The Ecological Consequences of Changing Land Use for Running Waters, with a Case Study of Urbanizing Watersheds in Maryland

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ABSTRACT

The concept of "Smart Growth" has emerged as a response to the trend of increasing low-density sprawl and to the limited policy instruments available for controlling it. In the U.S., the spatial pattern of this land conversion has tended to be one of "exurban sprawl," in which the rate of increase in newly developed land greatly exceeds the rate of population growth, and the location of this development in the rural-urban fringe has led to increases in vehicle miles traveled *per capita*, with its attendant deleterious impact on air quality. Because streams, rivers, and groundwater integrate the landscape, providing a conduit for the transfer of energy and material from terrestrial habitats into freshwater systems, they are particularly vulnerable to environmental impacts from land use change. To determine what these impacts may be and how we might mitigate them requires an ability to predict the rate and pattern of development and its environmental impacts. It also requires that the scientific, public and private sectors work together to identify land use polices that will protect fresh waters.

We formed an interdisciplinary team of academic and government scientists and policy makers to study and eventually develop predictive models for how land use change will affect stream ecosystems in urbanizing watersheds. We asked: What is the existing relationship within a historical context between land use and stream ecosystem structure and function for urbanizing watersheds? How will land use change over the next 20 years and what are the ecological consequences of these changes within running-water ecosystems?

In this paper, we begin by presenting a conceptual model of the general relationship between land use change and the flow of water to and within streams *(hydrology)*, the shape and dynamics of stream channels *(geomorphology)*, and the ecological condition of streams *(ecosystem structure and function)*.

We then identify four urbanizing watersheds just north of Washington, D.C. to use as a case study and describe the type of empirical work that is required to fully develop forecasting models. Third, we present very preliminary forecasts to illustrate how one of our study watersheds may change over the next 20 years. We suggest that if the patterns of population growth and movement (which influence land use change) continue as they are today, the watershed will be completely built out by 2020 and the ecological impacts will likely be significant. Encouraging development in areas of the watershed that are already partially developed ("priority funding areas" program), could result in exactly the same outcome. If, however, conservation easements can be secured for large undeveloped areas, the ecological impacts could be quite different. We close with a focus on efforts within a single county (Montgomery County) that demonstrate how the merger of state of the art science, proactive policies, and creative public outreach can make a difference in watershed protection.

INTRODUCTION

Human-induced changes to natural landscapes have been identified as one the greatest threats to freshwater resources.[1] Land use influences sediment, hydrologic, and nutrient regimes, which in turn influence aquatic biota and ecological processes in fresh waters.[2] The ecological consequences of land use change can persist for many decades,[3] and it is not yet clear if the ecological damage can be reversed. Demographic trends and human activities are such that the rate of urbanization of the landscape is increasing rapidly and there are no signs that this pattern of increasing human alteration of the landscape will slow.

Land use change in developed countries largely takes the form of conversion of land from agriculture and forests to residential use. In the U.S., the spatial pattern of this conversion has tended to be one of "exurban sprawl" in which

[1] Dale, V.H., S. Brown, R.A. Haeuber, N.T. Hobbs. N. Huntly, R.J. Naiman, W.E. Riebsame, M.G. Turner and T.J. Valone. 2000. Ecological principles and guidelines for managing the use of land. *Ecological Applications* 10, 639-670; See also, Sala, O. E. et al. 2000. Global biodiversity scenarios for the year 2100. Science 287, 1170-1774.

land is fragmented at a rate of two to three times the rate of population growth, and the number of vehicle miles traveled increases at four to five times the population growth rate. Because development generally occurs in areas well outside of urban centers, low-density sprawl is often serviced by septic fields rather than sewage treatment plants, increasing per capita nutrient loadings and fecal coliform discharges into the aquatic environment.[4] In addition, this spatial pattern can be expected to have consequences for carbon sequestration as vegetative cover is lost, and consequences for carbon emissions as automobile usage increases.[5]

POLICY TO MANAGE LAND USE: A MOTIVATION FOR RESEARCH

In the face of continued growth pressures, increasing road congestion, school crowding, and the rising costs of providing public services to fragmented land uses, many local governments throughout the U.S. instituted growth control measures in the 1980s and 1990s. Examples of these measures include re-zoning rural land to larger minimum lot sizes and withholding public utilities (*e.g.*, public water and sewer) from that land, both of which raise the costs of development. These policy instruments are not direct controls. In fact, few direct controls on residential development are allowed, given the prohibition against "taking without just compensation," otherwise known as the "takings" clause in the U.S. Constitution. Localities can and do place moratoria on building in areas without sufficient road or school capacity, but by law these moratoria are temporary until new infrastructure can be built.

In the last few years, the concept of "Smart Growth" has emerged as a response to the national trends of increasing low-density sprawl and to the limited policy instruments available for controlling it. Although not precisely defined, Smart Growth encompasses those potential policy instruments that could be used by local and state governments to redirect future growth away from contiguous areas of open space and toward areas that already possess considerable residential infrastructure[6] (see www.smartgrowth.org). Maryland's newly implemented Smart Growth program contains two major features.[7] The first is the targeting of growth areas, outside of which state funds to support infrastructure will not be forthcoming, but within which in-fill development is encouraged. The second is the outright purchase or the purchase of development rights of contiguous, undeveloped land by localities or states, potentially with subsidies from the federal government, to be held as undeveloped lands in perpetuity.

