The Role of Natural Landscape Features in the Fate and Transport of Nutrients and Sediment

STAC Workshop Report

March 7-8, 2012
Buckeystown, Maryland

STAC Publication 12-04

About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

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Executive Summary

In response to a request from the Chesapeake Bay Program's (CBP) Maintain Healthy Watersheds Goal Implementation Team (GIT4), the CBP's Scientific and Technical Advisory Committee (STAC) sponsored a workshop on March 7-8, 2012 to consider whether there is a scientific basis for changing how the Chesapeake Bay Program Watershed Model assigns nutrient and/or sediment loading rates of natural landscape features based on their ecological health/condition, management status, and/or landscape position.

The workshop agenda included plenary sessions with expert panels on the fate and transport of nutrients and sediments by natural landscape features - forests, riparian buffers, streams, and wetlands – one panel on landscape ecology, and one presentation on how the current Chesapeake Bay Program Watershed Model estimates nutrient and sediment loading rates. Workshop participants then dispersed into breakout groups, one for each landscape feature, to discuss the following questions:

- What changes could be made to the existing Chesapeake Bay Program Watershed Model to better simulate the functioning of natural landscapes?
- What functions should be considered in any future modeling effort?
- What questions need to be addressed by the scientific community before any model or tool can appropriately simulate or account for natural landscape functions?

Summary of Findings

There was consensus among workshop participants that there is a scientific basis for adjusting Chesapeake Bay Program Watershed Model nutrient and sediment processing rates that are assigned to natural landscape features to better reflect the influence of landscape feature attributes that significantly affect actual rates. Hydrologic retention time and waterflow connectivity were recognized as important natural landscape feature attributes affecting nutrient and sediment retention.

Riverine floodplain wetlands are important landscape features because they are biogeochemically active and they are the dominant wetland class in the mid-Atlantic region. Sediment and nutrient storage is strongly influenced by floodplain-river connectivity, watershed land use, position in the watershed, and floodplain geomorphology. Additionally, in-stream nutrient processing rates are higher in streams with intact riparian forests because forest cover inhibits herbaceous encroachment on channel width, which reduces the width of the stream beds where nutrient processing occurs. Riparian forests also contribute organic material to the stream, which fuels microbial nutrient distribution processing.

- Hydrologic connectivity was identified as potentially the most influential factor for natural feature nutrient processing. Participants agreed that future modeling tools should account for waterflow connectiveness. In order to account for this linkage, modelers would need data on pathways for water movement (flow paths) across the watershed to better represent the connectivity. Overland flow paths can be mapped in a Geographic Information System (GIS) using digital elevation data derived from contours, LiDAR, or other information depicting topography.

- New landscape ecology metrics, such as the directional connectivity index, can improve understanding of how the arrangement of landscape features affects fluxes of sediments and nutrients in water bodies. Accurate stream mapping and identifying the landscape-stream transition zone are important to understanding residence time.

Summary of Recommendations

The CBP should pursue upgrades to the Chesapeake Bay Program Watershed Model that provide for more accurate estimates of nutrient and sediment loading rates from natural landscapes based on the considerations discussed in this report.

First, three new land use classifications should be immediately identified and mapped: riparian forest, forested floodplains (in general, these are wider and closer to water table than riparian forests), and other wetlands. The potential value of identifying additional new land use classes that also demonstrate a greater functional capacity for retaining nutrients and sediments should be evaluated.

Second, loading rates for the new land use classes should be adjusted based on spatially explicit landscape attributes, including directional connectivity, multi-direction flow fields, and flow path analysis.

Third, loading rates for the new land use classes should be adjusted based on landscape feature attributes including type, condition, and possibly forest age.

Inclusion of such upgrades to the watershed model will not only improve model accuracy, but will also improve the base of knowledge that can be used to target natural resource conservation investments to areas on the landscape that provide the highest water quality benefits.

The CBP should use scenario analysis to identify the most effective landscape features and the most effective configurations of features.

Further, the CBP should consider investing in watershed models for use at the local scale.

Introduction

The goal of the Chesapeake Bay Program's Maintain Healthy Watershed Goal Implementation Team is to maintain local watershed health across a range of landscape contexts. Through the pursuit of this goal, the Team's intention is to complement existing water quality and living resources habitat restoration initiatives with a new initiative to assure the protection of watershed health where watersheds currently are healthy. A similar, national "Healthy Watershed Initiative" (http://water.epa.gov/polwaste/nps/watershed/index.cfm) to support state and local healthy watershed identification and protection programs was launched by EPA in 2011.

As GIT4 developed its own healthy watershed strategy for the CBP Partnership, GIT4 members expressed interest in exploring how healthy watershed protection might be included explicitly within the water quality management regime of the Chesapeake Bay Total Maximum Daily Load (TMDL). Initial discussions around that question yielded such a wide range of relevant science and policy questions that the GIT proposed to examine the issue with the CBP's STAC in a two-stage workshop approach. The approach was to: first, conduct a scoping workshop to identify and prioritize the key questions; and second, based on that prioritization, conduct a STAC scientific workshop to address those science questions. At this stage, the GIT recognized that key policy questions, like whether the TMDL's nutrient and sediment accounting system could be restructured to accommodate "crediting conservation," were not appropriate for treatment in a STAC workshop, but should be pursued through other means after the workshop's findings were reported.

The STAC agreed to the GIT's two-stage proposal and a scoping workshop was held on May 31, 2011 at Virginia Commonwealth University's Rice Center. The scoping workshop resulted in the identification of two topics for further consideration.

1. Is there a scientific basis for recognizing a higher efficiency rating for some best management practices (BMPs) based on the assurance that they will remain in place in perpetuity? Or must additional factors beyond protection in perpetuity be coupled with the BMP, such as the BMP's landscape position?

2. Can landscape/watershed-scale functions, critical land use thresholds, and land use planning practices (including resource land preservation) be identified for use in the existing Bay TMDL accounting framework?

These were presented to STAC at STAC's June 2011 meeting, at which time STAC authorized the formation of a Steering Committee to further focus and plan a full STAC workshop. After further discussion, the Steering Committee refined the purpose of the workshop to the following statement with which the Steering Committee recruited scientists for the presentations and discussions that are summarized in this report:

To examine and discuss whether there is a scientific basis for changing Chesapeake Bay Program Watershed Model nutrient and/or sediment processing (retention) rates that are assigned to natural landscape features (wetlands, forests, riparian buffers, streams, hyporheic zones) based on the management status of the features, either individually or collectively (protected vs. unprotected from anthropogenic degradation), or based on their landscape position with respect to receiving waters and to each other.

Presentations:

The agenda for the workshop (see Appendix A) included presentations by scientists who are actively investigating nutrient and sediment processing in particular natural landscape features including upland and riparian forests, streams, and wetlands. There were also presentations by scientists who specialize in the new analytical tools of landscape ecology, and one presentation by a Chesapeake Bay Program modeler on the current approach employed by the CBP Watershed Model to estimate processing rates of natural landscape features.

