
Sediment Deposition (rapid visual)	Pearson Correlation	.446*	.406*	.391	-.260	-.633**	.755**	1	-.317	.352
	Sig. (2-tailed)	.029	.049	.059	.219	.001	.000		.131	.092
LN_Percent Impervious	Pearson Correlation	-.921**	-.608**	-.453*	.443*	.372	-.182	-.317	1	-.980**
	Sig. (2-tailed)	.000	.001	.023	.027	.073	.395	.131		.000
Combo Model Output (IC and FC)	Pearson Correlation	.935**	.624**	.443*	-.458*	-.366	.210	.352	-.980**	1
	Sig. (2-tailed)	.000	.001	.026	.021	.078	.324	.092	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

As shown above, biology correlates far more strongly with landscape factors than with substrate-related variables. Average permeability correlates more strongly with landscape factors than does median permeability, average sediment concentration, or any of the other substrate-related variables. Average permeability also correlates more strongly with biology than do any of the other substrate variables. Of average permeability, median permeability, and average sediment concentration, average permeability is the strongest correlate with independently-collected substrate data (Wolman pebble count data and sediment deposition score). All these observations might seem to suggest that average permeability is superior to median permeability or average sediment concentration when it comes to representing streambed permeability's role in benthic ecology. The observations also might seem to suggest that the data produced by the standpipe infiltration protocol more faithfully represent the ecological role of substrate conditions than our other forms of substrate data. These patterns hold up in Spearman correlations as well, suggesting the data transformations used in the correlation matrix did not distort the relationships.

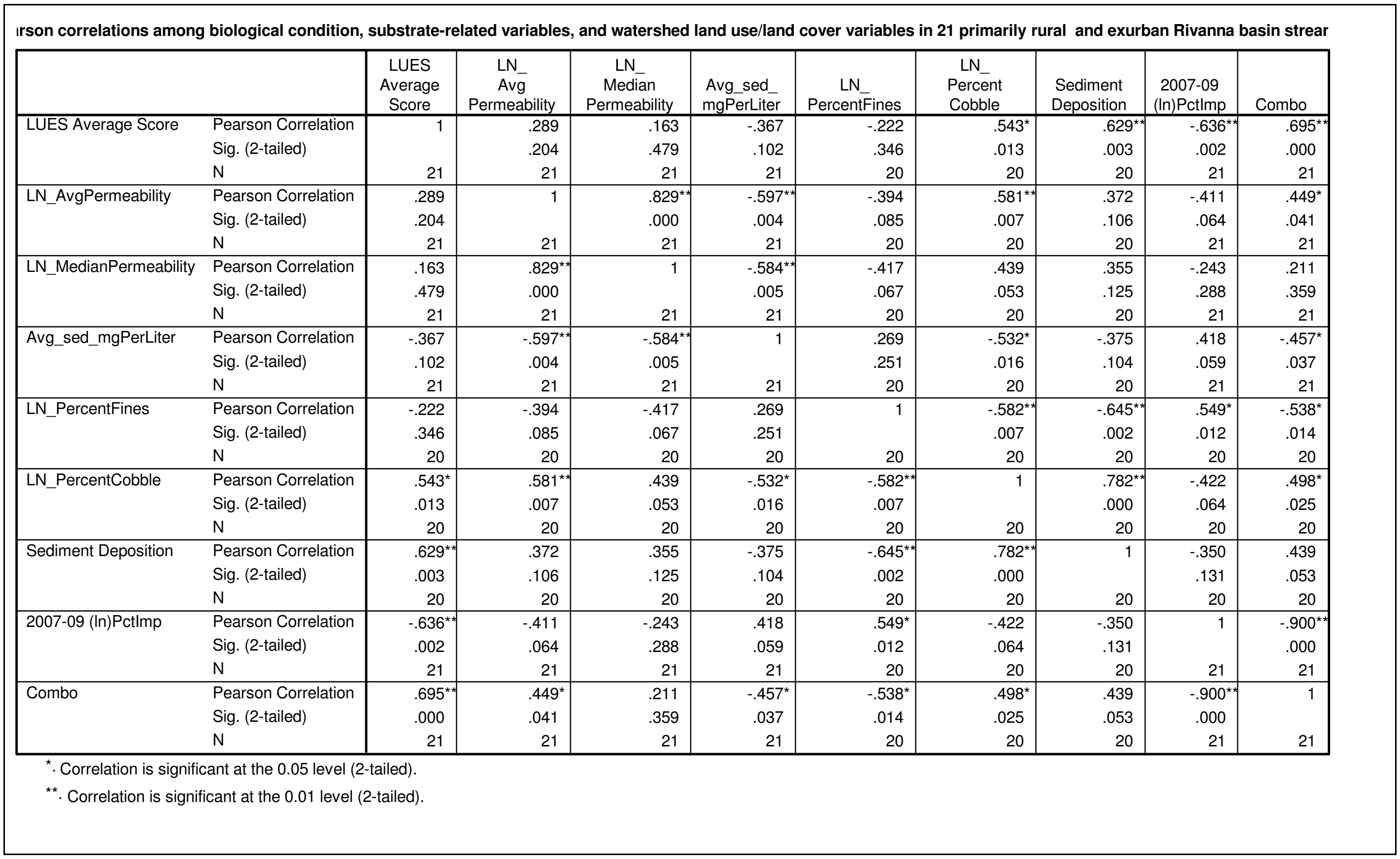
The best fit for the relationship between average permeability and biology in Set 1 is a logarithmic curve, as shown below.



The above-illustrated relationship has a *p*-value of 0.003; theoretically quite strong. Yet there is a great deal of scatter. Note in particular that when permeability values are at their lowest (under 500 cm/hr), biological condition scores range from best to worst. That is, both the very best and the very worst biological scores occur when permeability is held constant.

In the above plot, the three clustered cases with the lowest scores are all urban streams with watershed IC exceeding 25%. These systems are excluded in Set 2, and when we examine the relationship in Set 2 between actual biological index scores and scores predicted by the model derived from Set 1, we find no statistical significance (Pearson coefficient =0.29, *p*=0.20). In other words, for 21 out of 25 cases in Set 1, the model's supposed significant fit does not apply. The reason the model misrepresents the statistical strength of the permeability/biology relationship is because of the coincidental occurrence of very low biological index scores and low permeability values in urban streams. In all likelihood, the severe biological degradation in these urban streams is largely unrelated to the permeability values. However, these sites have high leverage on the statistical relationship.

We find also in Set 2 that the other expression of permeability, *i.e.* median permeability, does not correlate significantly with biology, nor does average sediment concentration. Meanwhile, rapid visual sediment deposition score continues to correlate with biology (see table below).



rson correlations among biological condition, substrate-related variables, and watershed land use/land cover variables in 21 primarily rural and exurban Rivanna basin strear

		LUES Average Score	LN_ Avg Permeability	LN_ Median Permeability	Avg_sed_ mgPerLiter	LN_ PercentFines	LN_ Percent Cobble	Sediment Deposition	2007-09 (ln)PctImp	Combo
LUES Average Score	Pearson Correlation	1	.289	.163	-.367	-.222	.543*	.629**	-.636**	.695**
	Sig. (2-tailed)		.204	.479	.102	.346	.013	.003	.002	.000
	N	21	21	21	21	20	20	20	21	21
LN_AvgPermeability	Pearson Correlation	.289	1	.829**	-.597**	-.394	.581**	.372	-.411	.449*
	Sig. (2-tailed)	.204		.000	.004	.085	.007	.106	.064	.041
	N	21	21	21	21	20	20	20	21	21
LN_MedianPermeability	Pearson Correlation	.163	.829**	1	-.584**	-.417	.439	.355	-.243	.211
	Sig. (2-tailed)	.479	.000		.005	.067	.053	.125	.288	.359
	N	21	21	21	21	20	20	20	21	21
Avg_sed_mgPerLiter	Pearson Correlation	-.367	-.597**	-.584**	1	.269	-.532*	-.375	.418	-.457*
	Sig. (2-tailed)	.102	.004	.005		.251	.016	.104	.059	.037
	N	21	21	21	21	20	20	20	21	21
LN_PercentFines	Pearson Correlation	-.222	-.394	-.417	.269	1	-.582**	-.645**	.549*	-.538*
	Sig. (2-tailed)	.346	.085	.067	.251		.007	.002	.012	.014
	N	20	20	20	20	20	20	20	20	20
LN_PercentCobble	Pearson Correlation	.543*	.581**	.439	-.532*	-.582**	1	.782**	-.422	.498*
	Sig. (2-tailed)	.013	.007	.053	.016	.007		.000	.064	.025
	N	20	20	20	20	20	20	20	20	20
Sediment Deposition	Pearson Correlation	.629**	.372	.355	-.375	-.645**	.782**	1	-.350	.439
	Sig. (2-tailed)	.003	.106	.125	.104	.002	.000		.131	.053
	N	20	20	20	20	20	20	20	20	20
2007-09 (ln)PctImp	Pearson Correlation	-.636**	-.411	-.243	.418	.549*	-.422	-.350	1	-.900**
	Sig. (2-tailed)	.002	.064	.288	.059	.012	.064	.131		.000
	N	21	21	21	21	20	20	20	21	21
Combo	Pearson Correlation	.695**	.449*	.211	-.457*	-.538*	.498*	.439	-.900**	1
	Sig. (2-tailed)	.000	.041	.359	.037	.014	.025	.053	.000	
	N	21	21	21	21	20	20	20	21	21

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

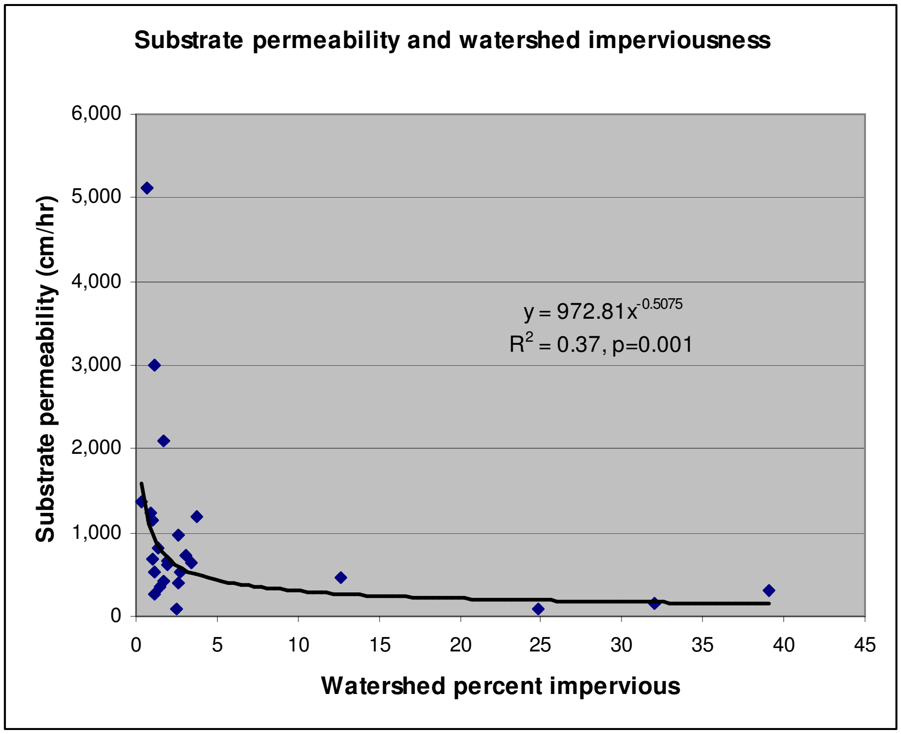
It appears the streambed permeability and fine sediment concentration data gathered for this study does not reveal relationships between these parameters and benthic macroinvertebrate community health. This is not to say, however, that no such relationship exists. Also, because we gathered no fish data for this study, we cannot speak to relationships between fish and streambed permeability or fine sediment concentration.