Before the advent of Smart Growth policy, growth controls were only occasionally motivated by environmental concerns. A few environmentally sensitive areas, such as the Critical Areas surrounding the Chesapeake Bay, were set-aside in the 1980s for protection. For the most part, growth controls have been motivated by the desire of localities to control congestion and the costs of providing public services. Smart Growth ostensibly addresses both

[2] Naiman, R.J., J.J. Magnuson, D.M. McKnight and J.A. Stanford. *The freshwater imperative.* Island Press, Washington, D.C., 1995; See also, Palmer, M. A. *et al.* 1997. Biodiversity and ecosystem function in freshwater sediments. Ambio 26, 571-577; See also, Palmer, M. A. *et al*. 2000. Linkages between sediment biota and life above sediments: potential drivers of biodiversity and ecological processes. *BioScience* 50, 1062-1068; See also, Gleick, P. H. *The world's waters: The biennial report on fresh water resources.* Island Press, Washington, D.C, 1998.

[3] Harding, J.S., E.G. Benfield, P.V. Bolstad, G.S. Helfman and E.B.D. Jones. 1998. Stream Biodiversity: the ghost of land-use past. *Proc. Nat. Acad. Sciences*. 95, 14843-14847; See also, Scully, N.M., P.R. Leavitt and S.R. Carpenter. 2000. Century-long effects of forest harvest on the physical structure and autotrophic community of a small temperate lake. *Canadian Journal of Fisheries and Aquatic Science* 57, 50-59.

[4] Appleyard, S. 1995. Impact of urban development on recharge and groundwater quality in a coastal aquifer near Perth, Western Australia. *Hydrogeology Journal* 3, 65-75.

[5] Brown, S., J. Sayant, M. Cannell and P.E. Kauppi. 1996. Mitigation of carbon emission to the atmosphere by forest management. *Common Wealth Forestry Review* 75, 80-91; See also, Silver, W.L., R. Ostertag and A.E. Lugo. 2000. The potential for carbon sequestration through reforestration of abandoned agriculture and pasture lands. *Restoration Ecology* 8, 394-407.

[6] Duany, E.P-Z. and J. Speck. *Suburban Nation: the Rise of Urban Sprawl.* North Point Press,, N.Y., N.Y., 2000.

environmental as well as public finance problems, yet little in the way of analysis of the ecological consequences of Smart Growth development has been pursued. It is worth considering at this point what criteria might be used if the new regime of growth controls were to be motivated solely on ecological criteria.

Streams, rivers, and groundwater integrate the landscape, providing a conduit for the transfer of energy and materials from terrestrial habitats into freshwater systems and ultimately the oceans. Given the projected trends toward increasing sprawl, scientists are faced with tough questions. How is land use linked to the health of rivers and streams? Will our waterways be clean enough to meet even the minimum standards of the Clean Water Act (*i.e.*, fishable, swimmable)? Will so-called "Smart Growth" protect or improve the ecological health of watersheds? What ecosystem services do our waterways provide that are essential for us to protect, and what steps can be taken to ensure this protection?

The urgency of these questions requires an ability to predict the rate and pattern of development as well as its environmental impacts. It requires that the scientific, public, and private sectors work together to identify land use polices that will protect ecosystem services. The science underlying projections of how the amount, location, and form of future development of land may impact streams and rivers needs to be center-stage in influencing public policy in this arena. Scientists are increasingly being asked to provide policy makers and managers with projections of future environmental impacts assuming different rates of population growth, shifts in preferences and technology, and changes in the regulatory environment. Such predictions require an understanding of the complex relationships among the behavior of economic agents, and the regulatory constraints and incentives governing this behavior, resulting land use changes, and the ultimate effect on ecological processes.[8]

To develop this understanding, teams composed of scientists, managers, and policy makers must be assembled to integrate knowledge: (1) economists to forecast the amount and spatial pattern of land use change based on policy scenarios and projections of changes in demographics and real incomes; (2) hydrologists to link changes in land use to altered flow regimes; (3) geomorphologists to link land use change and hydrological change to changes in the morphology and dynamics of streams; (4) ecologists to link changes in land use, hydrology, and geomorphology to ecological processes; and (5) land use planners to take into account this new information in revising regional land use plans (Figure 1). Solving the "land use -ecological impacts problem" requires intensive collaborations among professionals from extremely diverse fields, who quickly find they are not only plagued with different disciplinary languages, but their efforts are challenged with critical knowledge gaps, disciplinary mismatches in modeling approaches and geographic and temporal scales, and considerable propagation of uncertainties.[9] Promises of new and expanded data bases, as well as more advanced mathematical and computing tools, offer hope that forecasting the effects of land use change on the future of fresh waters may be on the horizon.

7 Maryland Department of Planning. *Smart Growth in Maryland*. http://www.mdp.state.md.us/smartgrowth/index.html, 2001.

8 Nilsson, C., Pizzuto, J.E., Moglen, G.E., Palmer, M.A, Stanley, E.H., Bockstael, N.E., and Thompson, L.C., (in preparation). "Ecological Forecasting and Running-Water Systems: Challenges for Economists, Spatial Analysts, Hydrologists, Geomorphologists, and Ecologists." submitted to Ecosystems.