A brief summary of each of the presentations is provided in Appendix B.

Summary of Panel Discussions:

Forests

The first panel of the Beneficial Effects of Healthy Watersheds STAC Workshop addressed riparian forests, and other forests (sometimes referred to as "upland forests" to distinguish them from riparian forests). Historically, forests were the natural land cover for 95% of the Chesapeake Bay watershed, but currently cover just 55% (USFS Forest Inventory Analysis 2011).

The forest panel focused on the role of the forested landscape—i.e., the percent forest cover of a watershed and the distribution of forest on the landscape—and what impact that would have on reducing nitrogen, phosphorus, and suspended sediment inputs. Panelists did not address specific aspects of forests such as composition, structure, and health, even though those too may be important.

Bern Sweeney hypothesized that every tree in a watershed contributes to improving overall water quality in the stream. Furthermore, he showed how the percent forest in a watershed is a better indicator of health than percent forest in riparian areas. Riparian forests function as a barrier to the stream with increasing removal from increasing width (e.g., >30 m to get >70% removal). Wider buffers are more effective because they filter out fine sediment which otherwise severely impact stream functioning. A riparian forest also enables a stream to widen, therefore leading to decreased flow velocities, creating more time and space for in-stream processing, especially along the stream bottom. The riparian forest provides a variety of organic material to the stream fueling microbial and macrobenthic activity on the wider stream.

Luc Claessens discussed hydrologic connectivity and the effect of land use and buffer features on nitrate concentration. He analyzed land cover distribution using process-based models, an important tool for predicting and understanding the spatial and temporal variation in nitrogen cycling. The concentration of nitrate increases in the absence of forests. The impact of non-forested land uses on nitrate concentration depends on the spatial location of the land uses in the watershed which can be more informative than simply looking at proportional land use.

Donald Weller combined models to predict the nitrate reduction benefits of existing buffers across the Chesapeake watershed, based on flow path estimates. Furthermore, he estimated what the potential reductions would be for a 100% Bay-wide buffer restoration effort (filling in all buffer gaps). He scaled the buffers to 30 m LandSat data but suggested that the same method could be applied to higher resolution data.

All panelists agreed that conservation of established forests is much preferred over forest restoration. Additionally, all mentioned the occurrence of a riparian buffer downslope from an agricultural field is likely to offer the greatest opportunity for pollutant removal because of the higher potential nitrogen (nitrate) loading coming off that field. It was evident that the hydrologic connectivity of forests and its associated pollutant removal can be difficult to prove in field settings—models and whole watershed studies can help with this issue. The speakers on this panel and other workshop participants as well qualified their statements about N, P, and sediment by saying that the multitude of other ecosystem services provided by forests (such as habitat improvement) should be factored into the discussion and may, in fact, have greater importance than pollutant reduction to the overall well-being of the watershed.

Wetlands

This panel provided an overview of the role of wetlands in retaining sediments and nutrients in the Chesapeake Bay Watershed. Located at the interface between upland and aquatic ecosystems, wetlands have both the opportunity and mechanisms to retain and transform sediments and nutrients. These retention and transformation functions form the basis for the wetland ecosystem service of regulating water quality and have been well documented. However, quantifying specific retention capabilities of natural wetlands in the Chesapeake Bay Watershed requires understanding the wetland type, wetland condition, and the inherent controls over the fate and transport of sediments and nutrients.

Stephen Faulkner, USGS, summarized the range of nutrient retention rates reported in the peer-reviewed literature and the attributes of wetlands in the Chesapeake Bay Watershed relevant to improving quantification of nutrient and sediment retention rates. Hydrogeomorphic (HGM) functional classification indicates that riverine wetlands are the dominant wetland class in the mid-Atlantic region, but the presence of depressional and slope wetlands requires knowledge of hydrologic flowpaths to accurately quantify retention rates. Roads, vegetation removal, and ditching/draining are the primary wetland stressors impacting wetland processes and functions. With the likelihood that these stressors will increase in the future, rapid assessment techniques are needed to accurately assess wetland conditions affecting sediment and nutrient retention rates.

Scott Ator, USGS, discussed the importance of wetland-upland interactions and the role of groundwater hydrology in the Mid-Atlantic Coastal Plain. Many wetlands are connected to upland land uses through shallow groundwater and this affects the fate and transport of nitrogen. New data are changing assumptions about how water and nitrogen are moving through this landscape. Spatial proximity of wetlands to drainage features can alter flowpaths, so more extensive, current geochemical data are needed to better understand recharge-discharge relationships affecting denitrification rates. Results from these and other studies are being used to construct a conceptual model of wetland effects on water quality in the Mid-Atlantic Coastal Plain.

Greg Noe, USGS, presented a summary of current work on nutrient cycling and sediment deposition rates in floodplain wetlands driven by surface water. These wetlands retain large amounts of sediments and nutrients representing a significant fraction of river loads. The retained amounts increase with increasing disturbance in the watershed and greater hydrologic linkages between the stream/river and the wetland. Sediment and nutrient retention is strongly influenced by floodplain-river connectivity, river load, watershed land use, position in the watershed, and floodplain geomorphology, all of which may be used to develop predictive models.

Streams

The Healthy Streams Panel discussed the various processes by which nutrients, primarily nitrogen and particulate-bound phosphorus were retained or transported in streams. Some nutrients are processed within the stream and either retained through deposition or removed through natural, biotic processes. Speakers discussed the importance of residence time – the amount of time water has to interact with the surrounding geologic and biotic surfaces. The slower water moves, the more opportunities there are for uptake, deposition, and processing of nutrients. The speakers generally concluded that healthier, unchannelized streams are more likely to have higher nutrient retention efficiencies and to deliver lower nutrient loads downstream. Speakers also found that forested watersheds have lower nitrate-N loading rates than those currently used in the Chesapeake Bay model and this could possibly be a recommendation for improvement.

Paul Bukaveckas, Virginia Commonwealth University, described the importance of nutrient retention in riverine systems. The nutrient retention services of streams and riverine systems play a critical role in reducing nutrient loads. There are three main factors that influence the efficiency of these retention rates: the amount of the incoming load, hydrology, and biotic activity. One of the most important hydrological factors includes residence time. A slower moving stream provides more opportunities for biotic assimilatory uptake of nitrate and ammonia by benthic biofilm communities. It also allows particulate-bound phosphorus to be trapped on the floodplain. While increased loads can lead to increased retention, it is not a linear relationship and efficiency declines with increased loads. Healthy, non-channelized streams tend to have higher residence times; however, they are also more likely to be shaded, and therefore to have lower biotic activity which decreases nutrient retention. Ultimately, healthy and restored streams with high transient water storage should demonstrate increased nutrient retention.