The absence of detectable relationships between streambed permeability or substrate fine sediment concentration and benthic condition may well be due to the variance of permeability values noted at the outset of this discussion. To address this, Dr. May recommends that the field protocol could be adjusted to better address the high within site variability. For the current study, at each site one riffle was sampled at 3 different locations within the riffle. The recommendation is to increase to a total of three adjacent riffles, with three samples in each riffle. This change in the sampling strategy would make for stronger comparisons among streams, would provide an ability to track changes through time, and would be more likely to reveal the relationship between permeability and benthic health than the protocol used for this study.

3.3.2.3) Streambed permeability and substrate sediment concentration correlated moderately with watershed land use/land cover, as did other substrate-related variables.

In each of the subsets above, average permeability and average sediment concentration correlated with watershed land use/land cover factors. We note also that the pebble count parameters, percent fines and percent cobble correlated significantly with landscape factors in rural and exurban streams.

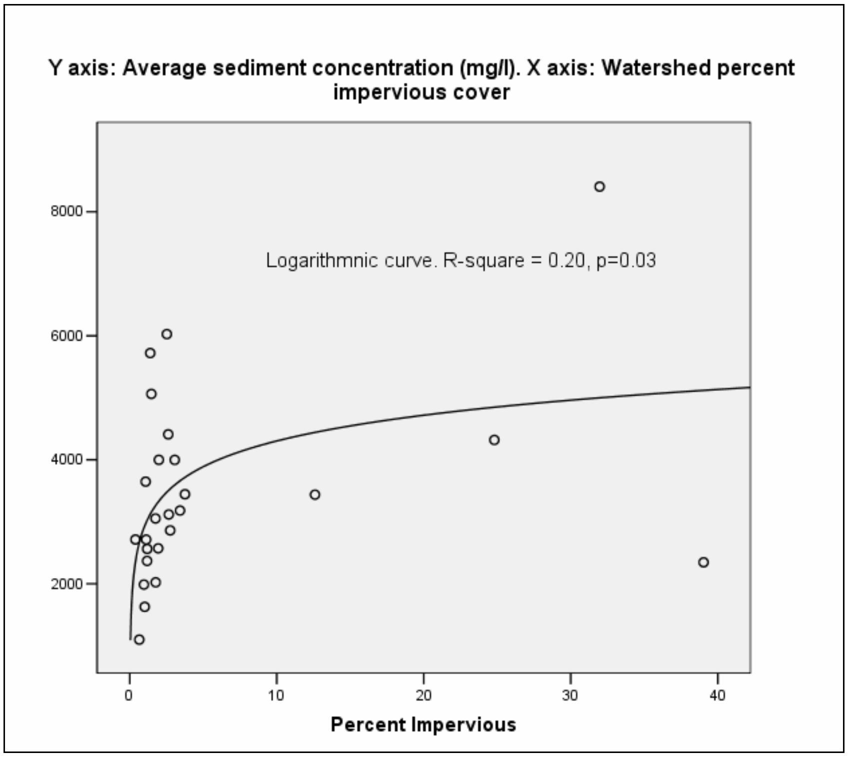
An example of the relationship between permeability and LU/LC is shown in the plot below.



Above: Average streambed permeability and watershed impervious cover in 25 Rivanna basin streams.

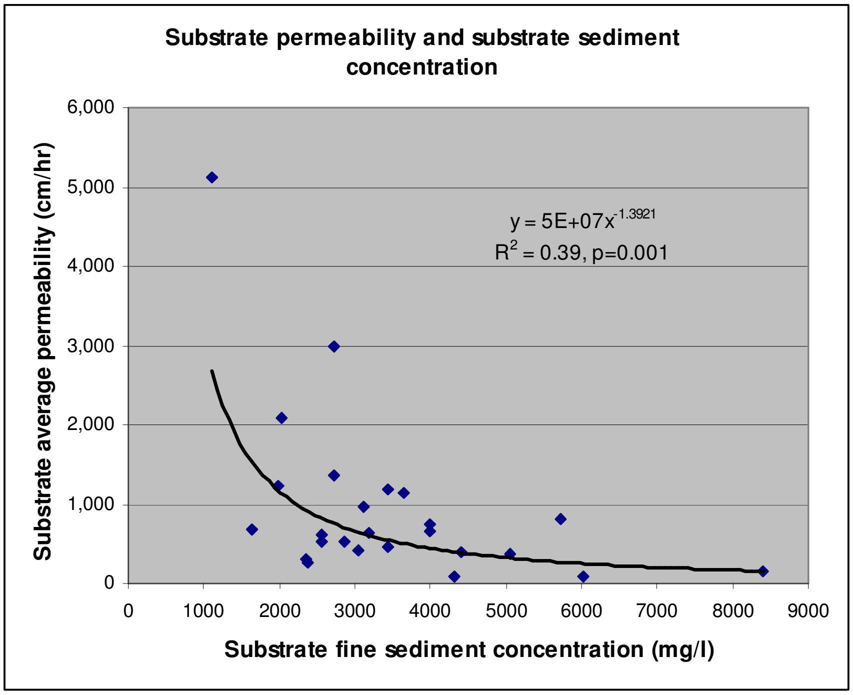
The above-illustrated relationship between permeability and percent impervious surfaces is imperfect because of the high within-stream variability and because factors other than imperviousness may affect permeability. Despite these limitations, a statistically significant relationship is observed in the form of a power curve with an R-squared of 0.37 and a p-value of 0.001. The power relationship indicates that permeability values tend to decrease rapidly as the amount of impervious surface increases in a basin.

There was a weak relationship between substrate sediment concentration and watershed impervious cover, as shown below.

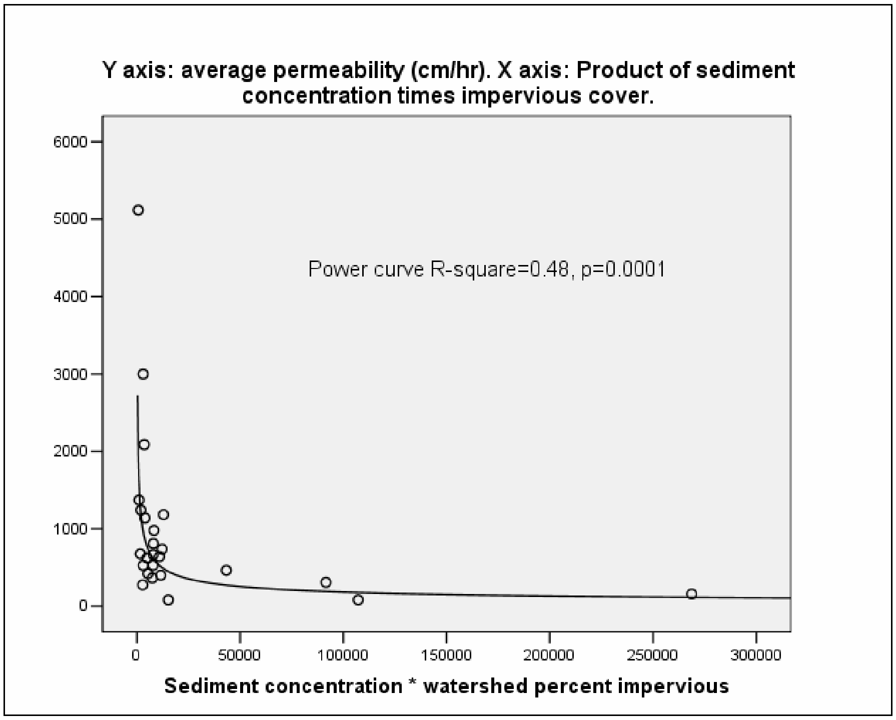


A weak linear relationship was also observed between forest cover and sediment concentration (R-square=0.19, p=0.03).

The weak relationships between sediment concentration and LU/LC suggest that changes in stormflow hydrographs may play a role in reducing streambed permeability. An increase in storm runoff affects the degree of channel armoring because higher flood flows pass through the channel at a greater frequency and magnitude. Because the streambed must adjust to these changes, the packing and interlocking of coarse grains on the surface may increase bed strength. Increased bed strength would decrease porosity (similar to the effects of soil compaction) and thus reduce permeability. In this study, streambed permeability was significantly correlated with direct measurements of fine sediment (R-square=0.39, p=0.001; see plot below)



However, the interaction between fine sediment and impervious surfaces is a better predictor of permeability and explained 48% of the observed variability (see plot below).



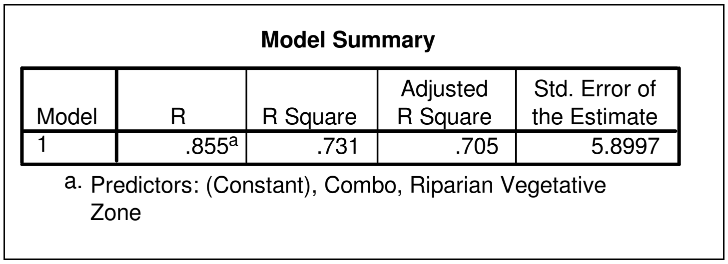
There are two primary factors that affect streambed permeability. The first is porosity, which is largely determined by the amount of fine sediment that fills interstitial spaces between large particles. However, the armoring and interlocking of coarse surface grains is adjusted to withstand flood flows. These factors can affect porosity by increasing particle packing and interlocking, thus reducing interstitial volume and permeability. The second factor that affects streambed permeability is hydraulic head pressure. Previous research by Cover et al. (2008) observed a strong correlation between permeability and the product of drainage area and channel slope (referred to as the stream power index) in a study of streams with variable size and steepness. Unpublished data by C. May in the Shenandoah Valley found that the permeability of riffles within an individual stream was strongly affected by riffle gradient. Both the stream power index and riffle gradient were tested as possible predictors or covariates of permeability in this study of the Rivanna basin. Neither were significant predictors of streambed permeability.

3.3.3) Forested riparian buffers may help improve biological health, but only within constraints set by watershed-wide land use/land cover.

The table in Appendix A shows correlation coefficients and significance values for relationships between biological index scores and reach-scale habitat variables in different data subsets. For reference, the correlations between biological condition and watershed LU/LC are also shown. In the various subsets shown in the table, riparian zone condition correlates with health more consistently than any other reach-scale variable. In order to test the importance of the health/riparian zone relationship relative to landscape factors, we focused on 1st through 4th order streams. We observed stronger correlations between buffer conditions and biology when 5th order streams were excluded from the analysis, and we assumed that the shading and cooling impacts of tree canopies have stronger effects in smaller streams. We next needed to identify a subset with normal data distribution for both variables. The largest subset in which these criteria were satisfied was a subset comprising twenty-four 1st through 4th-order systems with IC ranging from 0.4% to 10%. In this subset, riparian zone score condition did not co-vary with landscape factors, but did correlate with the residuals of the LU/LC→biology described in Section 3.1.2 (Pearson r=0,46, p=0.03). From these data we built the following model:

$$\textit{Average bio index score} = -1.47 + (0.85 \times CO) + (0.77 \times \textit{riparian zone score})$$