9 Benda, L. *et al.* Avoiding train wrecks in interdisciplinary problem solving. BioScience (in revision).

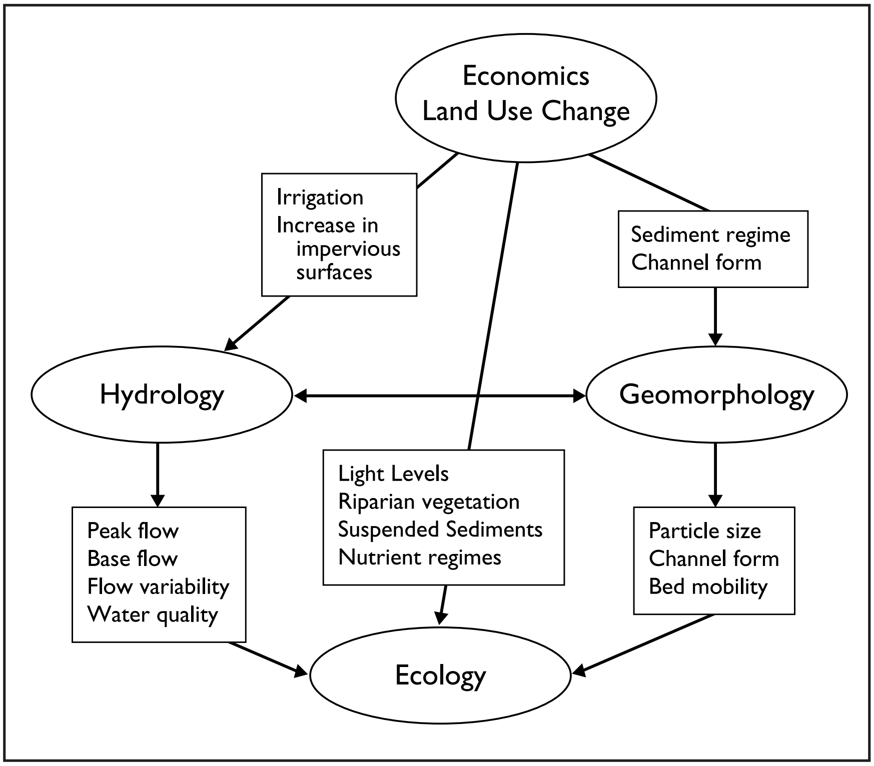

Figure 1 Conceptual model for the effects of land use change on stream and riverine ecosystems. The major mechanisms by which land use directly or indirectly (via hydrology or geomorphology) influences the ecological conditions are shown inside the boxes.

STUDYING THE LINK BETWEEN LAND USE AND FRESH WATERS

We have formed an interdisciplinary team to study and eventually develop predictive models for how land use change will affect stream ecosystems in urbanizing watersheds. Our goals are to ask: (1) What is the existing relationship within a historical context between land use and stream ecosystem structure and function for urbanizing watersheds? and, (2) How will land use change over the next 20 years and what are the projected ecological consequences of these changes within running-water ecosystems?

Our work is proceeding along three lines. First, we identified and conceptually modeled the general relationship between land use change and the flow of water to and within streams (hydrology), the shape and dynamics of stream channels (geomorphology), and the ecological condition of streams (ecosystem structure and function) (Figure 1). This part of our work was influenced by an international team of scientists who participated in three workshops held at the National Center for Ecological Analysis and Synthesis in Santa Barbara, California in 2000 and 2001. Participants brought expert knowledge to the table to synthesize current understanding of how land use influences running-water ecosystems.[10]

[10] NCEAS. Hydrological Regimes website. www.ucsb.nceas.edu, 2001.

Second, we identified four urbanizing watersheds just north of Washington, D.C. to use in an intensive empirical study. These watersheds were selected because they differ in their extent and pattern of development and drain into the highly valued Chesapeake Bay. Our empirical work involves two large efforts: 1) the collection of new and existing data on land use and the ecological conditions of these watersheds; and, 2) the assembly of new and existing data on human-induced changes in land use within these watersheds over the past decade.

Third, we are using the findings from the empirical study in conjunction with new or existing theory to develop models to predict the following: the amount and pattern of future growth (changes due to development) in these watersheds; changes in hydrology and geomorphology that will result from land use changes; and, the future ecological structure and function of streams within these watersheds. This phase is in the initiation stages – we are currently developing quantitative forecasting models. We will be using a forecasting approach in which predictions of spatial pattern, timing, and amount of land use change will be generated from economic models of development. Land use projections will then be used as input into hydrologic models that describe future flow regimes, and information on land conversion and hydrology will be used to forecast channel form, sediment supply, and particle sizes on the streambed. Finally, all of this information will be linked to models predicting various aspects of ecological change. In this paper, we use some highly simplified assumptions and models to produce "forecasting illustrations" of land use change for the year 2020 for one of our study watersheds. We refer to these as "illustrations" because they are meant only to demonstrate our process – the model development to generate actual forecasts will take several more years.

THE EFFECTS OF LAND USE CHANGE

Land use change occurs largely through human actions affected by economic incentives and constrained by regulation. These changes can have both direct and indirect effects on freshwater ecosystems-the former have immediate ecological impacts (*e.g.*, destruction of wildlife habitats), while the latter have impacts that are transmitted via altered flow or sediment transport patterns (*e.g.*, lower productivity due to increasing turbidity). Transmission of these hydrologically and geomorphically mediated impacts sometimes involves long lag times, but it can also occur quite quickly.

ECONOMIC BEHAVIOR AND LAND USE CHANGE

Although natural succession and climatic events are important forces in altering land cover over time, the predominant cause of land cover/land use change is human intervention. Actions that induce change take different forms in different parts of the world. In much of the U.S. (including our study area), and especially over the last few decades, the principal form of change has been the transformation of forests and farms into residential subdivisions, often with relatively large lot sizes.

To be of most use to environmental scientists, forecasts of future land use change must include the amount of change, its timing, and its spatial pattern. Until recently, economists have pursued two quite distinct types of analysis of residential development. Regional or macro-economic theoretical and empirical studies have attempted to explain changes in aggregate amounts of development and average housing prices either at a regional or national level. This type of analysis focuses on the temporal dynamics of the problem but abstracts the spatial dimension. In the short term, movements in the U.S. economy (interest rates, construction costs), together with the regional economy's competitiveness in national and world markets, affect rates of residential development. In the long term, as individuals have the ability to adjust to changing circumstances, demographic changes and migration patterns play an increasingly important role.[11] In both the short and long term, factors (including public policies) that affect the supply of land for housing will also exert an important effect. These regional and/or macro models are extremely important for explaining the total amount of development but have not been well integrated with spatially explicit models of micro-level decision making.