Keith Eshleman, University of Maryland Center for Environmental Science (UMCES), discussed a study in which he investigated trends in surface-water nitrate-N concentrations and loads from predominantly forested watersheds in the Chesapeake Bay Basin. Using LOADEST, a model developed by the USGS, Eshleman was able to determine the mean annual discharge-weighted nitrate-N concentration and mean nitrate-N loads for several forested watershed basins. For all of these forested watersheds, Eshleman found statistically significant decreasing trends in nitrate-N concentrations, while also finding that the mean nitrate-N load was half as large as the value used in the Chesapeake Bay Program watershed model. Additionally, Eshleman found significant decreasing trends in nitrate-N loads for over half of the watersheds. He concluded that the temporal dynamics of nitrate-N in forested watersheds need to be accounted for in both water quality modeling efforts and TMDL analyses.

Durrell Scott, Virginia Tech, reiterated the importance of higher residence time for nutrient retention and removal, especially in pools and the hyporheic zone. Land use change has transformed many streams to export water more quickly during high flow events, providing lower water retention time and increasing the amount of nutrients transported downstream. "Healthy" streams are generally more complex and thus have higher in-stream residence time, providing more opportunities for biogeochemical transformations to take place between nutrients and sediment and microbial surfaces.

Landscape Ecology

This panel provided an overview of how spatial relationships and connectivity among landscape features affect sediment and nutrient retention in the Chesapeake Bay Watershed. While site-specific aspects of individual patches such as land use class, plant community, or elevation play a vital role in sediment processes and nutrient cycling, geospatial attributes and hydrologic linkages at the watershed scale are also important determinants of sediment and nutrient transport to the Chesapeake Bay. While the tools and data necessary to forecast how future changes in land use/land cover may affect sediment and nutrient retention at the watershed scale are still being developed, these concepts need to be incorporated into spatially explicit models addressing the fate and transport of sediments and nutrients in the watershed.

Laurel Larsen, USGS, described new strategies to quantify directional connectivity on the landscape. These approaches are part of the growing field of ecohydrology that combines ecological (graph theory) and hydrological (percolation theory) methods. Metrics, such as the directional connectivity index, may provide a more robust and sensitive indicator of declining ecosystem function than currently used measures (e.g., habitat area). These methods can improve understanding of how the arrangement of landscape features affects fluxes of sediments and nutrients from watersheds to tributaries. Improved measures of directional connectivity can serve as a planning tool or performance measure for conservation and restoration efforts.

Matt Baker, University of Maryland Baltimore County (UMBC), summarized methods and approaches in landscape ecology relevant to the concept of connectivity. Various landscape ecology techniques are used to link functional distance to hydrologic responses. Accurate stream mapping at high resolutions provides a way to identify the landscape-stream transition zones, which are important for understanding surface water transport. Approaches including multi-direction flow fields, flow-path analysis, and buffer characterizations relative to stream network position can be used in conjunction with water quality data to test assumptions of overall watershed function.

Summary of Plenary Discussion

In a final plenary session, workshop participants revisited the question around which the workshop was convened:

> Is there a scientific basis for changing Chesapeake Bay Program Watershed Model nutrient and/or sediment processing (retention) rates that are assigned to natural landscape features (wetlands, forests, riparian buffers, streams, hyporheic zones) based on the management status of the features, either individually or collectively (protected vs. unprotected from anthropogenic degradation), or based on their landscape position with respect to receiving waters and to each other?

There was consensus among workshop participants that there is a scientific basis for adjusting Chesapeake Bay Program Watershed Model nutrient and sediment processing rates that are assigned to natural landscape features to better reflect the influence of factors that significantly affect actual rates. In riverine systems, the generally higher processing rates on floodplains could be captured to some degree by including a floodplain land cover class. Because the functionality of floodplains in this regard is heavily dependent upon whether they are still hydrologically connected to their rivers, if it is possible at the scale of the watershed model it would be useful to differentiate between floodplains that are hydrologically connected to their rivers and those that are not.

Participants also recognized that first order streams typically exhibit higher processing rates than larger waterways, but small streams may be unseen at the current scale of the watershed model. Adding a higher resolution stream layer could better represent the greater contribution from this class of streams. Further, because of the contribution that forest buffers make to stream nutrient and sediment processing capacity, it would also be worth differentiating between streams that have forested buffers and those that do not within the stream data layer used in the watershed model.

Participants also discussed the potential value of running the watershed model with alternative future scenarios of land cover/land use to examine the water quality effects of a range of proportions of existing natural landscape features. For example, with some of the model improvements identified above in place, a model run could be conducted with plausible scenarios of 100% of existing forests, riparian buffers, and wetlands intact; and another run conducted with significantly less of those natural features on the landscape. The comparisons would likely illustrate the net benefit that could be realized from the protection of natural landscape features and in that way could be useful to conservationists and land use planners.

Another factor that was emphasized as being very important was residence time, which is not the same as connectivity. Watershed geomorphology, soil type, forest cover, impervious surface, etc. could have an effect on residence time, particularly residence time on and within land and wetland areas. While residence time in streams is also important, the greatest benefits appear to be from increased residence time on the land. Workshop participants repeatedly discussed how important it was to slow down the water before it hits the stream.

Recommendations:

The CBP should pursue upgrades to the Chesapeake Bay Program Watershed Model that incorporate more accurate estimates of nutrient and sediment processing rates based on the considerations discussed in this report.

First, three new land use classifications should be identified immediately: riparian forest, forested floodplains, and other wetlands. The potential value of identifying additional new land use classes that also demonstrate a greater functional capacity for retaining nutrients and sediments should be evaluated.

Second, for landscape features that are recognized by that new land use classification, the model should be able to quantify – based on spatial arrangement within the landscape, connections to pollutant sources, and estimates of the features' functionality in nutrient and sediment reduction - the degree to which the landscape features provide protection to downstream waters by intercepting nutrients and sediments.