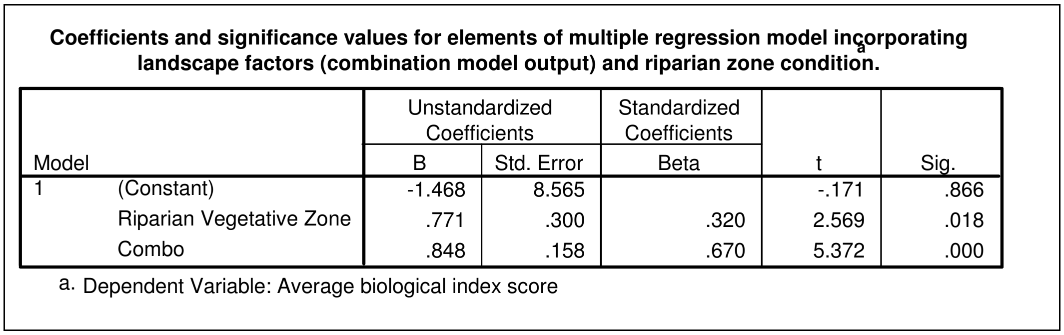
. . .where *CO* is the output of the combination model. The model's R-square is 0.73, as compared to 0.66 when riparian scores are not included. This model has lower Akaike and Bayesian information criteria values than a single-factor regression, meaning that for this dataset, adding the riparian zone data is statistically justified (*i.e.* the model is not over-parameterized). Model specifications are shown below.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.855[a]	.731	.705	5.8997

a. Predictors: (Constant), Combo, Riparian Vegetative Zone

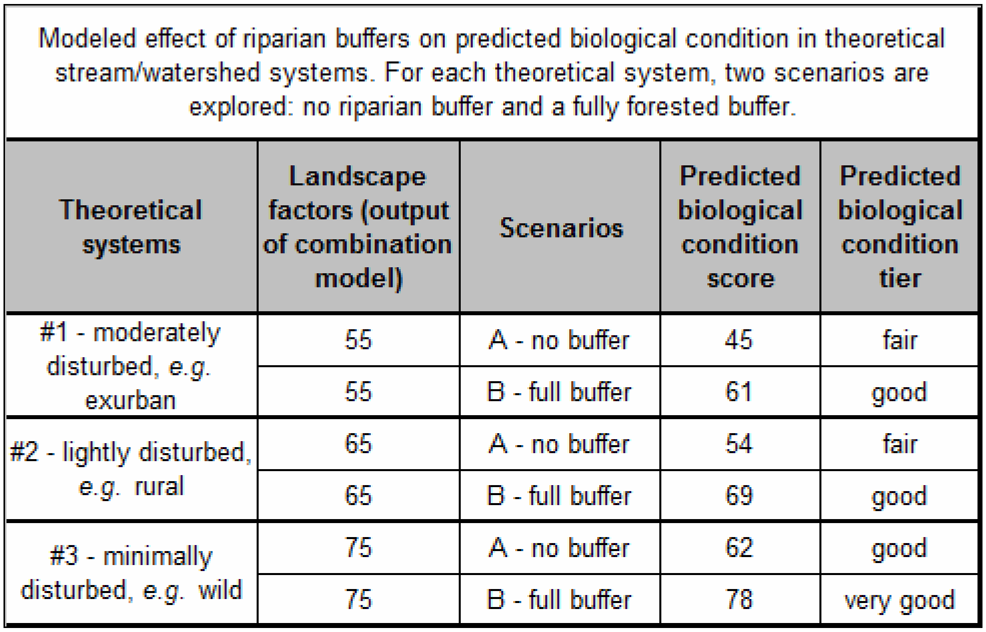


Coefficients and significance values for elements of multiple regression model incorporating[a] landscape factors (combination model output) and riparian zone condition.

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-1.468	8.565		-.171	.866
	Riparian Vegetative Zone	.771	.300	.320	2.569	.018
	Combo	.848	.158	.670	5.372	.000

a. Dependent Variable: Average biological index score

Though the riparian zone factor is a significant independent variable, we note that the landscape factor is about twice as strong (landscape and riparian standardized coefficients are 0.67 and 0.32, respectively). Still, the model suggests that riparian zone integrity can offset watershed-scale landscape disturbance. The table below shows how the model predicts the impact of riparian buffers in 3 theoretical systems.



Modeled effect of riparian buffers on predicted biological condition in theoretical stream/watershed systems. For each theoretical system, two scenarios are explored: no riparian buffer and a fully forested buffer.

Theoretical systems	**Landscape factors (output of combination model)**	**Scenarios**	**Predicted biological condition score**	**Predicted biological condition tier**
#1 - moderately disturbed, *e.g.* exurban	55	A - no buffer	45	fair
	55	B - full buffer	61	good
#2 - lightly disturbed, *e.g.* rural	65	A - no buffer	54	fair
	65	B - full buffer	69	good
#3 - minimally disturbed, *e.g.* wild	75	A - no buffer	62	good
	75	B - full buffer	78	very good

Theoretically, according to this model, with landscape-scale conditions held constant, a fully forested 60-foot wide riparian buffer can mean a significant difference in biological condition (15.4 index points). In many cases, this difference would be sufficient to change the health tier to which the stream would be assigned. Note, for example, that the theoretical exurban system would meet the Virginia regulatory standard if it had a fully forested buffer, but would fall far below the standard if it had no buffer. Conversely, the theoretical rural system would meet the standard if fully buffered, but would fail with no buffer.

The model should be interpreted qualitatively rather than literally. For instance, the model should not be interpreted to mean that the installation of a forested riparian buffer where none existed before will always improve biological index scores by 15.4 points. The model's applicability is limited to 1st to 4th order systems with minimal to substantial (but not severe) landscape disturbance The model does not speak to the role of riparian condition in heavily disturbed landscapes. Our data from urban and dense suburban systems did not meet normality criteria needed to apply appropriate statistical tests. Provisos notwithstanding, we believe this model is useful. Our data provide evidence that riparian buffers can make an important difference. This is reason for optimism! From a management perspective, it is certainly more practical to contemplate controlling conditions in a riparian zone than in an entire watershed.

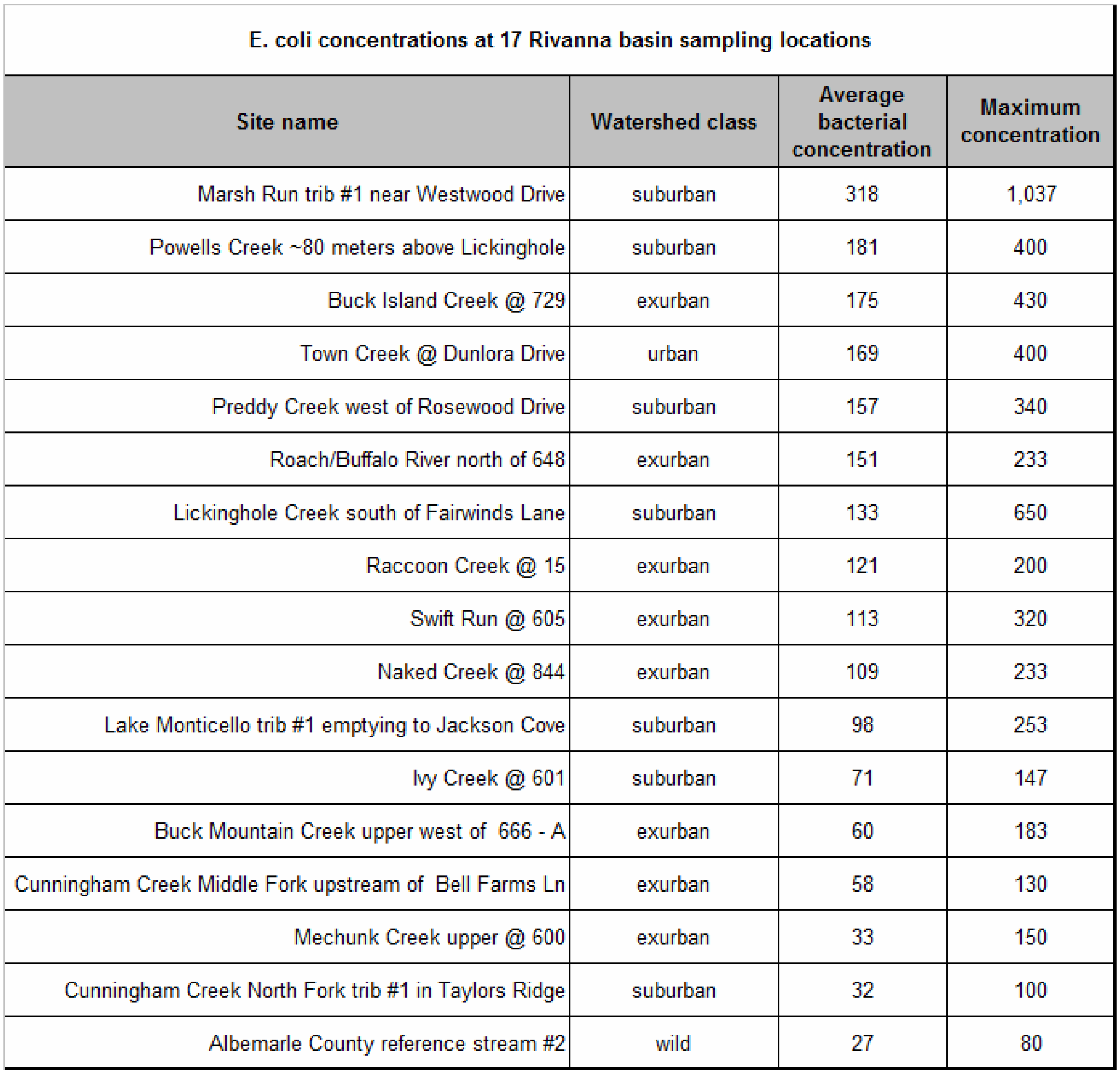
3.4) Bacterial counts were little related land use/land cover, and were completely unrelated to biological condition as measured by benthic macroinvertebrate samples.

Elevated levels of fecal bacteria can pose human health risks. Historically, for reasons described in Section 2.8, StreamWatch has focused its monitoring efforts on benthic macroinvertebrates. But for this study we decided to also explore relationships between environmental variables and bacteria. This was new territory for us, and we limited bacterial data collection to about one-third of our sites.

According to the Virginia Department of Environmental Quality, "pathogenic (disease-causing) bacteria, viruses, and protozoans are often found in fecal waste. These pathogens can cause a variety of illnesses and diseases when ingested during recreational contact or consumed in contaminated water and shellfish. Fecal waste from humans or other warm-blooded animals may enter a water body from various sources including faulty wastewater treatment plants, livestock, malfunctioning septic systems, untreated sewage discharge, pets, stormwater runoff, wildlife, or boat waste. Since it is not practical to monitor for every pathogen, "indicator" species are monitored. The presence of indicator species suggests the presence of fecal waste that may include pathogenic microorganisms that pose a health risk." (Virginia Department of Environmental Quality, 2007).

For eight months, we collected monthly water samples and tested for the concentration of the indicator bacterial species *E. coli* at 17 sites (see methods in Section 6.8). The field and lab protocol we used is different than that used by the Virginia DEQ, but there is evidence that the two methods produce similar results (Beckley, 2006). The Virginia standard for single E. coli samples is 235 colony forming units per 100 milliliters of water. Above this bar, water quality fails the standard and is considered potentially hazardous to human health.

At 8 of 17 locations, *E. coli* concentrations exceeded 235 cfu/ml on at least one occasion (see table below).



E. coli concentrations at 17 Rivanna basin sampling locations			
Site name	**Watershed class**	**Average bacterial concentration**	**Maximum concentration**
Marsh Run trib #1 near Westwood Drive	suburban	318	1,037
Powells Creek ~80 meters above Lickinghole	suburban	181	400
Buck Island Creek @ 729	exurban	175	430
Town Creek @ Dunlora Drive	urban	169	400
Preddy Creek west of Rosewood Drive	suburban	157	340
Roach/Buffalo River north of 648	exurban	151	233
Lickinghole Creek south of Fairwinds Lane	suburban	133	650
Raccoon Creek @ 15	exurban	121	200
Swift Run @ 605	exurban	113	320
Naked Creek @ 844	exurban	109	233
Lake Monticello trib #1 emptying to Jackson Cove	suburban	98	253
Ivy Creek @ 601	suburban	71	147
Buck Mountain Creek upper west of 666 - A	exurban	60	183
Cunningham Creek Middle Fork upstream of Bell Farms Ln	exurban	58	130
Mechunk Creek upper @ 600	exurban	33	150
Cunningham Creek North Fork trib #1 in Taylors Ridge	suburban	32	100
Albemarle County reference stream #2	wild	27	80

E.coli counts were not strongly related to land use/land cover, though there was a weak tendency for *E. coli* to increase with watershed population density. Interestingly, *E.* coli showed no correlation with watershed cattle density (see table below). It is also worth noting that bacterial results were completely unrelated to biological condition as measured by our standard benthic macroinvertebrate protocol. This suggests that bacterial counts may be poor indicators of stream ecological condition, and, conversely, that benthic monitoring, while providing excellent data about overall ecological health, may fail to detect water quality problems that could pose risks to human health.

Bacterial concentrations were not strongly related to land use/land cover.