Microeconomic analysis of regional housing markets attempts to explain the variation in housing prices (and indirectly the value of land in residential use) within a region or land market. The spatial pattern of development has typically been addressed in theoretical models-the principal one being the bid-rent model of Alonso,[12] Muth,[13] and Mills[14] in which increases or decreases in commuting costs to one or more central business districts determine outcomes. The equilibrium model can be solved for both prices and densities of development, where the solution is characterized by concentric rings of decreasing density of development around city centers. While robust in explaining much of the early development around cities, this model is not very effective in explaining the patterns of fragmented, low-density sprawl that we have seen over the past few decades. The empirical microeconomics literature on price variation has typically employed hedonic property value models in which market prices are regressed on property characteristics. The approach has a theoretical underpinning[15] but all that can be observed is the result of many forces interacting. Nonetheless, hedonic models have been used to determine statistically the characteristics of properties that matter to people.

Given the importance of land use change, there are growing attempts to redress the shortcomings of the above models. One such approach, taken in this study, attempts to embed micro-economic models of decision making into more comprehensive and realistic spatial models and to integrate the spatial model with regional economic models of aggregate changes.[16] The owner of each undeveloped parcel of land is viewed as taking into account the various signals the market, as constrained by regulations, provides in deciding on the future of his/her parcel. In general, the owner of an undeveloped parcel faces three alternatives in each time period – to begin the process of development, to sell the development rights and preserve the parcel in perpetuity, or to post-

[11] Mills, E. and B. Hamilton. *Urban Economics*. Addison-Wesley, New York, 1994; See also, DiPasquale, D. and W. Wheaton. *Urban economics and real estate markets*. Prentice Hall, Englewood Cliffs, N.J., 1996.

[12] Alonso, W. *Location and land use*. Harvard University Press, Cambridge, Massachussetts, 1964.

[13] Muth, R. *Cities and housing*. University of Chicago Press, Chicago, 1969.

[14] Mills, E. *Studies in the structure of the urban economy*. Johns Hopkins University Press, Baltimore, MD, 1982.

[15] Rosen, S. 1974. Hedonic processes and implicit markets: product differentiation in pure competition. *J. Political Economy* 82, 34-55.

[16] Bockstael, N.E. 1996. Economics and Ecological Modeling: The Importance of a Spatial Perspective. *American Journal of Agricultural Economics* 80, 1168-1180; See also, Irwin, E. and N. Bockstael in *Advances in Spatial Econometrics* (ed. Anselin, L. and R. Florax, eds) (In press, 2002); See also, Irwin, E. and N. Bockstael. Interacting Agents, Spatial Externalities and the Evolution of Land Use Change. *Journal of Economic Geography* (In press, 2001).

pone either terminal decision and continue using the parcel in its current open space use. Once either the first or second decision is made, the parcel's future is no longer in question.

Factors that affect the decision – or put another way, the optimal timing of development or preservation – are factors that make a parcel more or less valuable in residential use vs. as open space use. There will also be personal factors that affect such a decision, but these cannot be modeled and must be treated as stochastic. Factors such as the characteristics of a parcel that make it valuable in residential use, factors that affect its value in farming or forestry, and factors that affect the costs of development of a parcel will enter into the decision. Incorporated into the model are factors that can be altered by direct and indirect policies – such as the lot sizes allowable by zoning, the provision of public utilities, the distances along publicly supplied roads, the terms of agricultural preservation programs that support public purchase of development easements, the location of publicly supplied open space, etc.

The importance of the various factors in affecting the value of land in different uses and the role of public policy in altering those factors are, by and large, research questions. The approach used in this paper as an illustration of the research process by which land use change is predicted employs historical data to estimate the parameters of the relationships influencing the change. The way in which factors that describe a land parcel and its location in the landscape affect its value in residential use is captured through estimation of hedonic models of residential property values. Competing risk hazard models are employed to estimate the parameters of models that attempt to capture the optimal timing of development or preservation, based on the predicted value in residential use, as well as factors that affect the value in other uses and the costs of conversion. These models help explain the order in which land parcels are converted over time. The rate of conversion is driven by regional aggregate demand for and supply of land for housing. With estimated parameters in hand, the models can be used to forecast the future, under scenarios in which different policies are adopted and/or different rates of population and income growth are forecast.

HYDROLOGICALLY-MEDIATED EFFECTS OF LAND USE CHANGE

The intimate links between the land and surface water in streams and rivers occur largely out of sight: movement of water and nutrients from groundwater through the deep streambed where groundwater and surface waters mix (hyporheic zone) into channels and in the reverse direction have huge impacts on the biological processes occurring within these waterways.[17] Additionally, more visible "above ground" links between the land and running waters have huge impacts on biological processes.[18] For example, overbank flows that inundate floodplains and riparian zones adjacent to running waters may determine the form and rate of a diverse array of ecologically important processes. Floodplain inundation may be required to initiate biogeochemical

[17] Boulton, A., S. Findlay, P. Marmonier, E.H. Stanley and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics* 29, 59-81.