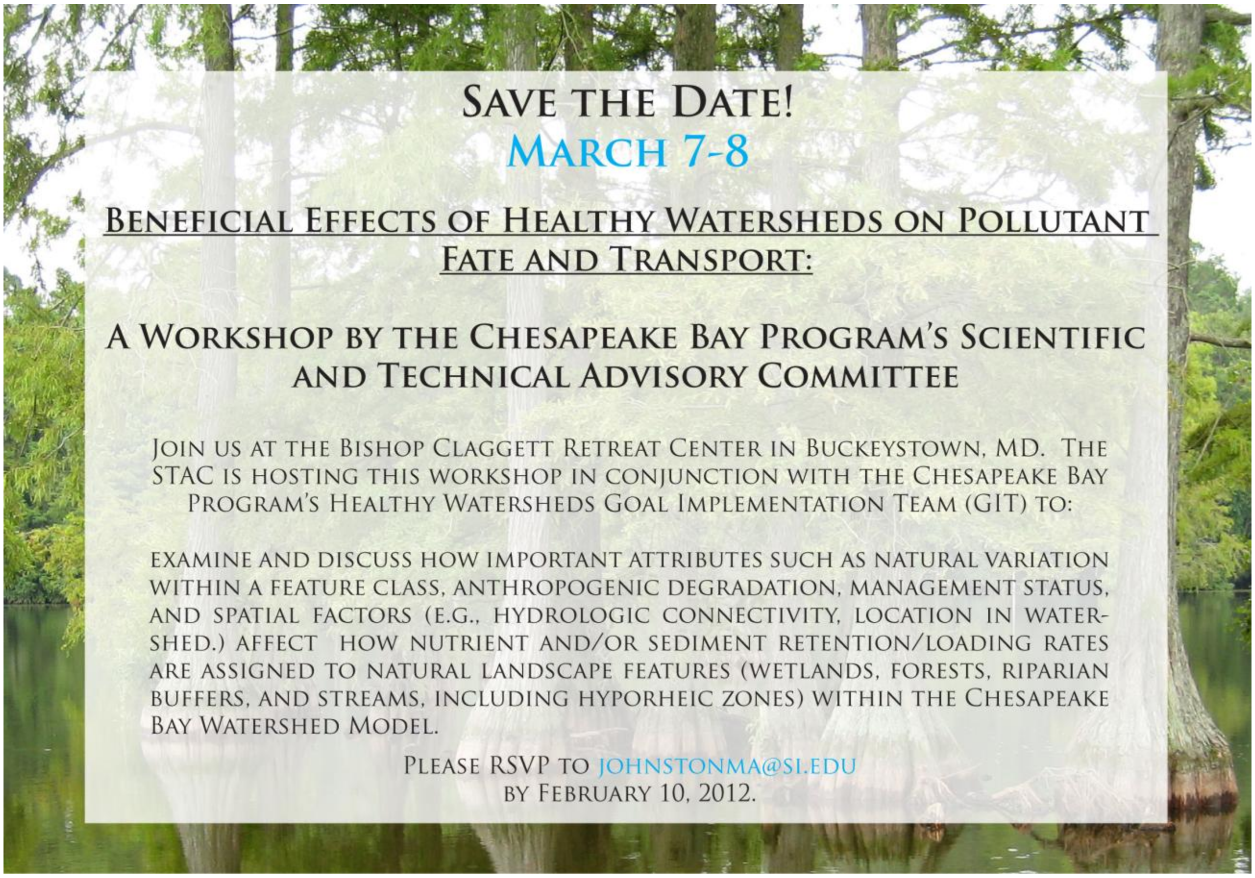
Inclusion of such upgrades to the watershed model will not only improve model accuracy, but also will improve the base of knowledge that can be used to target natural resource conservation investments to areas on the landscape that provide the highest water quality benefits.

Once such improvements are included in the watershed model, the net effects on nutrient and sediment fluxes from the landscape to the Bay's tributaries should be evaluated at the landscape scale by conducting model runs that simulate alternative future scenarios (e.g., with and without conversion of existing riparian forest buffers to non-forested land uses).

Over the longer term, scientists and modelers should evaluate whether ecological condition assessment (e.g., forest age, ecosystem health) could be incorporated into the Bay watershed model to further enhance the differentiation among landscape features in terms of nutrient and sediment processing.

It may also be possible, and desirable, to develop and incorporate into the Bay watershed model upgrades to the model's estimates of in-stream nutrient processing based on considerations such as whether riparian forest is present.

Appendix A. Workshop Announcement and Agenda



Beneficial Effects of Healthy Watersheds on Pollutant Fate and Transport:
A CBP STAC workshop to examine how natural landscape features protect water quality
Date: March 7-8, 2012

Location: Claggett Retreat Center 3035 Buckeystown Pike, Buckeystown, MD

Purpose of the workshop

To examine and discuss how important attributes such as natural variation within a feature class, anthropogenic degradation, management status, and spatial factors (e.g., hydrologic connectivity, location in watershed.) affect how nutrient and/or sediment retention/loading rates are assigned to natural landscape features (wetlands, forests, riparian buffers, and streams, including hyporheic zones) within the Chesapeake Bay Program Watershed Model.

General Workshop Guiding Questions

- *How can we improve quantification of nutrient and sediment retention/loading rates of existing forests, wetlands, riparian buffers, and streams, including hyporheic zones, in the Chesapeake Bay Watershed?*
- *How can the beneficial effects of existing forests, wetlands, riparian buffers, and streams, including hyporheic zones, in the Chesapeake Bay Watershed be credited by the Bay TMDL?*

March 7, 2012

9:00 am Breakfast (Provided)

10:00 am **Welcome –** Mark Bryer, The Nature Conservancy

10:15 am **Why does this all matter? –** Ann Swanson, Chesapeake Bay Commission
Swanson will address the underlying policy issues that this workshop seeks to inform.

10:30 am **Healthy Forests/Riparian Buffers Panel**

- Nitrogen removal in forests and riparian buffers: The role of spatially variable hydro-ecology - Luc Claessens, University of Delaware
- Trees, water quality, and stream ecosystem health: Lessons learned from the field and literature - Bern Sweeney, Stroud Center
- Nitrate removal by Chesapeake watershed riparian buffers and potential additional removal from buffer restoration - Don Weller, Smithsonian Environmental Research Center

12:00 pm **Lunch (Provided)**

1:00 pm Healthy Streams Panel

- In-stream nutrient retention: Do healthy streams do it better? - Paul Bukaveckas, VCU
- Trends in surface-water nitrate concentrations and loads from predominantly forested subwatersheds of the Chesapeake Bay basin - Keith Eshleman, UMCES
- Hydrologic retention within streams: Where, when and why this matters - Durelle Scott, VT

2:30 pm Break (Provided)

2:45 pm Healthy Wetlands Panel

- The importance of groundwater flow patterns to the mitigation of nitrate transport by depressional wetlands - Scott Ator, USGS
- Factors influencing nutrient and sediment retention by riverine wetlands in the Chesapeake watershed - Greg Noe, USGS
- Wetland condition and functional assessment: Effects on nutrient and sediment retention - Steve Faulkner, USGS

4:15 pm Closing Remarks – Mark Bryer, The Nature Conservancy

4:30 pm Recess

March 8, 2012

9:00 am Breakfast (Provided)

10:00 am **Welcome –** Mark Bryer, The Nature Conservancy

10:10 am **Landscape Ecology Overview**

- Connectivity: A critical component of hydrological and ecological flux assessments - Laurel Larsen, USGS
- Linking landscape scale patterns of nutrient and sediment sources and buffers to hydrologic connectivity - Matt Baker, UMBC

11:15 am **Chesapeake Bay Program Watershed Model Panel** –Gary Shenk, EPA-CBPO

Shenk will address how the current Chesapeake Bay Watershed Model estimates nutrient and sediment loading rates of the natural landscape features (forests, wetlands, riparian buffers, streams, including hyporheic zones) and discuss opportunities to include improved simulation of these features in the current or future versions of the model.