Spearman correlations		**Cattle density**	**Percent forest cover**	**Percent impervious**	**Population density**	**Average biological index score**
Average E. coli concentration	Coefficient	0.13	-0.28	0.38	0.45	0.09
	Significance	0.62	0.27	0.13	0.07	0.74
Maximum E. coli concentration	Coefficient	0.07	-0.32	0.41	0.51	0.02
	Significance	0.79	0.22	0.10	0.04	0.95

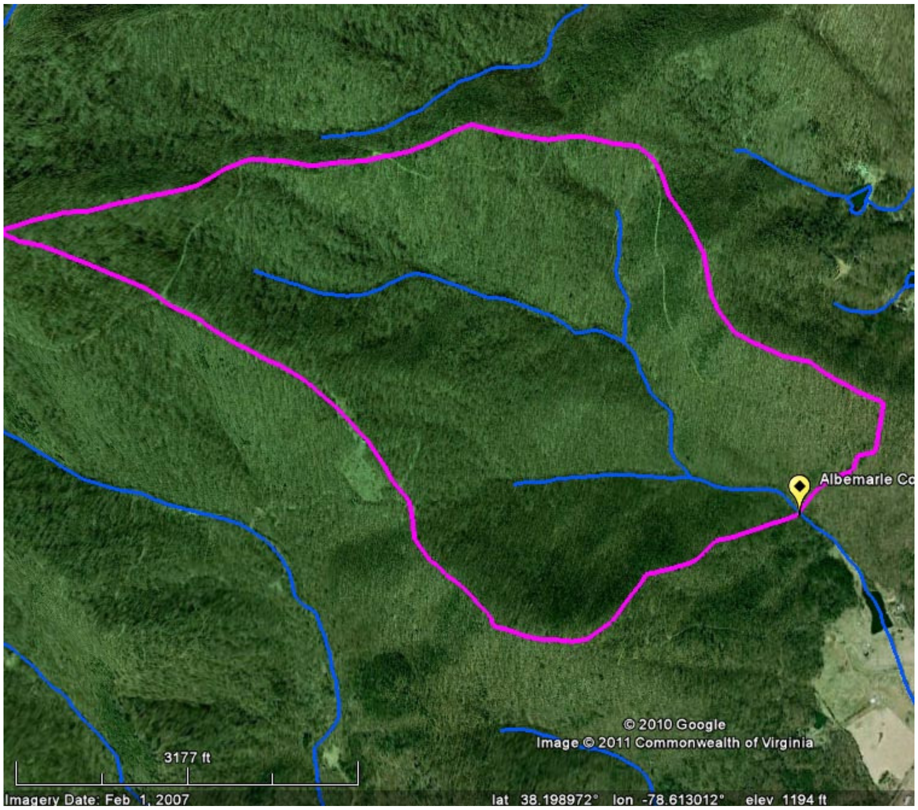
We found a correlation between *E. coli* and bank stability and frequency of riffles. The correlation is puzzling inasmuch as the bacterial counts did *not* correlate with other attributes of the stream channel, including slope and sediment conditions, nor with land use attributes such as cattle density or forest cover. We are not aware of direct ecological relationships between these channel qualities and bacterial counts, and we cannot comment on the statistical relationship other than to say it is either a coincidence or a mystery.

E. coli concentrations were well correlated with two channel morphological features (bank stability and riffle frequency), but not with other channel or riparian habitat features.

		(ln) Slope	**Frequency of Riffles**	**Bank Stability**	**d50 particle (mm)**	**% Fine Sand/Clay**	**Sediment Deposition**	**Riparian Vegetative Zone**
Average E. coli concentration	Pearson Correlation	-0.28	-0.73	-0.76	-0.06	0.38	-0.34	-0.07
	Significance	0.292	0.001	0.000	0.818	0.136	0.175	0.776

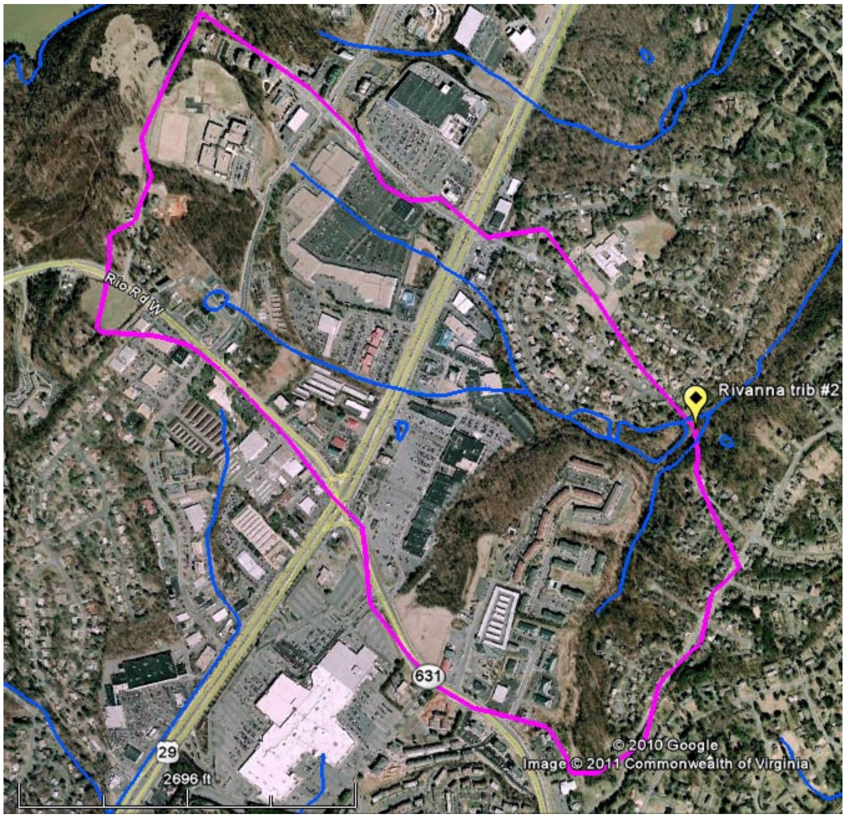
4) Bird's eye tour: typical and atypical examples of relationships between biological health and environmental factors.

The following series of images and notes guides the reader through eight stream/watershed systems to illustrate both the patterns and the uncertainties documented in this study. The examples were chosen to support a narrative discussion, and are not proportionally representative of Rivanna systems. In fact, the series has more than its share of atypical cases. We'll begin, though, with 5 systems with stream health that performs within expected ranges based on watershed land use intensity.

<table>
<tr><th>Name, size, land cover, biological condition (assessed health, average score, and average number of sensitive taxa</th><th>Watershed (pink outline) and site (yellow icon)</th></tr>
<tr><td>**Albemarle County reference stream #2**
• **0.7 square miles**
• **Class – wild**
• **Impervious - 1.0%**
• **Forest - 99%**
• **People/sq mile - 0**
• **Health - very good (76)**
• **Sensitive bugs - 12**</td><td>
</td></tr>
<tr><td colspan="2">We begin with one of our reference systems. The watershed is 99% forested, with 1% impervious cover comprised of dirt roads. Like all other reference watersheds we studied, this minimally disturbed basin supports an exceptionally diverse and healthy aggregation of stream organisms. Interestingly, the stream has a fair amount of sediment, but biological condition is not affected in any obvious way. On average, we found a whopping 12 sensitive taxa per sample at this site.</td></tr>
</table>

Rivanna trib #2 in Woodbrook

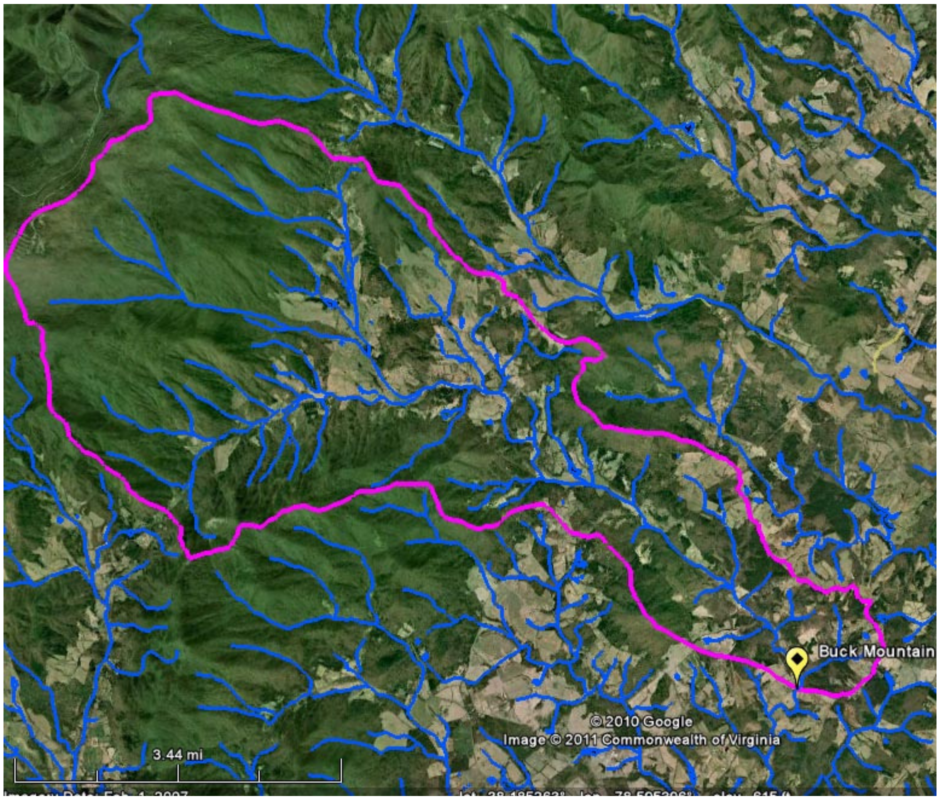
- **0.5 square miles**
- **Class – urban**
- **Impervious - 43%**
- **Forest - 37%**
- **People/sq mile– 1,800**
- **Health - very poor (20)**
- **Sensitive bugs - 0**



This example, a watershed spanning 29 North in the Woodbrook area, represents the other end of the spectrum. Impervious surfaces cover 43% of the watershed -- the highest of any system in our study. Unsurprisingly, stream biological health is the poorest of any found in this study. A perfectly intact stream buffer at this site does not seem to help. We found virtually no sensitive taxa in repeated visits.

Buck Mountain Creek upper west of Rt 666

- **20.9 square miles**
- **Class - rural/exurban**
- **Impervious - 1.2%**
- **Forest - 82%**
- **People/sq mile – 50**
- **Health - very good (72)**
- **Sensitive bugs - 9**



We turn next to three additional systems that perform as expected based on watershed land use/land cover, but that have contrasting buffer conditions. At upper Buck Mountain Creek, the buffer is only fair (see photo to right). Beginning about 100 yards upstream of the site the buffer is partially forested, but nearer the site there are no trees at all. A low bridge and a frequently-used ford cross the stream a short distance from our sampling station. Despite these habitat defects, biological condition is excellent, perhaps because the watershed overall is more than 80% forested and only 1.2% impervious (see photo above). Systems like this and the reference system discussed above suggest that stream benthic communities can overcome local habitat problems if the watershed as whole is fairly intact.