[18] Lake, P.S. *et al.* 2000. Global change and the Biodiversity of Freshwater ecosystems. *Bioscience* 50, 1099-1107.

transformations that ensure long-term survival of diverse riparian vegetation through flow-mediated dispersal of seeds and opening of soil patches for seed germination.[19]

Because of the complex hydrological linkages between groundwater, surface water, and riparian zones, the impacts of changes in land use are also quite complex. Any change that influences the movement of water between land, soils, groundwater, hyporheic zones, surface waters, and floodplains has the potential to have dramatic ecological consequences. For example, in arid regions the reduction in transpiration caused by tree clearing causes saline water tables to rise and pollute surface waters.[20] Urban development tends to have the opposite effect, lowering water tables because the watershed is paved with impervious surfaces such as roads, buildings and carparks that reduce infiltration. Infiltration rates will be higher in areas of low density cluster development than in highly urbanized centers unless there is considerable investment in artificially constructed retention ponds and groundwater recharge sites.[21] Runoff from warm paved areas may cause thermal pollution in addition to delivering a plethora of organic and inorganic pollutants to the stream network.[22] Thus, we stress that an alteration in land use that influences *any* part of the visible or invisible water network (*e.g.*, the water table and thus, groundwater flows, overland run-off, overbank flows, etc.) may have important ecological consequences. Focusing on how land use influences mean flows, peak flows, or baseflows in streams is far too simplistic. Even if peak flows and baseflows are within acceptable ranges from an ecological standpoint, if groundwater residence times are too short and/or the exchange of water between the hyporheic zone and the groundwater environment is greatly reduced, nutrients may reach unacceptable levels in river channels and estuaries and biodiversity may be significantly reduced.

Surface flows are far easier to monitor than groundwater exchanges and thus most research linking ecology and hydrology has focused on water in the channel. Certainly, the importance of the flow regime in shaping aquatic communities is well-recognized in stream ecology; both flood flows and low flows have dramatic effects on the structure of biotic communities and rates of ecological processes.[23] Several striking examples of the importance of the natural flow regime include major changes in ecosystems caused by the introduction of flow regulation schemes.[24]

To date, our work has focused on the impacts of land use change on peak flows, in part because of the high quality hydrologic models that are available for predicting peak flows. Accurate measurement and prediction of low flows is limited, particularly with respect to how low flow behavior is influenced by land use change or changes in water appropriation policies. The inability to quantify changes in low flow behavior is problematic because the timing, duration, and spatial extent of low and no flow conditions can dramatically alter ecosystem dynamics, particularly when drought conditions are novel to a system and biota lack adaptations for resisting or recovering from desiccation.

[19] Stromberg, J.C., D.T. Patten, and B.D. Richter. 1991. Flood flows and the dynamics of Sonoran riparian forests. Rivers 2, 221-235; See also, Messina, M.G. and W.H. Conner. (eds.) *Southern Forested Wetlands Ecology and Management*. Lewis Publishers, 1998.

[20] Salama, R., T. Hatton and W. Dawes. 1999. Predicting Land Use Impacts on Regional Scale Groundwater Recharge and Discharge. *Journal of Environmental Quality* 28, 446-460.

[21] Tourbier, J.T. 1994. Open space through stormwater management: helping to structure growth on the urban fringe. Journal of Soil and Water Conservation 49, 14-21; See also, Ellis, J.B. 2000. Infiltration systems: a sustainable source-control option for urban stormwater quality management? *Journal of the Institute of Water and Environmental Management* 14, 27-34.

[22] Van Buren, M., W. Watt, J. Marsalek and B. Anderson. 2000. Thermal enhancement of stormwater runoff by paved surfaces. *Water Research* 34, 1359-1371.

[23] Poff, N.L. and K. Nelson-Baker. 1997. Habitat heterogeneity and algal-grazer interactions in streams: explorations with a spatially explicit model. *Journal of the North American Benthological Society* 16, 263-276; See also, Stanley, E.H., Fisher, S.G. and Grimm, N.B. 1997. Ecosystem expansion and contraction in streams. *BioScience* 47, 427-435; See also, Puckridge, J.T., F. Sheldon, K.F. Walker and A.J. Boulton. 1998. Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49, 55-72; See also, Richter, B.D. and H.E. Richter. 2000. Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. *Conservation Biology* 14, 1467-1478.

Since low flows may be as important in regulating biodiversity and ecological processes in streams as are floods, new approaches for predicting flows at all stages are required.[25]

GEOMORPHICALLY-MEDIATED EFFECTS OF CHANGING LAND USE

Land use interacts with altered flow regimes to influence geomorphic factors that are critically important ecologically. Under scenarios of changing land use, the geomorphologic factors of most interest from an ecological perspective for streams like those in the Chesapeake Bay region include changes in the magnitude and frequency of bedload transport, increased suspended load, changes in bed particle size (not only mean particle size but also variability in particle sizes, as well as changes in the sizes of the largest particles on the streambed), and larger-scale features such as channel cross-sectional and planform geometry. If the availability of geomorphic microhabitats is reduced by land use changes, this can have dramatic consequences for the abundance and diversity of instream biota.[26] To fully comprehend the ecological consequences of altered land use requires linking information from hydrological models (*e.g.*, magnitude and frequency of peak flows) to geomorphic information (*e.g.*, size and mobility of the largest particles on the bed) and then to knowledge of faunal attributes (*e.g.*, ability of fauna to utilize flow refugia during floods).[27]

It is difficult to predict changes in stream morphology and dynamics in any watershed. We must take output from hydrological models and forecast particle size distributions using bedload transport equations that predict the movement of individual size fractions.[28] Boundary conditions that specify the volume flux and size distribution of the sediment supply are also needed, as well as initial conditions that specify the distribution of particle sizes throughout the watershed at the beginning of the time period to be simulated. These are daunting requirements, but they must be met if the geomorphic changes caused by land use are to be accurately assessed. Progress will require improvements in our understanding of sediment transport theory, as well as detailed fieldwork to calibrate models. Recent studies demonstrate, for example, that the fraction of the streambed in motion at different flows can be estimated, but only if detailed, site-specific observations are available for calibration.[29]