12:30 pm Lunch (Provided)

1:30 pm Breakout Discussion Session Groups
Participants will break into groups to discuss the following:

- What changes could be made to the existing Bay Program model to better simulate the functioning of natural landscapes?
- What functions should be considered in any future modeling effort?
- What questions need to be addressed by the scientific community before any model or tool can appropriately simulate or account for natural landscape functions?

3:00 pm Break

3:00 pm General Session Discussion

4:00 pm Concluding Remarks – Mark Bryer, The Nature Conservancy

4:30 pm Adjourn

Appendix B. Abstracts of Workshop Presentations

Healthy Forests

Nitrogen removal in forests and riparian buffers: The role of spatially variable hydro-ecology

Luc Claessens, Department of Geography, University of Delaware

N removal in forests and riparian buffers is largely controlled by spatio-temporal linkages between hydrology and ecosystem processes. These processes are highly non-linear and spatially variable. Understanding the effect of this spatial variability is critical for quantifying the N removal functions of forests and riparian buffer. I examined the role of spatially variable hydro-ecology, and addressed three questions by means of case studies: (1) What is the effect of land use on N concentration? (2) How does spatial organization of land cover affect N concentration? (3) How can we quantify the effect of landscape features on N removal?

Effect of land use: The 280 km^2 White Clay Creek watershed of PA and DE has a wide range of land use. Results from synoptic sampling illustrate that examining land use effects is important for prioritizing N reduction efforts. E.g., urban areas had relatively low N concentrations; this suggests that N reduction efforts in these urban areas will lead to only minimal improvements. Also, agricultural hotspots of N loading (e.g., mushroom farms) could be prioritized for innovative N reduction efforts (e.g., denitrification bioreactors).

Effect of spatial organization: The 890 km^2 Opequon Creek watershed of VA and WV has mixed land use. Results from synoptic sampling illustrate that lumped land use categorization of agricultural and forested land might not capture relevant N removal processes. 'Effective' land use is introduced, which weights land use using spatial metrics of hydrologic connectivity. Preliminary modeling results suggest that spatial factors could easily be incorporated by using 'effective' land use instead of true proportional land use. The results also illustrate the role of riparian forests in in-stream N removal.

Spatial process-based modeling: The RHESSys hydro-ecological watershed model is presented, which couples spatial variable hydrology with carbon and nitrogen cycling. This type of modeling approach is well suited for quantifying N removal in forest and riparian buffers, because it accounts for spatial variability and local heterogeneity, and it incorporates spatio-temporal linkages between hillslopes, riparian zones and streams. This modeling approach can answer questions on various factors, including spatial (where should we have buffers?), design (what should be the configuration?), process (how effective would the buffer be?) and temporal factors (how long would it take for the buffer to become effective?).

In conclusions, examining land use effects is important for prioritizing N reduction efforts. Approaches based on waterflow connections could improve coarse-scale models and could be used for targeting forest and buffer preservation and restoration. Further, spatial process-based models are an important tool for predicting and understanding the spatial and temporal variation in N cycling.

Trees, water quality, and stream ecosystem health: Lessons learned for the field and literature

Bernard W. Sweeney, Stroud Water Research Center

Field studies at the Stroud Water Research Center on tributaries in both the Hudson River and Schuylkill River show a strong positive correlation between the percent forest cover in a watershed and the water quality score (based on macroinvertebrate data) of streams flowing out of the watershed. Further work on a subset of those study streams shows that stream function (i.e., the ability to process / uptake nutrients) exhibits the same positive correlation. The data suggest that for a given watershed, the more forest, the better the habitat and water quality and the healthier the ecosystem, and hence the more ecosystems services per unit length of stream. Thus, every tree counts in a watershed. Trees in upland forests are critical to intercepting and infiltrating rain and thus promoting more natural, sustained, and cleaner stream flow. Some of this is due to the better soil structure beneath forested land due to high organic content resulting from leaf litter storage and decay. Trees in riparian forests can serve as barriers to pollutants entering a stream. Long term (>20 years) studies at the Stroud Preserve (Marshalton PA) show that a 30 m wide forest buffer can remove on average about 43% of the sediments and 26% of the nitrate nitrogen moving toward a small stream. A literature review confirms that a forest buffer of >30 m is needed to get >70% sediment trapping efficiency which is needed to make sure that the finer sediments are removed. The literature also confirms that riparian buffers filled with forest help provide better in-stream habitat conditions and promote a healthier and functionally better stream ecosystem than do buffers without forest. A significant factor contributing to increased function is the significantly greater width of stream channels associated with streams having intact forested riparian areas. Greater stream width translates into more ecosystem per unit length of stream because most ecosystem activities in streams is associated with the stream bottom. It is estimated that more that 50% of the stream ecosystem can be lost due to stream narrowing resulting from riparian deforestation in a small watershed. Hence, we may be significantly underestimating the potential level of ecosystem services in small streams (e.g., due to denitrification or biotic uptake) if riparian forest cover were to be restored.

Modeling the aggregate effects of riparian buffers in the Chesapeake Bay watershed.

Donald. E. Weller, Smithsonian Environmental Research Center

and Matthew E. Baker, University of Maryland - Baltimore County

We developed a simple model to estimate the effects of riparian buffers on the cropland nitrate load delivered to streams, and we applied the model to the entire Chesapeake Bay watershed. For each of 1929 sub-basins comprising the watershed, we quantified the prevalence of cropland and riparian buffers using NLCD2001 land cover, then separated the cropland into buffered and unbuffered categories. Cropland was considered buffered if the topographic flow path connecting it to the stream network passed through a streamside forest or wetland. We applied a published linear model that predicts stream nitrate concentration in each subwatershed from the proportions of unbuffered and buffered cropland and physiographic province. We also applied a published regional regression model to predict mean annual stream flow from mean annual precipitation and temperature, and then we multiplied the predicted stream flows and nitrate concentrations to estimate nitrate loads. We analyzed alternate land cover scenarios to estimate the current removal of nitrate in riparian buffers, and the upper limit of additional removal that might be achieved through buffer restoration. Across the entire Chesapeake Bay watershed, we estimated that croplands release 80 Gg of nitrate nitrogen, but 13gG (16%) of that are currently removed by riparian buffers. At most, 19gG (24%) more might be removed through a complete buffer restoration that addressed all cropland runoff. The remainder of the edge of field load (48gG, 60%) would have to be addressed by other management practices. The importance of buffer nitrate removal differed among Physiographic provinces. The Coastal Plain had the both the highest percentage removal in current buffers (40%) and the greatest potential for additional removal in restored buffers (41%). Current nitrate removal (9%) and potential restoration removal (19%) were much lower outside the Coastal Plain because of lower current buffer prevalence and lower average nitrate removal efficiency for buffers outside the Coastal Plain. This is the first attempt to estimate the Bay-wide effects of current buffers and the Bay-wide potential for buffer restoration, and we discuss some future refinements to improve the analysis.