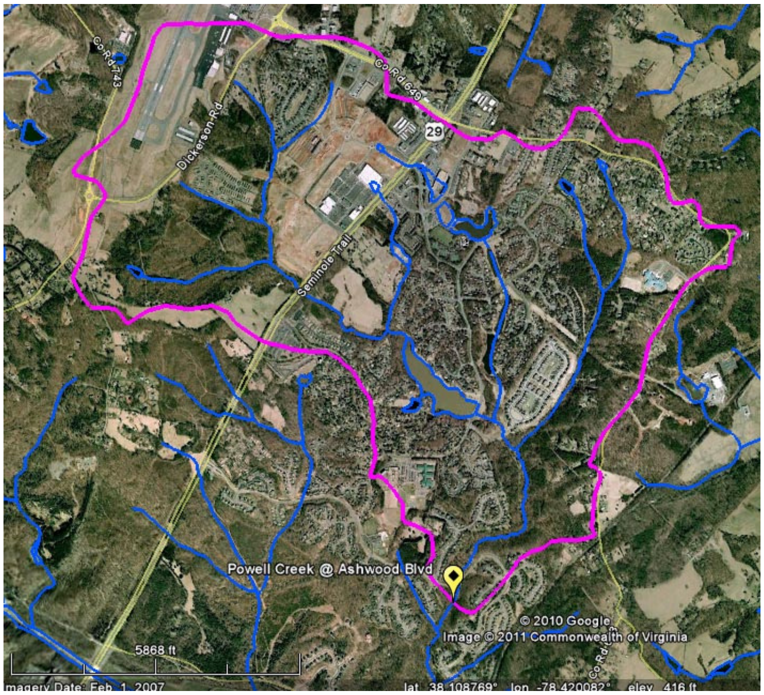
Lake Monticello trib emptying to Jackson Cove

- **0.9 square miles**
- **CLASS: suburban**
- **Impervious - 12.6%**
- **Forest - 66%**
- **People/sq mile - 950**
- **Health - poor (40)**
- **Sensitive bugs - 4**

On the other hand, the Lake Monticello tributary above and Powell Creek (next in the series) have respectively excellent and good buffers in the reaches where we collected our samples. However, stream biology is poor. Both systems are urbanized, with high amounts of impervious cover and about 1,000 or more people per square mile. Their biological condition is about what we expect based on watershed land use/land cover.

Powell Creek @ Ashwood Blvd

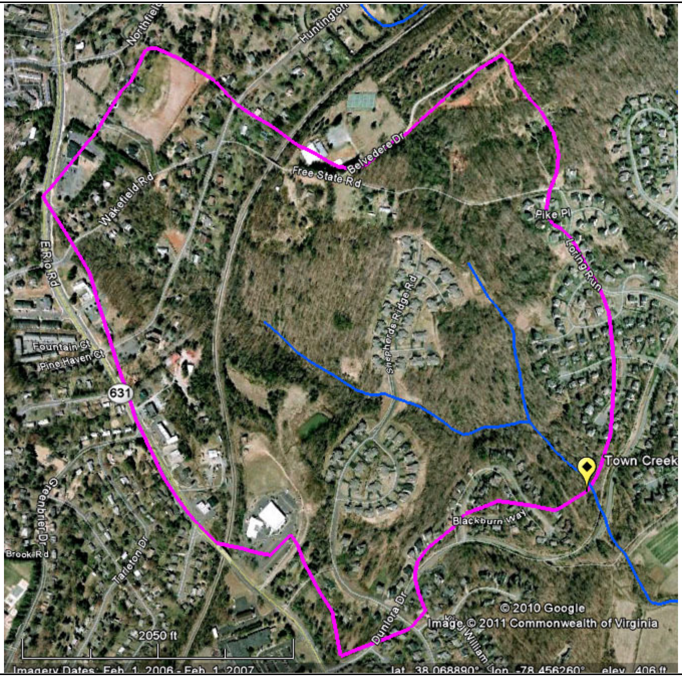
- **2.9 square miles**
- **CLASS: urban**
- **Impervious - 16.7%**
- **Forest - 51%**
- **People/sq mile– 1,500**
- **Health - poor (29)**
- **Sensitive bugs - 2**



Powell Creek and the previous example show that good buffers at the reach scale do not necessarily rescue stream health in highly disturbed systems. But, as we'll see in the next example, not all systems with this level of land use intensity perform this poorly. Why do some systems outperform land use/land cover-based expectations?

Town Creek @ Dunlora Drive

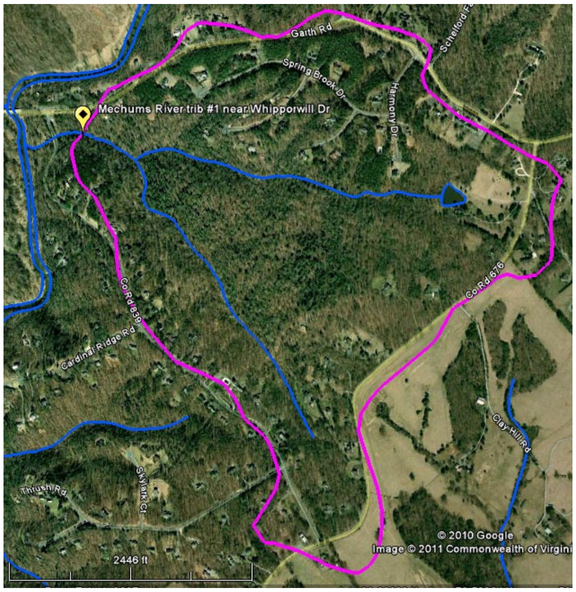
- **0.4 square miles**
- **Class – urban**
- **Impervious - 15.4%**
- **Forest - 48%**
- **People/sq mile – 1,200**
- **Health - fair (52)**
- **Sensitive bugs - 6**



Town Creek drains part of the Dunlora community at the northeast edge of Charlottesville. This is an urban watershed with land use intensity very similar to that of Powell Creek. But biological condition in Town Creek is much better than at Powell, and much better than our land cover/stream health models predict. This may be due to the configuration of the developed and forested areas within the watershed. Notice that a large portion of the impervious cover lies towards the edges of the basin—up on the ridges—and that the streams are fairly deeply buffered for much of their lengths (not just in the reach where we conducted our sampling).

Mechums River trib near Whipporwill Drive

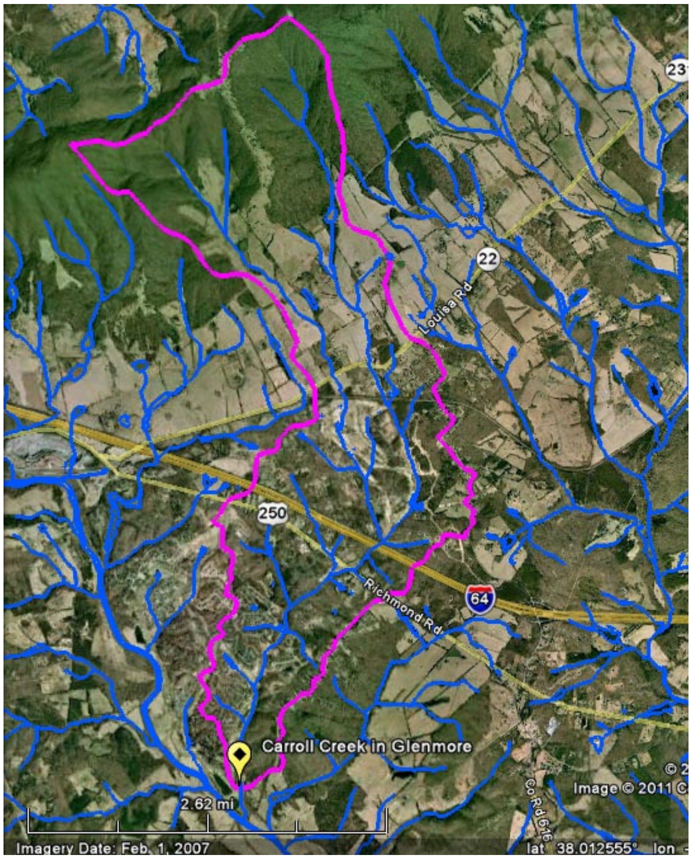
- **0.5 square miles**
- **Class – suburban**
- **Impervious - 5.8%**
- **Forest - 89%**
- **People/sq mile - 340**
- **Health - good (66)**
- **Sensitive bugs - 9**



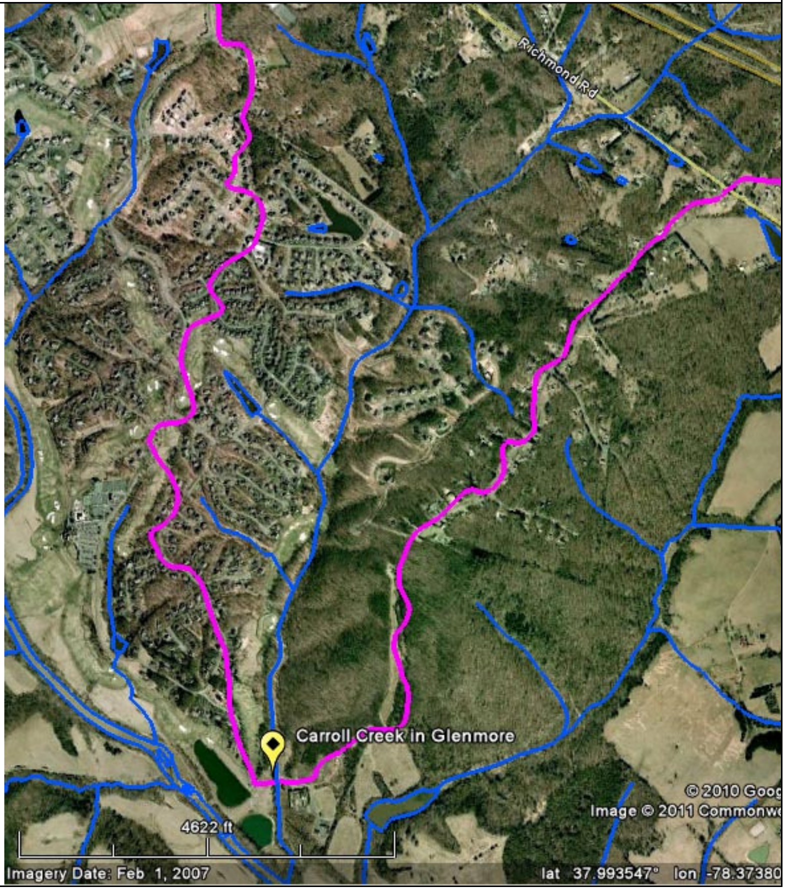
This watershed in western Albemarle is another outperformer, with much better stream health than most systems with this level of imperviousness. Despite nearly 6% impervious cover, stream biology is very good. We find the same number of bug types here as we do in rural systems such as upper Buck Mountain Creek. In this basin, development is limited exclusively to the fringes. The landscape is nearly 90% forested—a rarity for a suburbanized area—and the streams are generally very deeply buffered along their entire lengths. As with Town Creek, development is configured in way that creates distance between impervious surfaces and streams.

Carroll Creek in Glenmore

- **5.8 square miles**
- **Class - suburban**
- **Impervious - 4.2%**
- **Forest - 66%**
- **People/sq mile - 262**
- **Health - poor (39)**
- **Sensitive bugs - 3**



This system lends further anecdotal evidence to the notion that development configuration may be an important factor to stream health. In the top photo, which shows the whole basin, overall development throughout the watershed doesn't appear to be very intensive. The photo to the right, however, zooms in on the lower one-third of the watershed, and here housing development is intensive. The fact that development is concentrated near the stream and near our sampling location may explain worse-than-expected biological conditions.



5) **Recommendations for further study.**

Riparian buffers

In the current study we found evidence that forested riparian buffers are important to stream biology, and can help dampen the impacts of watershed-scale land disturbance. A future study designed specifically on buffers could provide a more quantitative assessment of buffer effects. The study should be designed to determine appropriate buffer widths to achieve stream health targets in various settings, accounting for land use/land cover, topography, stream bank erosion risk, and other factors.

One improvement to the current study would be to hand-digitize the forest cover in the buffers adjacent to data collection sites. We could then re-analyze relationships between buffers and biological condition, using the biological data we have already collected. Hand-digitization could potentially improve the quality of our buffer condition data, facilitating more precise estimates of buffer effects on benthic communities.

Slope-weighted flow path modeling

Our study suggests that in addition to aggregate land disturbance (e.g. watershed percent impervious), the spatial configuration of land disturbance is important. For instance, a shopping center adjacent to a stream may have more impact than a shopping center more distantly placed.

Slope-weighted flow path modeling in GIS could address the distance factor. With this approach, a water “packet” migrates from the land to the stream monitoring site carrying a stressor value derived from the land use/land cover where the packet originates. Theoretically, the packet’s stressor value diminishes with time and distance as it flows away from its origin. The stressor value can also increase if the packet passes through more "bad" land use/land cover. At the monitoring site, aggregate LU/LC-mediated stress is a function of all the stressor values of all the packets that pass through the site. Thus a few packets with high stressor values would be unimportant in a huge river dominated by many packets with low stressor values.