The interaction between flow and bed composition can exert significant control over biological processes that occur in streams.[30] The three most ecologically important geomorphic factors include substrate size and mobility, suspended sediment concentrations, and channel form. Because each of these three variables is so ecologically important, problems with effective quantification and modeling (particularly as a function of land use changes) are currently a central focus of our group work. Because urbanization is one of the more significant land use changes in our study area, the effects of urbanization also play a central role in our study. Urbanization can lead to increased channel

[24] Rosenberg, D.M. and V.H. Resh. *Freshwater biomonitoring and benthic macroinvertebrates.* Chapman and Hall, Routeledge, 1993; See also, Jansson, R., C. Nilsson, M. Dynesius and E. Anderson. 2000. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. *Ecological Applications* 10, 203-224; See also, Nilsson, C. and K. Berggren. 2000. Alterations of riparian ecosystems resulting from river regulation. *BioScience* 50, 783-792.

[25] Nilsson, C., Pizzuto, J.E., Moglen, G.E., Palmer, M.A, Stanley, E.H., Bockstael, N.E., and Thompson, L.C., (in preparation). "Ecological Forecasting and Running-Water Systems: Challenges for Economists, Spatial Analysts, Hydrologists, Geomorphologists, and Ecologists." submitted to Ecosystems.

[26] Allan, J.D. *Stream ecology: structure and function of running waters.* Chapman & Hall, London, 1995; See also, Gordon, N.D., T.A. McMahon and B.L. Finlayson. *Stream Hydrology: an Introduction for Ecologists.* Wiley, Chichester, England., 1992.

[27] Biggs, B.J.F., M.J. Duncan, S.N. Francoeur and W.D. Meyer. 1997. Physical characterization of micro-form bed cluster refugia in 12 headwater streams, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 31, 413-422; See also, Matthaei, C.D. and C.R. Townsend. 2000. Long term effects of local disturbance history on mobile stream invertebrates. *Oecologia* 125, 119-126.

area,[31] and possibly incision,[32] changes that influence the water surface elevation during high discharges, which in turn influences bed mobility and other significant ecological variables.

ECOLOGICAL EFFECTS OF CHANGING LAND USE

Healthy freshwater ecosystems are those in which the ecological structure and function is sufficiently unperturbed so that biotic assemblages thrive and ecological processes continue unimpeded. The ecological structure of running-water systems includes the number and diversity of riparian plants, aquatic invertebrates, and fish, as well as various measures of water quality (*e.g.*, dissolved oxygen, nutrient concentrations). Further, ecologists consider the types and abundance of wood and riparian inputs as important structural attributes of running-water systems because they provide habitat and food for biota.[33]

Ecological function refers to ecological processes that are vital to the provision of ecosystem services (*e.g.*, the breakdown of organic material, the recycling of nutrients, primary production). Measurements of ecological function provide a different view of the state of ecosystems than do structural measures. Functional measures are dynamic and provide data by which different ecosystems may be compared even if the species abundance or composition varies. On the other hand, functional measurements are less routinely used and are rarely available from existing monitoring databases. Thus ecologists must often infer function based on structural measures.

To date, work on relating land use change to the ecological state of streams has been limited almost entirely to correlating structural measures of ecological condition to existing or historical land use patterns.[34] These correlations often use published data sources that were collected for water quality monitoring and assessment at large spatial scales.[35] Sampling sites are typically on major streams and/or tributaries that are inevitably responding to cumulative impacts of mixed land uses and an amalgam of environmental conditions (*e.g.*, climatic or geologic) making it difficult to attribute ecological state solely to changing land use.[36] Studies that examine a large number of sites (hundreds) can readily identify significant trends across the range of land use types, but they suffer from an inability to predict the ecological condition at any single location.[37] Thus, our understanding of how land use leads to ecological change in streams is qualitative and is derived in ignorance of the specific processes by which changing land use alters the ecological condition at a site. This is particularly true for our understanding of how the ecological states of streams are mechanistically linked to land use change via *specific hydrologic and geomorphic effects.*

We suggest that several factors are of preeminent (1st order) importance (Figure 2). First, modification of the watershed in ways that alters riparian vegetation may influence biota as well as the entire carbon-nutrient cycle. In the Chesapeake Bay region, the dominant species of plants contributing litter inputs to streams has changed dramatically over the last 300 years. However, as agricultural fields were first abandoned and then reclaimed, many of the

[28] Wilcock, P.R. 1998. Two-fraction model of initial sediment motion in gravel-bed rivers. *Science* 280, 410-412.

[29] Wilcock, P.R. 1997. *A method for predicting sediment transport in gravel-bed rivers. Misc. Report to the U.S. Forest Service*; See also, Wilcock, P.R. and B.W. McArdle. 1997. Partial transport of a sand/gravel sediment. *Water Res. Res.* 33, 235-245.

[30] Hart, D.D. and C.M. Finelli. 1999. Physical-biological coupling in streams: the pervasive effects of flow on benthic organisms. *Annual Review of Ecology and Systematics* 30, 363-395; See also, Cardinale, B.J., C.M. Swan, M.A. Palmer, S. Brooks and N.L. Poff. The influence of habitat heterogeneity on the rates of ecological processes in a stream ecosystem. *Ecology* (2002, In press).

[31] Hammer, T.R. 1972. Stream channel enlargement due to urbanization. *Water Res. Res.* 8, 1530-1540; See also, Pizzuto, J.E., W.C. Hession and M. McBride. 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. *Geology* 28, 79-82.

[32] Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26, 407-417.

[33] Gregory, S.V., F.J. Swanson, W.A. McKee and K.W. Cummins. 1991. An ecosystems perspective of riparian zones: focus on links between land and water. *BioScience* 41, 540-551; See also, Naiman, R.J. and H. Decamps. 1997. The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics* 28, 621-658.