Healthy Streams

In-Stream Nutrient Retention: Do Healthy Streams do it Better?

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Riverine networks provide an important ecosystem service by retaining nitrogen and phosphorus thereby mitigating anthropogenic contributions to coastal eutrophication. Retention rates and efficiency (the proportion of input load that is retained) are governed by three factors: nutrient loads, hydrology and biotic activity. Hydrology, and specifically water transit time, govern the duration over which nutrients will be resident within the system, and therefore the potential for retention to occur. Retention occurs through biotic and abiotic mechanisms; the former include autotrophic and heterotrophic assimilatory uptake by benthic biofilm communities, the latter is the passive trapping of particulate matter within the stream and its floodplain. Biotic uptake retains dissolved inorganic fractions, particularly nitrate and ammonia, whereas sediment trapping is more important for retention of particulate-bound phosphorus. In temperate regions such as the Mid-Atlantic, cold-weather periods are associated with low retention due to high discharge and low biotic activity. Warmer months favor high retention due to low discharge and greater biotic activity. Nutrient loads set the upper limit for retention such that when other factors (hydrology, biotic activity) are equal, retention would be expected to increase with load. This response however is not linear and therefore retention efficiency declines with increasing load. Healthy streams are characterized by channel conditions that enhance transient storage which, in combination with having low nutrient loads, are likely to favor high retention efficiency. Impaired waters, particularly those that have been channelized, have low retention as well as high nutrient loads resulting in low retention efficiency. These effects may be partially offset by higher rates of biotic activity, as might be expected where riparian disturbance lessens canopy shading and increases autotrophic production. Empirical evidence comes from surveys of nutrient retention in streams with varying land use and from experimental manipulations of streams via restoration projects. Surveys have shown that impaired streams had greater NO_3 removal due to higher primary production but lower removal efficiency due to higher NO_3 loads (Hall et al. 2009). Stream restoration projects have demonstrated that enhancing transient water storage through in-stream structures or back-water connectivity increases nutrient retention (Bukaveckas 2007).

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Trends in Surface-Water Nitrate-N Concentrations and Loads from Predominantly-Forested Watersheds of the Chesapeake Bay Basin

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Despite the fact that about 60% of the Chesapeake Bay watershed is characterized as forested land, there are very few published studies describing long-term trends in streamwater nitrate-N concentrations in Chesapeake Bay subwatersheds dominated by forests. We addressed this question by analyzing long-term nitrate-N data from two gaged research watersheds in western Maryland (Upper Big Run and Black Lick), as well as from seven stations operated by state water quality agencies and located in predominantly-forested watersheds. We believe that these seven watersheds are the only gaged predominantly-forested watersheds for which adequate publically-accessible data are suitable for long-term (i.e., 1985-present) analysis of trends. We computed annual loads and discharge-weighted concentrations of nitrate-N for these nine watersheds using LOADEST (a program model developed by the U.S. Geological Survey and the standard model used by many federal and state monitoring programs); we performed the same analysis for four Potomac River subwatersheds as a comparison. Mean annual discharge-weighted nitrate-N concentrations among the forested basins ranged from 0.14 to 1.00 mg N L^{-1}—nearly an order of magnitude of total variation; the mean nitrate-N load for these watersheds was 2.16 kg ha^{-1} yr^{-1}, nearly half as large as the constant value of 3.5 kg ha^{-1} yr^{-1} used in the Chesapeake Bay Program watershed model. Our results showed statistically-significant ($p<0.05$) decreasing trends in nitrate-N concentrations for all nine forested subwatersheds, with slopes ranging between -0.004 and -0.039 mg N L^{-1} yr^{-1}; five of the nine forested watersheds showed statistically-significant decreasing trends in nitrate-N load also. Three of the four Potomac River subwatersheds used for comparison showed decreasing nitrate-N concentrations (slopes -0.024 to -0.047 mg N L^{-1} yr^{-1}). A separate analysis of atmospheric nitrate-N deposition trends showed declines of about 40% during this period due to implementation of the 1990 Clean Air Act Amendments that has dramatically reduced emissions of NOx from stationary sources within the airshed. Streams draining forested watersheds thus appear to be responding in a "direct" manner to reductions in atmospheric nitrate-N—similar to their well-known response to reductions in sulfate deposition. We concluded that the temporal dynamics of nitrate-N in forested watersheds need to be accounted for in both water quality modeling efforts and TMDL analyses.

Hydrologic Retention Within Streams: Where, when and why this Matters

Durelle Scott

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One ecosystem service provided by "healthy" streams is the ability to process and remove nutrients (e.g., nutrient retention). Within the stream channel, nutrient retention generally occurs in areas of higher residence time, such as in pools or within the hyporheic zone. Nutrients come in contact with sediment and microbial surfaces, allowing for biogeochemical transformations to take place. For example, nitrate will be converted to N_2 gas in areas of lower O_2 conditions. Streams that are more "complex" will generally have higher in-stream residence times and therefore greater nutrient removal. Over the course of the year, in-stream transformations have a large impact on solute concentrations under baseflow

conditions, when the channel acts like a "reactor". In contrast, residence times are low during high flow (high velocity), resulting in minimal nutrient processing and the stream channel acting more like a "pipe". Land use change and hydrologic modifications have shifted more of the water export to higher flow events, which means that these stream channels will have less of an opportunity to reduce annual nutrient export to downstream ecosystems. In contrast, baseflow can represent greater that 50% of the annual water export in forested watersheds, suggesting that in-stream processing reduces downstream nutrient export in forested watersheds.

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Healthy Wetlands

The Importance of Ground-Water Hydrology to Wetland-Upland Interactions, Mid-Atlantic Coastal Plain

Scott Ator, USGS

Untested assumptions about ground-water hydrology may contribute to misunderstanding of the importance of wetlands to water quality in nearby streams. Shallow ground-water flow paths often are critical vectors for nitrogen movement near wetlands, and must be sufficiently understood as part of any investigation of nitrogen fate and transport. The effectiveness of relatively natural, restored, and prior-converted (drained and used for agriculture) wetlands at mitigating agricultural impacts on local streams is under investigation at eight sites in the Upper Choptank Watershed, Maryland, as part of the U.S. Department of Agriculture Wetland Conservation Effects Assessment Project (CEAP-Wetlands). Hydrologic and geochemical observations at some sites challenge common initial assumptions based on local topography. At one site, ground-water flow is controlled by a relatively distant drainage feature and often is in the opposite direction of initial assumed flow paths. At another site, relatively low nitrate concentrations in shallow ground water beneath a grass buffer adjacent to a restored wetland might be assumed to reflect reduction of much higher nitrate in ground water recharged through uphill cropland. Geochemical data indicate, however, that sampled water beneath the buffer likely recharged through the buffer or the wetland. Ground water containing higher nitrate from beneath the cropland may pass beneath the buffer toward the wetland. Understanding gained from the Choptank Watershed and similar local studies is being used to construct a conceptual model predictive of the effects of wetlands on water quality in the wider Mid-Atlantic Coastal Plain.