Bank stability and sedimentation

Evidence in this study suggest that in rural and urban systems, bank stability and sedimentation are distinctive factors affecting stream biology, and that these factors may be operating at least partially independently of the overarching influence of land use/land cover. Evidence further suggests that some streams are more prone to bank erosion than others. This evidence is based on limited data. It would be desirable to conduct a study designed to evaluate the factors associated with bank erosion and the effects of bank erosion on stream biology. One potential outcome would be a model that predicts the risk of bank erosion based on known factors. This model could potentially be combined with the IC/FC model that we generated with the current study, improving our ability to predict and manage stream biological condition in the Rivanna.

6) Appendix A – Methods

6.1) Site selection

We gathered stream biological and habitat data at 51 sites in drainages with widely varying land use intensity. Sites were selected to ensure a stratified dataset, with representation of urban, suburban, exurban, rural, and wild (reference) systems. Nearly all stations were situated on warmwater Piedmont streams. The full range of Rivanna basin stream orders were represented, with the result that sites and watersheds of smaller streams were sometimes nested within the larger watersheds of distant downstream sites. In our judgment, nesting did not diminish the distinctiveness of the studied systems, and we treated data from all sites as independent samples. Site locations are shown in Section 2.4.

6.2) Assessing biological condition.

StreamWatch's methods for collecting stream invertebrates and producing biological index scores are described in Section 2.7.

Biological condition was measured an average of six times at each site. Assessments of biological condition were based on an analysis of the multiple biological index scores generated during the study period, per StreamWatch's established assessment protocol. Assessments are driven by average score, variance, and trend. The procedure is outlined in the table below.

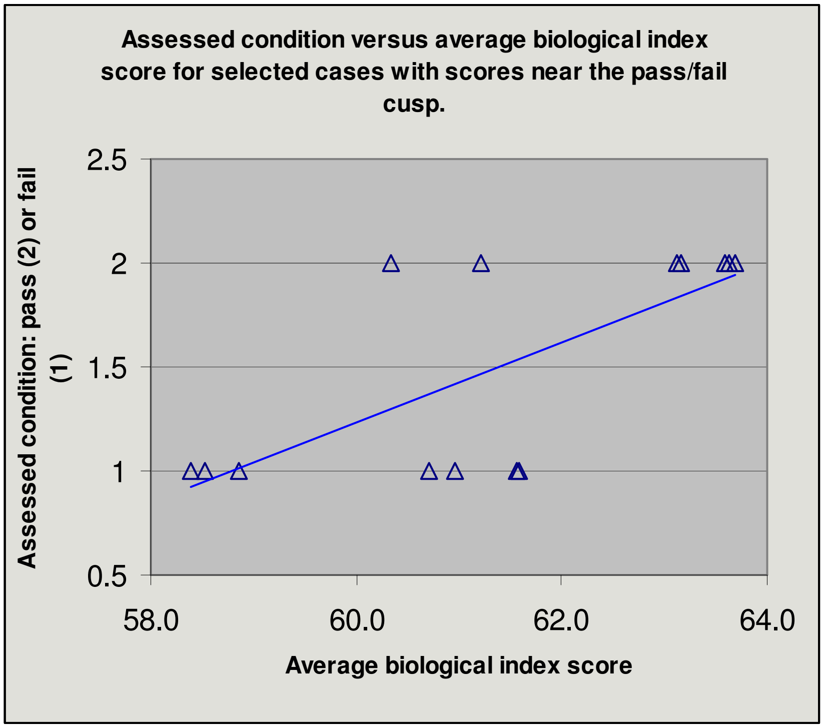
	STEP 1 - ASSIGN to category based on median or mean, whichever is lowest, according to these ranges of scores:	**STEP 2 - DEMOTIONS**		**STEP 3 - PROMOTIONS Promote Step 2 result to next highest tier if 1) number of samples in latter 2/3 of period is at least 3 and equals or exceeds 1.5 times the number of samples in first third and 2) below-listed criteria are met**
		IF	**Demote to**	
Very good (provisional)	70 and above	any below 60	good	NA
		33% or more below 55	fair	
		any below 50	fair	
Good	60 to 69.9	33% or more below 55	fair	NA
		any below 50	fair	
Fair	40 to 59.9	**Lesser of avg/med is below 50, and**		Lesser of med/avg is >=55, and all scores in latter 2/3 are >=60.
		33% or more below 35	poor	
		any below 30	poor	
Poor	25 to 39.9	NA	NA	Lesser of med/avg is >=35, and all scores in latter 2/3 are >=40.
Very poor	0 to 24.9	NA	NA	Lesser of med/avg is >=20, and all scores in latter 2/3 are >=25.

In the StreamWatch assessment classification scheme, the categories “good” and “very good” meet the Virginia regulatory standard. Sites assessed as “fair”, “poor”, or “very poor” fail the standard.

6.2.1) Relationship between average biological index score and the Virginia biological standard.

As described above, multiple samples were collected at each site. Biological index scores were generated for each sample, and assessments were generated on the basis of the average of multiple scores, score variance, and trend. The Virginia biological standard, established by the Department of Environmental Quality, is set at a biological index score of 60. That is, samples with scores that equal or exceed 60 meet the standard. When multiple samples are taken, all scores are considered. Therefore an average score exceeding 60 does not necessarily mean the standard has been met. In fact, with average scores near but greater than 60, the site often fails because the set of values comprising the average includes values that are sufficiently low to drive the assessment down into the fair category (non-supporting).

To estimate a cutoff at which average scores are likely to pass or fail the standard, we created a subset of data comprised of 14 sites that were, in terms of average score, close to pass/fail cusp. Average scores in this set ranged from 58.4 to 63.7. Half the sites met the standard; half failed. We plotted a categorical variable (pass or fail), represented by integers (2 or 1), against the average scores (see figure below). The relationship was expressed as a linear regression. We calculated the value at which the average score generated a value of 1.5 (halfway between pass and fail), reasoning that this value represented the point at which the average score was equally likely to produce either a passing or failing assessment. The resulting value was 61.4. Recognizing that this estimate is based on limited data and is imprecise, we rounded the figure to 61.



6.3) Classification of land use/land cover

Digitized land use/land cover and impervious surface data were developed by WorldView Solutions, Inc. from planimetrics and 1-foot resolution aerial photography. Land use/land cover classes (deciduous forest, pine plantation, open land, *etc*.) were created using an automated feature extraction process followed by manual cleanup. An accuracy assessment based on a non-randomized set of 700 photo-interpreted and field-verified points returned an overall classification accuracy of 97%. Site-defined watersheds were delineated for each site, and watershed land use/land cover statistics were calculated for each watershed. Complete meta-data for the LU/LC map and classification are available at
http://dl.dropbox.com/u/9965884/Website%20files/land_cover_metadata_faq.htm

6.4) Estimating human population density

Population density for each subwatershed was estimated based on 2008 data supplied by the Weldon Cooper Center for Public Service. Localities' populations were adjusted slightly to account for the effects of non-residential (workforce) populations. Using a geographic information system, localities' populations were distributed onto the landscape via geographical points representing buildings and addresses. Areal densities for each subwatershed were then calculated.

6.5) Estimating cattle populations

Under guidance from a trained interpreter of aerial imagery of agricultural landscapes, a project team composed of StreamWatch staff and volunteers estimated cattle population densities of Rivanna subwatersheds by locating and counting cattle that were visible in 2009 Virginia leaf-off base map imagery. Year 2010 USDA estimates of county cattle populations, apportioned to the Rivanna basin according to contributing land area, give an estimate of about 23,750 head for the Rivanna basin. Our imagery-based count identified approximately 13,500 head on the Rivanna landscape in early spring 2009, or approximately 57% of the 2010 USDA-derived estimate. Both the USDA-based estimates and the imagery-based counts are subject to error. We believe we located a majority of the Rivanna's cattle, and we reason that the spatially distributed cattle counts we generated provide a useful representation of relative cattle densities across Rivanna subwatersheds. We note that cattle operations are generally non-intensive in the Rivanna basin, with an average of 31 head per square mile according to the USDA-based estimate of the overall Rivanna cattle population. By contrast, agriculturally intensive counties in the nearby Shenandoah Valley (Rockingham and Augusta counties) have densities of 130 head per square mile.

6.6) Reach-scale habitat data

We gathered reach-scale data per three methods: Wolman pebble count, stream slope survey, and EPA rapid visual assessment. All reach-scale data were developed in reaches terminating at our biosampling stations and extending upstream for a distance of twenty to forty times base-flow channel width.

Pebble counts were conducted in 10 transects per reach, with transects selected to reflect the proportion of pool and riffle habitat extant in the reach. Ten particles were collected and measured at each transect, for a total of 100 particles (Rosgen 1996). The surveys produced data for median particle size (d50), percent fine sand/clay (≤0.24 mm), and percent cobble (64-256 mm).

The rapid visual protocol involves walking the stream reach and scoring each of ten habitat parameters using a standard field sheet (Barbour 1999). Scores range from zero to twenty. The field sheet provides guidance by qualitatively and quantitatively describing condition gradients of habitat features and appropriate scores for given conditions (see field sheet below). The rapid visual protocol is subject to observer bias. To reduce bias and increase data quality, StreamWatch has added additional standards to the protocol. Specifically, StreamWatch breaks the reach into ten or more sub-reaches, scores each sub-reach, and averages the sub-reach scores.

Of EPA rapid visual data, parameters regarded as reliable and useful for this study were: sediment deposition, bank stability, frequency of riffles, and riparian buffer.

HABITAT ASSESSMENT FIELD DATA SHEET—HIGH GRADIENT STREAMS (FRONT)

STREAM NAME	LOCATION	
STATION #__________ RIVERMILE__________	STREAM CLASS	
LAT _______________ LONG _______________	RIVER BASIN	
STORET #	AGENCY	
INVESTIGATORS		
FORM COMPLETED BY	DATE ________ TIME ________ AM PM	REASON FOR SURVEY

Parameters to be evaluated in sampling reach

Habitat Parameter	**Condition Category**			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
1. Epifaunal Substrate/ Available Cover	Greater than 70% of substrate favorable for epifaunal colonization and fish cover; mix of snags, submerged logs, undercut banks, cobble or other stable habitat and at stage to allow full colonization potential (i.e., logs/snags that are not new fall and not transient).	40-70% mix of stable habitat; well-suited for full colonization potential; adequate habitat for maintenance of populations; presence of additional substrate in the form of newfall, but not yet prepared for colonization (may rate at high end of scale).	20-40% mix of stable habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 20% stable habitat; lack of habitat is obvious; substrate unstable or lacking.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
2. Embeddedness	Gravel, cobble, and boulder particles are 0-25% surrounded by fine sediment. Layering of cobble provides diversity of niche space.	Gravel, cobble, and boulder particles are 25-50% surrounded by fine sediment.	Gravel, cobble, and boulder particles are 50-75% surrounded by fine sediment.	Gravel, cobble, and boulder particles are more than 75% surrounded by fine sediment.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
3. Velocity/Depth Regime	All four velocity/depth regimes present (slow-deep, slow-shallow, fast-deep, fast-shallow). (Slow is < 0.3 m/s, deep is > 0.5 m.)	Only 3 of the 4 regimes present (if fast-shallow is missing, score lower than if missing other regimes).	Only 2 of the 4 habitat regimes present (if fast-shallow or slow-shallow are missing, score low).	Dominated by 1 velocity/ depth regime (usually slow-deep).
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
4. Sediment Deposition	Little or no enlargement of islands or point bars and less than 5% of the bottom affected by sediment deposition.	Some new increase in bar formation, mostly from gravel, sand or fine sediment; 5-30% of the bottom affected; slight deposition in pools.	Moderate deposition of new gravel, sand or fine sediment on old and new bars; 30-50% of the bottom affected; sediment deposits at obstructions, constrictions, and bends; moderate deposition of pools prevalent.	Heavy deposits of fine material, increased bar development; more than 50% of the bottom changing frequently; pools almost absent due to substantial sediment deposition.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
5. Channel Flow Status	Water reaches base of both lower banks, and minimal amount of channel substrate is exposed.	Water fills >75% of the available channel; or <25% of channel substrate is exposed.	Water fills 25-75% of the available channel, and/or riffle substrates are mostly exposed.	Very little water in channel and mostly present as standing pools.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