[34] Cole, J.J., G.M. Lovett and S. Findlay. *Comparative analyses of ecosystems: patterns, mechanisms, and theories*. Springer-Verlag, New York, N.Y., 1991.

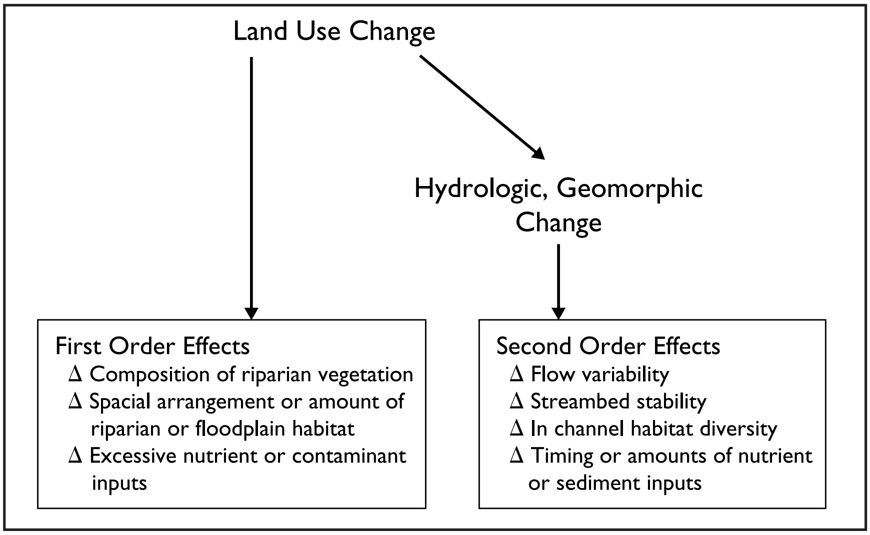

Figure 2 The primary factors that link land use and the ecological conditions of fresh water streams and rivers according to their assumed importance. First order factors are those that current research suggests will have the most profound or immediate impacts; second order factors are also important but may act more slowly or lead to less damage.

dominant plants were able to continue in their functional role in the watershed. Conversion of land to suburban/urban uses permanently alters the landscape in ways that eliminate these dominant plants in their functional roles, and this may influence the quality and quantity of food for invertebrates[38] that may in turn influence decomposition rates.[39]

Second, on the landscape scale, changes in the amount and arrangement of riparian and floodplain habitat have particularly dramatic influences on running-water ecosystems.[40] Stream and riparian zones not only serve as habitat but act as corridors for movement of biota. If these corridors are disrupted, this may lead to a series of ecological changes. For example, the patterns of dispersal and migration of species will be altered, causing invasion or isolation of species. In many parts of the world, a large portion of invaders will be alien species, causing interspecific competition and even loss of native species. Another effect is isolation of existing populations that will increase the risk of genetic depletion. Third, land use changes that magnify the influx of nutrients or contaminants (*e.g.*, from agriculture or commercial development) may have lethal or non-lethal effects on the biota and may alter rates of primary and secondary production.

Second-order factors that can influence ecological states when land use change occurs include a host of hydrologically and geomorphically-mediated effects (Figure 2). Changes in flow variability (*e.g.*, the timing and frequency of floods and droughts), streambed mobility (*i.e.*, how stable the bottom is for resident biota), sediment inputs and habitat diversity may have less immediate effects than habitat loss or contamination but they are well known to influence biodiversity.[41] Changes in light levels (*e.g.*, due to changes in water clarity or riparian vegetation) or nutrient inputs (*e.g.*, due to altered soils and run-off)

[35] Johnson, L.B., C. Richards, G.E. Host and J.W. Arthur. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. *Freshwater Biology* 37, 193-208; See also, Townsend, C.T., C.J. Arbuckle, T.A. Crowl and M.R. Scarsbrook. 1997. The relationship between land use and physiochemistry, food resources and macroinvertebrate communities in tributaries of the Taieri River, New Zealand: a hierarchically scaled approach. *Freshwater Biology* 37, 177-191; See also, Wang, X. and Z. Yin. 1997. Using GIS to assess the relationship between land use and water quality at a watershed level. *Environmental International* 23, 103-114; See also, Thornton, K.W., G.E. Saul and D.E. Hyatt. Environmental Monitoring and Assessment Program Office of Research and Development, Environmental Protection Agency, Research Triangle Park, NC, 1994.

[36] Strayer, D.L. et al. Effects of land-cover change on stream ecosystems: roles of empirical models and scaling issues. *Ecosystems*. (submitted).

[37] Wang, X. and Z. Yin, 1997; See also, Strayer, D.L. et al., (submitted); See also, Peters, R.H. 1986. The role of prediction in limnology. *Limnology and Oceanography* 31, 1143-1159.

[38] Cummins, K.W., M.A. Wilzbach, D.M. Gates, J.B. Perry and W.B Taliaferro. 1989. Shredders and riparian vegetation. *BioScience* 39, 24-30.