Factors influencing nutrient and sediment retention by riverine wetlands in the Chesapeake watershed

Greg Noe, USGS

Floodplains are the last location in watersheds for significant material retention before river loading into coastal waters. Three questions prioritize research to help identify the roles of floodplains in reducing pollutant loads to the Chesapeake Bay and help manage floodplains to trap more pollutants. What are nutrient cycling and sediment deposition rates in floodplains? What are the controls of floodplain trapping? What is the percent retention of river loads by floodplains? Floodplain ecosystems are fundamentally influenced by hydrogeomorphic controls. Namely, four dimensions of river corridors influence floodplain ecosystem processes – longitudinal, lateral, vertical, and temporal gradients in hydrology and geomorphology – by determining river-floodplain connectivity. This hydrogeomorphic heterogeneity of connectivity is critical to the prediction and scaling of floodplain effects on water quality (Noe 2012).

Floodplains in the Coastal Plain of the Chesapeake floodplain trap large quantities of sediment, nitrogen (N), and phosphorus (P). Sedimentation and associated nutrient trapping rates increase in watersheds with greater river loads (Noe and Hupp 2005). The historically blackwater rivers in the Chesapeake, which had low sediment availability, are now disturbed and their floodplains trap as much material as alluvial rivers with large Piedmont watershed and river loads. Nutrient and sediment trapping also increase with floodplain connectiveness within a river. Floodplain reaches that have been disconnected by channelization and levee building along the Pocomoke River have the lowest floodplain trapping rates, whereas the floodplain downstream of the channelized reach have very high trapping rates. The high trapping rate and large floodplain area in many Coastal Plain rivers translates into large retention rates of river loads of sediment, N, and P. The annual load of material typically (the median among rivers) trapped by floodplains represents from 22%, 59%, and 119% of the annual river load of N, P, and sediment (Noe and Hupp 2009).

The highest sediment river yields occur in the Piedmont of the Chesapeake Bay watershed, and the lowest yields occur in the Coastal Plain (Gellis et al. 2008), suggesting that floodplain trapping could be large in the Piedmont, but less floodplain area and connectivity is found in the Piedmont. Very little has been known about rates of floodplain trapping in the Piedmont of the Chesapeake Bay watershed. In the urban, Piedmont watershed of Difficult Run, nutrient mineralization rates in floodplains were low, and similar to rates of plant uptake, indicating that nitrogen and phosphorus deposited with sedimentation is likely to be retained by the floodplain and not exported back to the river (Noe et al. in review). Averaged across all sites, the loading rate of sediment, N, and P inputs to the floodplain were greater than bank erosion rates, with trapped nutrients cycling internally within the floodplain. Within floodplains, strong differences were found in sediment and nutrient fluxes across the geomorphic units of floodplains. Sediment balance, the difference between floodplain deposition and bank erosion, was strongly depositional at sites in the middle and lower watershed, and slightly erosional in the upper watershed (Hupp et al. in review). These results in the Piedmont Difficult Run, when compared to results in the Coastal Plain watersheds, matches some of the SPARROW sediment model predictions that small streams in the Piedmont are sediment sources and large streams in the Coastal Plain are sediment sinks (Brakebill et al. 2010).

From the known locations of historic mills in the Difficult Run watershed we modeled stream impoundment from mill dams. At most 41% of the stream length was impounded by mill dams through history, including most but not all floodplain research sites (Hupp et al. in review). However, the depth of legacy sediment and floodplain thickness throughout the watershed were not related to the location of mill dam impoundments, nor were rates of floodplain sediment deposition. It can be concluded that mill dams were not responsible for the trapping of all legacy sediment in stream valleys, and that the modern floodplain is not a terrace, but instead is fluvially active with large sediment trapping rates. The intensive study of Difficult Run floodplain has shown that Piedmont floodplains can trap large quantities of sediment and nutrients.

The geomorphology of the stream-floodplain system has been shown to explain sediment gain and loss in the Chesapeake Piedmont, and potentially is a predictive tool for mapping sediment sources from bank erosion and sediment sinks from floodplain trapping. For any river reach in three different Piedmont watersheds, the sediment balance between floodplain deposition and bank erosion was highly correlated with the ratio of bank height to floodplain width (Schenk et al. in review). The negative log-log relationship held across three different Piedmont watersheds of widely differing land use and geology (r=-0.78; Difficult Run, Little Conestoga Creek, and Linganore Creek). Reaches with taller banks and narrow floodplains had more bank erosion than floodplain deposition, whereas reaches with shorter banks and wider floodplains had more floodplain deposition than bank erosion. The floodplains of these three

Piedmont watersheds are hotspots of sediment transport. Floodplain trapping rates per hectare of floodplain are the equivalent of roughly 20 to 100 times greater than watershed sediment yields per hectare ('Floodplain trapping factor').

A comparison of N cycling and retention among four created and six natural floodplain wetlands located in the Virginia Piedmont identified wetland attributes that could be used to design created and restored wetlands to optimize N retention. First, wetlands and locations within wetlands with greater waterflow connections to streams had greater total N sedimentation and soil ammonification (Wolf et al. in review). Second, microtopographic heterogeneity within wetlands increased coupled soil nitrification and denitrification (Wolf et al. 2011a). Third, older created wetlands developed soils conducive to coupled denitrification (Wolf et al. 2011b).

In conclusion, there are clear hydrogeomorphic controls on trapping of sediment, N, and P by riverine floodplain wetlands that could be used to model and predict retention fluxes. In general, floodplain-river connectivity, river load, and floodplain geomorphology have been shown to explain spatial variation in floodplain trapping. Specifically, floodplain trapping varies depending on the physiographic province of the watershed, watershed land use, floodplain disconnection, the geomorphic planform of floodplains and streams, geomorphic complexity within floodplains, and position in a watershed.

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Wetland Condition and Functional Assessment: Effects on Nutrient and Sediment Retention

Stephen Faulkner, U.S. Geological Survey

Wetlands in the Chesapeake Bay Watershed are uniquely suited to mitigate the negative impacts of nonpoint source pollution. However, the complex interactions of hydrology, soil biogeochemistry, nutrient loadings, ecological condition, and landscape position result in a wide range of reported nutrient and sediment retention rates due to variability in the specific processes controlling those rates. Reported denitrification rates in natural forested wetlands range from <1 to >800 kg N ha^{-1} y^{-1} (Mitsch et al. 2001, Lowrance et al. 2006) while published phosphorus retention in natural wetlands range from 1.4 to 36 kg P ha^{-1} (Walbridge and Lockaby 1994, Richardson and Qian 1999). Therefore, quantifying the retention capabilities of natural wetlands in the Chesapeake Bay Watershed requires understanding of the wetland type, wetland condition, and the inherent controls over the fate and transport of sediments and nutrients.