HABITAT ASSESSMENT FIELD DATA SHEET—HIGH GRADIENT STREAMS (BACK)

Parameters to be evaluated broader than sampling reach

Habitat Parameter	**Condition Category**			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
6. Channel Alteration	Channelization or dredging absent or minimal; stream with normal pattern.	Some channelization present, usually in areas of bridge abutments; evidence of past channelization, i.e., dredging, (greater than past 20 yr) may be present, but recent channelization is not present.	Channelization may be extensive; embankments or shoring structures present on both banks; and 40 to 80% of stream reach channelized and disrupted.	Banks shored with gabion or cement; over 80% of the stream reach channelized and disrupted. Instream habitat greatly altered or removed entirely.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
7. Frequency of Riffles (or bends)	Occurrence of riffles relatively frequent; ratio of distance between riffles divided by width of the stream <7:1 (generally 5 to 7); variety of habitat is key. In streams where riffles are continuous, placement of boulders or other large, natural obstruction is important.	Occurrence of riffles infrequent; distance between riffles divided by the width of the stream is between 7 to 15.	Occasional riffle or bend; bottom contours provide some habitat; distance between riffles divided by the width of the stream is between 15 to 25.	Generally all flat water or shallow riffles; poor habitat; distance between riffles divided by the width of the stream is a ratio of >25.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
8. Bank Stability (score each bank) Note: determine left or right side by facing downstream.	Banks stable; evidence of erosion or bank failure absent or minimal; little potential for future problems. <5% of bank affected.	Moderately stable; infrequent, small areas of erosion mostly healed over. 5-30% of bank in reach has areas of erosion.	Moderately unstable; 30-60% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "raw" areas frequent along straight sections and bends; obvious bank sloughing; 60-100% of bank has erosional scars.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
9. Vegetative Protection (score each bank)	More than 90% of the streambank surfaces and immediate riparian zone covered by native vegetation, including trees, understory shrubs, or nonwoody macrophytes; vegetative disruption through grazing or mowing minimal or not evident; almost all plants allowed to grow naturally.	70-90% of the streambank surfaces covered by native vegetation, but one class of plants is not well-represented; disruption evident but not affecting full plant growth potential to any great extent; more than one-half of the potential plant stubble height remaining.	50-70% of the streambank surfaces covered by vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of the potential plant stubble height remaining.	Less than 50% of the streambank surfaces covered by vegetation; disruption of streambank vegetation is very high; vegetation has been removed to 5 centimeters or less in average stubble height.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
10. Riparian Vegetative Zone Width (score each bank riparian zone)	Width of riparian zone >18 meters; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zone 12-18 meters; human activities have impacted zone only minimally.	Width of riparian zone 6-12 meters; human activities have impacted zone a great deal.	Width of riparian zone <6 meters: little or no riparian vegetation due to human activities.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

6.7) Substrate permeability

To explore the condition of substrate in Rivanna streams, 25 sites were selected. The array of sites represented a broad range of stream and watershed conditions, ranging from undeveloped mountain streams to urban waterways. Within each stream one riffle was sampled (the same riffle at which benthic macroinvertebrate samples were collected). In each riffle three permeability measurements were made, with multiple replicate measurements made during each sample. After permeability measurements were completed, fine sediment was directly sampled using a bulk sampling core and vacuum pump extraction. Riffle gradient was also measured with an auto-level and survey rod for the full length of the riffle.

Within each riffle, in-situ measurements of substrate permeability were made with a perforated standpipe driven into the streambed. Three sample sites per riffle were measured, with five to six replicate samples drawn per site. The stand pipe was driven into the streambed to reach a sampling depth from 10 to 17cm below the bed surface. Water was pumped out of the standpipe in the upper 2.5 cm of the water column, and the rate at which interstitial water refilled the void was used to calculate subsurface flow rates through the gravel. From in-situ measurements in the standpipe, the water volume extracted per unit time is calculated as the 'inflow rate'. Permeability is then interpolated from empirical rating curves of permeability versus inflow rate (Terhune 1958; Barnard and McBain 1994). Permeability values are then corrected for temperature, using a viscosity correction factor. It is important to note that extremely low permeability values cannot be calculated because the existing rating curve does not extend to inflow rates < 2.0 ml/sec, resulting in a non-temperature adjusted permeability of 80 cm/hr.

Fine sediment stored in the streambed was directly sampled with a 30.5 cm diameter core sampler place directly over the site where permeability was measured. The core sampler was embedded into the streambed to a depth of 10-15 cm. Substrate within the core was overturned while a vacuum pump extracted the water, suspended sediment and organic matter contained within the core. Vacuum-extracted samples were filtered through a 1 mm diameter sieve and collected in a large storage container that was agitated while a 250 ml sub-sample was collected for laboratory analysis. The organic fraction of the sub-sample was combusted by igniting the sample on a glass fiber filter at 550°C for 24h, desiccated, and weighed. The ash-free dry mass of inorganic sediment <1 mm was weighed on a high precision balance. The <1 mm size fraction represents sediment consisting of coarse sand and finer particles, including silt and clay. The concentration of fine sediment was calculated by the mass of inorganic sediment divided by the sample volume.

6.8) Bacteria

Bacterial samples were collected by interns at 17 sites once per month for eight months from April through November 2008. For seven of the eight months, two samples were collected during each field visit. Samples were transported to a lab where Coliscan Easygel media were inoculated. Inoculated media were incubated for 24 hours, after which E. coli colonies were counted. Data were recorded in excel and were expressed in units of cfu/100ml. (Cfu stands for colony forming units.) Results from replicate samples were averaged.

Most samples were collected under base flow conditions, but the final samples were collected following a storm that delivered approximately 1 inch of rain over the two days preceding the collection.

7) Appendix B - Comprehensive correlation matrix

The subsets for this matrix were selected with the following rationale: The most complete dataset comprises all 1st to 5th-order streams (except for 3 with known point-source impacts). The next smallest set excludes urban and dense suburban systems (10% or greater IC). The 10% threshold was somewhat arbitrary by intention. We wanted to exclude the most disturbed systems in order to better detect patterns in systems that are more typical of the basin. At the same time, we did not want to bias our analysis with a hunt for a threshold that spuriously distinguishes portions of our dataset, and we did not want to infer that we had identified any such threshold. Instead, we picked a round number (10% IC) that we knew would separate heavily developed watersheds from moderately and lightly developed watersheds. The next smallest subset consists of systems with 4% or less IC. This range of IC is very similar that of the rural and exurban landscape that characterizes most of the Rivanna basin. The disadvantage of this subset, however, is that it contains fewer data points.

The same culling was applied to a more limited set consisting of 1st to 3rd order streams. The Center for Watershed Protection advises that its Revised Impervious Cover Model applies only to ≤3rd-order streams; and we wanted to reference our analyses against that model.

The last subset in the matrix consists of substantially and severely disturbed systems (≥10% IC). These all happen to be fairly small systems; none is larger than 3rd order

This correlation matrix shows associations (or lack thereof) between biological condition, land use/land cover (in the form of a model that incorporates impervious cover and forest cover as input variables), and local-scale habitat factors. Grey fill denotes statistical significance at the 0.05 level; purple denotes significance of 0.001 or greater. Correlations between health and local factors are best read across the rows labeled "residuals of combo model". Correlations between landscape disturbance and local factors are best read across the rows labeled "landscape factors (combo model output)". Correlations between health and landscape disturbance are read at the intersection of the rows labeled "average bio score" and the columns labeled "landscape factors (combo model output)".

Spearman correlations			Landscape factors (combo model output)	Stream Slope	Channel Alteration	Frequency of Riffles	Bank Stability	Sediment Deposition	d50 particle (mm)	% Fine Sand/Clay	% Cobble	Riparian Vegetative Zone	Cows Per Square Mile
Set A1 1-5th order; IC=0-43%; 40-42 cases	**Average bio score**	Coefficient	0.87	0.05	0.29	0.40	0.26	0.36	0.15	-0.33	0.36	0.35	0.25
		Significance	0.000	0.765	0.071	0.011	0.103	0.023	0.364	0.038	0.023	0.025	0.118
	Residuals of combo model	Coefficient	0.02	0.14	0.31	0.29	0.06	0.20	0.11	-0.07	0.07	0.39	0.01
		Significance	0.915	0.392	0.053	0.072	0.720	0.215	0.508	0.654	0.659	0.013	0.962
	Landscape factors (combo model output)	Coefficient		-0.03	0.16	0.27	0.27	0.28	0.11	-0.33	0.35	0.20	0.27
		Significance		0.869	0.328	0.090	0.090	0.075	0.482	0.039	0.028	0.21	0.082
	Stream slope	Coefficient	-0.03		0.08	0.40	0.46	0.40	0.36	-0.39	0.43	0.20	-0.62
		Significance	0.869		0.610	0.013	0.003	0.013	0.024	0.014	0.006	0.217	0.000
Set A2 1-5th order; IC=0-10%; 31-32 cases	**Average bio score**	Coefficient	0.74	0.42	0.41	0.50	0.50	0.41	0.28	-0.39	0.43	0.45	-0.28
		Significance	0.000	0.017	0.021	0.004	0.004	0.023	0.134	0.030	0.017	0.010	0.126
	Residuals of combo model	Coefficient	-0.08	0.20	0.24	0.35	0.20	0.17	0.12	-0.04	0.10	0.35	-0.05
		Significance	0.654	0.291	0.193	0.055	0.273	0.357	0.527	0.841	0.610	0.054	0.795
	Landscape factors (combo model output)	Coefficient		0.30	0.26	0.31	0.47	0.31	0.23	-0.38	0.41	0.27	-0.27
		Significance		0.101	0.159	0.093	0.007	0.091	0.204	0.034	0.021	0.15	0.128
	Stream slope	Coefficient	0.30		0.13	0.66	0.53	0.63	0.54	-0.52	0.71	0.31	-0.50
		Significance	0.101		0.487	0.000	0.003	0.000	0.002	0.003	0.000	0.101	0.005
Set A3 1-5th order; IC=0-4%; 24-25 cases	**Average bio score**	Coefficient	0.62	0.69	0.20	0.64	0.64	0.53	0.28	-0.38	0.53	0.42	-0.48
		Significance	0.001	0.000	0.358	0.001	0.001	0.008	0.188	0.066	0.007	0.041	0.016
	Residuals of combo model	Coefficient	-0.29	0.34	0.04	0.44	0.32	0.29	0.13	-0.03	0.11	0.21	-0.02
		Significance	0.163	0.093	0.840	0.031	0.126	0.176	0.533	0.889	0.595	0.319	0.911
	Landscape factors (combo model output)	Coefficient		0.53	0.12	0.34	0.54	0.31	0.19	-0.34	0.51	0.29	-0.49
		Significance		0.006	0.592	0.107	0.007	0.137	0.364	0.106	0.011	0.17	0.013
	Stream slope	Coefficient	0.53		0.23	0.62	0.46	0.64	0.55	-0.56	0.70	0.39	-0.42
		Significance	0.006		0.287	0.001	0.025	0.001	0.005	0.005	0.000	0.058	0.037
Set B1 1-3rd order; IC=0-43%; 23-25 cases	**Average bio score**	Coefficient	0.94	0.13	0.50	0.43	0.12	0.37	0.10	-0.40	0.48	0.65	0.20
		Significance	0.000	0.545	0.014	0.040	0.573	0.085	0.643	0.059	0.021	0.001	0.327
	Residuals of combo model	Coefficient	0.26	-0.13	0.48	0.20	-0.05	0.20	0.15	-0.21	0.19	0.49	0.16
		Significance	0.206	0.562	0.020	0.368	0.805	0.350	0.480	0.330	0.394	0.017	0.439
	Landscape factors (combo model output)	Coefficient		0.20	0.36	0.42	0.23	0.38	0.10	-0.42	0.49	0.48	0.21
		Significance		0.355	0.087	0.048	0.300	0.076	0.645	0.049	0.017	0.02	0.302
Set B2 1-3rd order; IC=0-10%; 14-15 cases	**Average bio score**	Coefficient	0.88	0.35	0.79	0.21	0.37	0.03	-0.08	-0.25	0.28	0.80	-0.45
		Significance	0.000	0.225	0.001	0.463	0.195	0.928	0.781	0.391	0.325	0.001	0.091
	Residuals of combo model	Coefficient	0.05	-0.25	0.45	0.14	0.19	0.02	0.10	-0.08	0.19	0.35	0.07
		Significance	0.850	0.381	0.104	0.622	0.506	0.952	0.729	0.782	0.522	0.226	0.810
	Landscape factors (combo model output)	Coefficient		0.38	0.62	0.18	0.42	0.16	-0.02	-0.30	0.28	0.63	-0.50
		Significance		0.178	0.017	0.532	0.137	0.581	0.952	0.291	0.337	0.02	0.059
Set B3 1-3rd order; IC=0-4%; 9-10 cases	**Average bio score**	Coefficient	0.84	0.61	0.51	0.19	0.68	-0.18	-0.39	-0.02	-0.02	0.66	-0.86
		Significance	0.002	0.062	0.160	0.615	0.046	0.650	0.295	0.966	0.966	0.054	0.002
	Residuals of combo model	Coefficient	-0.65	-0.50	-0.06	0.00	0.26	0.00	0.00	0.13	-0.28	-0.15	0.31
		Significance	0.043	0.137	0.879	1.000	0.505	1.000	1.000	0.732	0.460	0.696	0.389
	Landscape factors (combo model output)	Coefficient		0.58	0.37	0.05	0.41	-0.07	-0.28	-0.07	0.03	0.54	-0.83
		Significance		0.080	0.333	0.897	0.273	0.864	0.458	0.865	0.932	0.13	0.003
Set C 1-3rd order; IC=10-43%; 11 cases	**Average bio score**	Coefficient	0.84	-0.37	0.64	0.35	-0.16	0.23	0.40	-0.41	0.23	0.91	0.00
		Significance	0.001	0.293	0.045	0.327	0.649	0.528	0.249	0.243	0.521	0.000	1.000
	Residuals of combo model	Coefficient	0.27	-0.21	0.56	0.16	-0.36	0.51	0.20	-0.52	-0.03	0.65	0.00
		Significance	0.416	0.555	0.091	0.663	0.301	0.131	0.576	0.125	0.927	0.041	1.000
	Landscape factors (combo model output)	Coefficient		0.02	0.51	0.31	0.12	-0.11	0.35	-0.42	0.22	0.69	-0.20
		Significance		0.960	0.134	0.386	0.750	0.761	0.316	0.228	0.544	0.03	0.555

8) Appendix C - Overview of bedrock and soils in the Rivanna River drainage

Contributed by Aaron Cross, Geologist, Division of Geology and Mineral Resources, Virginia Department of Mines, Minerals, and Energy

The major headwater tributaries of the Rivanna River drainage — Swift Run, Buck Mountain Creek, Doyles River, Moormans River, and Stockton Creek — begin on the Eastern flank of the Blue Ridge Mountains and drain generally eastward. The higher slopes of the Blue Ridge are underlain by the late-Proterozoic/Cambrian-age metabasalt of the Catoctin Formation, while the lower slopes are underlain by the Proterozoic Swift Run Formation, a heterogeneous assemblage of phyllite and metasandstone with lesser metaconglomerate, schist, quartzite, and slate. These rocks produce the Myersville-Catoctin-Lew assemblage of stony, well-drained soils. Surface runoff is rapid and the hazard of erosion is severe. Most of this land is in forest.

At the foothills of the Blue Ridge Mountains, the Rivanna drainage begins to cross rocks of the Blue Ridge Basement Complex, which underlies the core of the Blue Ridge Anticlinorium, a major structural fold. The western upland portion of the Basement Complex is a disorganized assemblage of Middle Proterozoic pyroxene granulite gneisses and biotite granulite gneisses that have been intruded by plutons of Grenville age, particularly charnockite, a pyroxene-bearing granite/granodiorite containing blue quartz, as well as the Crozet Granite, a leucocratic, coarse-grained, porphyritic alkali feldspar granite. In the past, these units were grouped under the term Pedlar Formation. These granitic rocks in the western upland areas of the Basement Complex produce the Parkers-Chester-Porters assemblage of deep, stony, excessively drained soils, now mostly in second-growth forest. Surface runoff is rapid and the hazard of erosion is severe.

The western portion of the Basement Complex is separated from the eastern portion by a bifurcated belt of mylonite and cataclastic rocks. This belt represents a fault zone with multiple movement history — late pre-Cambrian extension, Paleozoic contraction, and reactivation during Mesozoic extension. Lithology is highly variable depending on the parent rock. In the central part of the Basement Complex, Braddock-Thurmont-Unison soils are formed on colluvial material washed from the Blue Ridge. These soils are deep and well drained, with loamy subsoil. Many of the soils within the Basement Complex are agriculturally important; unfortunately, they are subject to considerable sheet erosion when cultivated and in many places the red clay subsoil has been exposed.

The eastern portion of the Basement Complex is dominated by Proterozoic porphyroblastic biotite-plagioclase augen gneiss, sometimes referred to as the Lovingston Gneiss. Infolded into this augen gneiss is a long, thin graben containing the Mechums River Formation, a metagraywacke and meta-argillite with quartzose schist and conglomerate. Locally, the Lovingston Gneiss is intruded with a two-mica, two-feldspar granite, or with the alkali feldspar granite of the Proterozoic Robertson River Igneous Suite. Granitic rocks in the eastern part of the Basement Complex produce the Hayesville-Ashe-Chester assemblage of deep, well-drained soils. This soil is locally run down owing to poor farming methods.

Downstream from the Rivanna River Reservoir, the drainage passes through a succession of metasedimentary rocks of the Lynchburg Group, including the Lynchburg Fanglomerate, a matrix-supported, pebbly to cobbly lithic conglomerate; the Lynchburg Metagraywacke, containing beds of conglomerate, graphitic phyllite, metasiltstone, slate, and quartzite; and the Charlottesville Formation, a coarse-grained, pebbly metasandstone and quartzite interbedded with micaceous siltstone, graphitic phyllite, and slate. Amphibolite dikes cut the Lynchburg Group and occur as sills in the Charlottesville Formation; they are probably part of the Catoctin basalt feeder system. This collection of metasedimentary bedrock produces the Elioak-Hazel-Glenelg soil assemblage.

The Rivanna River exits the Blue Ridge Anticlinorium through a gap between Southwest Mountain and Carters Mountain, both of which are formed from Catoctin metabasalt and together represent the eastern limb of the Anticlinorium. The base of these slopes host Davidson soil, which is particularly well suited for cultivated crops.

To the east of the line of Southwest and Carters mountains is a broad belt of the Cambrian-age Candler Formation, composed of schistose and phyllitic metasiltstone, ferruginous metatuff, dolomitic marble, and phyllite. Adjacent to the Candler Formation is a belt of the Proterozoic- to Ordovician-age Mine Run Complex, composed of metagraywacke, quartzose schist, and mélange. Together, these metasedimentary rocks produce Nason-Tatum soils that are strongly acidic. Most of this area is in woodland, as these soils have low fertility and are not well suited for sustained agriculture.

Where the Rivanna drainage narrows toward its point of entry into the James River, it passes quickly through the Cambrian-age Chopawamsic Formation of interlayered felsic and mafic metavolcanics and the infolded Arvonia Formation of slate and porphyroblastic schist. These rocks produce shallow, poorly drained Manteo-Wehadkee soils. Near the point of entry, the Rivanna cuts into the Carysbrook Pluton of Proterozoic granite and the Columbia Pluton of Ordovician granite. These rocks produce Louisburg soils that are shallow, on slopes, and mostly in woodland.

For soil conservation purposes, soil management practices are far more important than natural factors such as soil type and slope. Regardless of setting or soil type, land disturbance practices such as forest clearance and construction, even when well managed, can increase the potential for erosion by factors many times greater than risks associated with natural circumstances (Pitt 2007).

References:

Virginia State Geological Map, 1993: Virginia Department of Mineral Resources
Soil Survey of Albemarle County, 1940: U.S. Department of Agriculture
Soil Survey of Albemarle County, Virginia, 1981: U.S. Department of Agriculture
Soil Survey of Fluvanna County, 1958: U.S. Department of Agriculture

9) **Appendix D - References**

Beckley, J. 2006. Coliscan Easygel: How Volunteer Monitoring Can Help the TMDL Process. PowerPoint presentation. http://www.deq.virginia.gov/tmdl/pdf/coliscan.pdf

Allan, JD, Erickson, DL and Fay, J. 1997. The Influence of Catchment Land Use on Stream Integrity across Multiple Spatial Scales. *Freshwater Biology* 37: 149–161.

Barbour, MT, Gerritsen J, Snyder, BD, Stribling JB. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water. Washington D.C.

Barnard, K, and McBain, S. 1994. Standpipe to determine permeability, dissolved oxygen, and vertical particle size distribution in salmonid spawning gravels. USDA Forest Service, Fish Habitat Relationships Technical Bulletin 15.

Burton, J, Gerritsen, J. TetraTech. 2003. A Stream Condition Index for Virginia Non-Coastal Streams. http://www.deq.virginia.gov/watermonitoring/pdf/vastrmcon.pdf

Coles, JG, Cuffney, TF, McMahon, G, Beaulieu, K. 2004. The effects of urbanization on the biological, physical, and chemical characteristics of coastal New England streams: U.S. Geological Survey Professional Paper 1695, 47 p.

Cover, M, May, CL, Dietrich, WE, and Resh, VH. 2008. Quantitative linkages among sediment supply, streambed fine sediment, and benthic macroinvertebrates in northern California streams. The North American Benthological Society 27: 135-149.

Karr, JR, Chu, EW. 1999. *Restoring Life in Running Waters – Better Biological Monitoring*. Island Press. Washington, D.C.

King, RS, Baker, ME. 2010. Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. Journal of the North American Benthological Society. 29(3):998–1008

Morse, CC, Huryn, AD, Cronan, CS. 2003. Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, USA. Environmental Monitoring and Assessment 89: 95-127.

McHugh, MH. 2009. Using gravel permeability to evaluate restoration efforts in Smith Creek, Virginia. Master's thesis, James Madison University. 50 p.

Murphy, JA. 2008. Biological Conditions at Thirty-Three Rivanna Basin Long-term Monitoring Sites. StreamWatch, Charlottesville VA. www.streamwatch.org/reports

Murphy, JA. 2006. Living in Our Watershed – Correlates of Biological Condition in Streams and Rivers of the Rivanna Basin. StreamWatch, Charlottesville VA. www.streamwatch.org/reports

Ourso, RT and Frenzel, SA. 2003. Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. Hydrobiologia. 501: 117-131.

Pitt, R, Clark, S, Lake, D. 2007. *Construction site erosion and sediment controls*. DEStech Publications, Inc. Lancaster, Pennsylvania.

Rosgen, DL. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.

Schueler, TR, Fraley-McNeal, L, Cappiella, K. 2009. Is Impervious Cover Still Important? Review of Recent Research. Journal of Hydrologic Engineering. 14:4: 309-315, 7 p.

State Water Control Board. 2006. 9 VAC 25-260. Virginia Water Quality Standards. Statutory Authority: § 62.1-44.15 3a of the Code of Virginia, with amendments effective January 6, 2011.

Terhune, LDB. 1958. The Mark VI groundwater standpipe for measuring seepage through salmon spawning gravel. Canada Fisheries Research Board Journal 15: 1027-1063.

Theobald, DM. 2004. Placing Exurban Land-use Change in a Human Modification Framework. Frontiers in Ecology and the Environment. 2(3): 139–144

United States Environmental Protection Agency, Office of Water. 2002. Biological Assessments and Criteria: Crucial Components of Water Quality Programs. Document reference: EPA 822-F-02-006.
http://www.epa.gov/waterscience/biocriteria/technical/brochure.pdf

Virginia Department of Environmental Quality. 2007. Virginia Citizen Water Quality Monitoring Program Methods Manual.
http://www.deq.virginia.gov/cmonitor/guidance.html