Using attributes such as geomorphic setting (e.g., riverine or flat) and dominant water source (e.g., surface or ground water) provides a more accurate and functional classification scheme for mid-Atlantic wetlands than using vegetation types since the forest communities are often the same across hydrogeomorphic classes. Riverine wetlands are the dominant (~65%) class in the mid-Atlantic region followed by flats (~10%), depressional (~10%) and slope (5%) wetlands (MAWWG 2012). This complexity and the dynamic nature of ecosystem processes are important considerations when thinking about controls over a process like sediment retention at different temporal and spatial scales. Hupp et al. (2008) reported mean sedimentation rates in forested wetlands in Louisiana ranged from 2 to 42 mm/yr depending on site hydroperiod, hydraulic connectivity, and local geomorphic setting along the transect (levee versus backswamp).

Wetlands are also subject to stressors and disturbance, therefore some measure of current conditions is necessary to evaluate potential impacts on wetland functions. Roads are the dominant wetland stressor in the coastal plain of Virginia followed by mowing, brush/tree cutting, and then ditching/draining (VIMS 2007). These various stressors may have differential effects on specific functions such that a high ranking for one set of functions does not necessarily apply to other functions. For example, ditching and draining resulted in significantly lower biogeochemical function scores for wetlands in the Nanticoke River watershed, but had little effect on the plant community (Whigham et al. 2007).

Condition assessments can range from the broader landscape scale (Level I) using remotely sensed data down to intensive on-site measurements (Level III), which are typically the most accurate. Rapid assessments are an intermediate approach to determine the general condition of individual wetlands by using easily measured field indicators that are linked to specific stressors. Wardrop et al. (2007) found that using a rapid assessment approach significantly shifted sites downward from the landscape assessment into lower condition categories across all wetland types. This resulted from the increased number of stressors identified by the rapid assessment that were missed by the Level I assessment.

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Landscape Ecology

Connectivity – A Critical Component of Hydrological and Ecological Flux Assessments

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Quantifying hydrologic and ecological connectivity has contributed to understanding of transport and dispersal processes and assessments ecosystem degradation or potential for restoration. However, there has been little synthesis across disciplines. The growing field of ecohydrology and recent recognition that losses of hydrologic connectivity are leading to a global decline in biodiversity underscore the need for a unified connectivity concept. One outstanding need in hydrology and ecology is a way to quantify directional connectivity that is consistent, robust to variations in sampling, and transferable across scales or environmental settings. Understanding connectivity in a particular direction (e.g., streamwise, along- or across-gradient, between sources and sinks, along cardinal directions) provides critical information for predicting contaminant transport, planning conservation corridor design, and understanding how landscapes or hydroscapes respond to directional forces like wind or water flow. In my presentation, I synthesized progress on quantifying connectivity and described a new strategy for evaluating directional connectivity that benefits from graph theory applications in ecology and percolation theory applications in hydrology. The new directional connectivity index (DCI) is essentially a graph-theory based, multiscale sinuosity index that is generalizable to a range of different structural and functional connectivity applications. It exhibits minimal sensitivity to image rotation or resolution within a given range and responds intuitively to progressive, unidirectional change. Connectivity-orientation curves (i.e., directional connectivity computed over a range of headings) provide a quantitative, information-dense representation of environmental structure that can be used for comparison or detection of subtle differences in the physical-biological feedbacks driving pattern formation. Case-study application of the DCI to the Everglades in south Florida revealed that loss of directional connectivity occurs more rapidly and is a more sensitive indicator of declining ecosystem function than other measures (e.g., habitat area) used previously. The DCI was also closely correlated to the integral connectivity scale commonly used in hydrology, which is a good predictor of flows and fluxes. Thus, in the Chesapeake Bay watershed, the DCI shows promise as a means of understanding how the arraignment of landscape features impacts fluxes from watersheds to tributaries. Overall, directional connectivity can serve as an early-warning indicator of environmental degradation and as a planning tool or performance measure for conservation and restoration efforts.

RELATED RESEARCH:

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Linking Landscape Scale Patterns of Nutrient and Sediment Sources and Buffers to Hydrologic Connectivity

Matt Baker, University of Maryland – Baltimore County

Landscape ecology seeks to link pattern and process across spatial scales. The discipline is widely known for emphasis on connectivity, fragmentation, and pattern analysis of categorical maps, which often form the basis for conservation planning and reserve design.

Connectivity applied to hydrologic transport in watersheds is perhaps best conceived as a directed network, where terrain is a critical input and key elements include hillslope, riparian, and stream channel transitions, shallow subsurface flow paths, instream transport, and floodplain interactions. Various geographic techniques may be used to represent connectivity, linking forms of functional distance to hydrologic response. Whereas shallow subsurface storage appears important for understanding variation in surface-subsurface interactions, studies suggest that the landscape-stream transition is most critical for understanding surface water transport. Thus, an often overlooked yet fundamental step in watershed analysis involves accurate stream mapping. Previous studies suggest that increasing the resolution of stream maps has large impacts on implicit connectivity and resulting inferences about hydrology and water quality. For example, we distinguished buffered and unbuffered landscape transport from instream transport (measured from 1:24000 stream maps) for cropland sources of nitrogen within the SERC study watersheds. Model comparison suggests that accounting for riparian buffer prevalence produced models far superior to those using source proportions alone or those involving sources and stream transport distance. Buffers were 1-2 orders of magnitude more effective than instream transport at removing nitrate depending on their physiographic context. Our results suggest that, in aggregate, low order stream removal of nitrate is far less substantial than field studies or regional analyses (e.g., SPARROW) suggest.

However, how one accounts for landscape-stream connectivity fundamentally alters interpretation of the results, as most regional models rely on much coarser stream maps. Further refinement of geographic measures may include multi-direction flow fields and buffer characterizations relative to network position, as well as exploration of such measures in watersheds with varying degrees of connection to subsurface reservoirs. In each case, geographic representation of watershed connectivity and observed patterns of water quality allow us to test assumptions about aggregate watershed function.

Important research related to my topic:

Besides the ongoing collaborative work between myself, Don Weller, and Tom Jordan (i.e., Baker et al. 2006, 2007 Land Ecol., Weller et al. 2011 Ecol Apps.), many groups are interested in the watershed connectivity question working from a variety of disciplinary perspectives and in many different contexts. Among those worth mentioning are the various SPARROW modeling groups across the US and Brian McGlynn's lab at Montana State University who think about watershed stream connections, Art Gold and Q Kellog's lab at URI and Philippe Vidon at SUNY ESF who think about spatial variation in riparian hydrologic properties, and Andrew Elmore at UMCES-AL who is working on developing estimates of buried streams in Maryland.