[39] Webster, J.R. and E.F. Benfield. 1986. Vascular plant breakdown in freshwater ecosystem. *Annual Review of Ecology and Systematics* 17, 567-594; See also, Webster, J.R., J.B. Wallace and E.F. Benfield in *Ecosystems of the World 22: River and Stream Ecosystems* (eds. Cushing, C.E., K.W. Cummins and G.W. Minshall). Elsevier, Amsterdam, 1995.

may influence primary and secondary production which in turn changes nutrient cycling.[42] Both the first order and second order factors may have profound impacts on stream ecosystems, but we know little about how and when these impacts are realized. As a consequence, these factors are currently the subject of a great deal of study as evidenced for example by the many projects being performed under the auspices of the U.S. federally-funded Water and Watersheds Program.[43]

CASE STUDY: URBANIZING WATERSHEDS IN MARYLAND

The Chesapeake Bay region is a 64,000 square mile drainage area that encompasses portions of the states of Maryland, Virginia, New York, West Virginia, Pennsylvania, Delaware as well as the District of Columbia, and includes as tributaries a number of large rivers (the Potomac, Patuxent, Susquehanna, Shenandoah). Land use change in the mid-Atlantic region of the eastern U.S. coastal states is currently dominated by conversion of forests and farms to developed, chiefly residential, uses. We are focussing on watersheds within the Chesapeake Bay region situated just north of Washington, D.C. in Maryland. Here, the trends in the spatial pattern of urbanization are characterized by additions of dwelling units both at the extensive (exurban sprawl) and the intensive (fill-in development) margins, with development rates rising dramatically over the past several decades. In the mid 1980s, approximately 60,000 acres were converted to developed uses per year as compared to about 130,000 acres/year during the mid 1990s. Rather than seeing compact additions to the edge of suburbia, new trends are toward low-density, fragmented sprawl in otherwise rural areas.

Our study watersheds that drain into the Potomac and Patuxent Rivers include the Northwest Branch, Paint Branch, and Hawlings Rivers, and Cattail Creek (Figure 3). The land use pattern in these watersheds is largely the result of their location relative to Washington, D.C. and the rapid increase in employment opportunities in that city since World War II. For several decades, residential growth occurred in waves of new construction that added development to the edge of the city, forming traditional suburbia – an ever-widening ring of residential land use around D.C. For the last few decades, however, there has been pressure for non-contiguous development in all but the extreme northwest sections of the Montgomery County where very large minimum lot-size zoning and a transferable development rights program has discouraged subdivision development.

Our study watersheds lie primarily within the Piedmont physiographic province, range in size from 13 to 28 square miles, and were selected because they are experiencing major changes in land use but with differing patterns. Three of these watersheds are in a single county (Montgomery County) but one of them (Cattail) lies in an adjacent county (Howard County) that has different growth and planning policies Differences in policy environments make the watersheds particularly interesting to study. All four watersheds have similar

[40] Naiman, R.J. and H. Decamps, 1997. The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics* 28: 621-658.

[41] Palmer, M.A. *et al.*, 1997; See also, Poff, N.L. and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46, 1805-1818.

[42] Sabater, F. *et al.* 2000. Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream. *Journal of the North American Benthological Society* 19, 609-620.

[43] Water and Watersheds Program, U.S.E.P.A. http://es.epa.gov/ncerqa/rfa/water.html

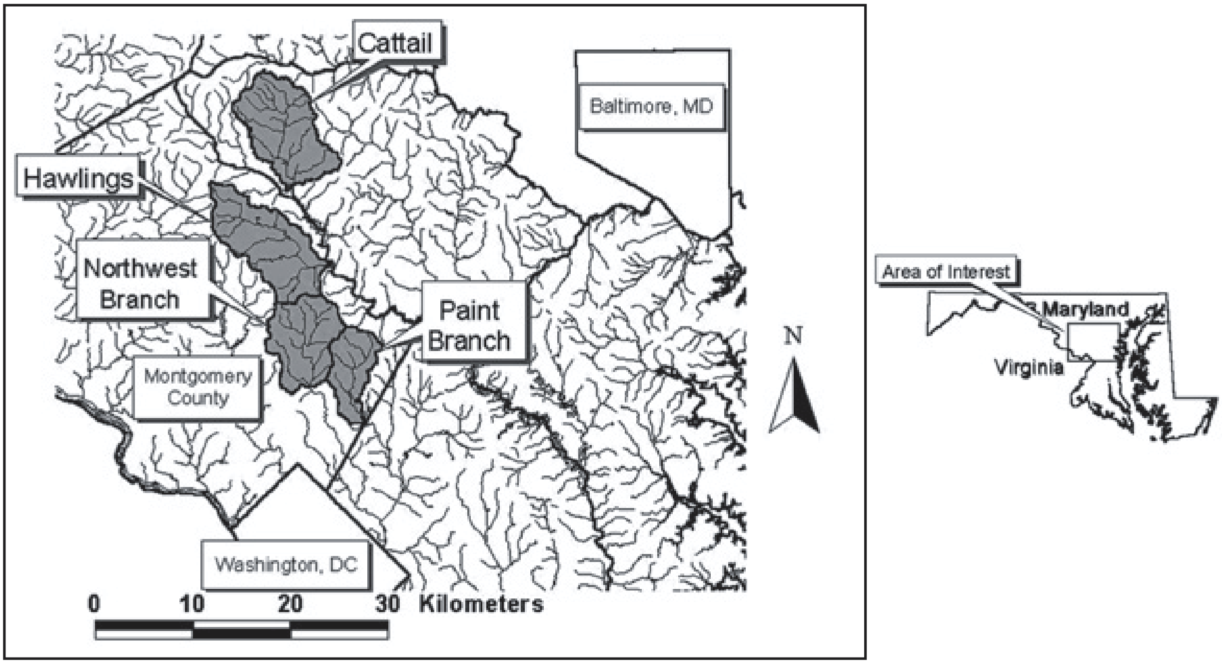

Figure 3 Geographic location and land use in the four Maryland study watersheds located just north of Washington, D.C. Northwest Branch, Paint Branch, and Hawlings are located within Montgomery County, while Cattail Creek is within a different jurisdiction: Howard County.

Table 1 Land use in four study watersheds in Suburban Maryland based on most recent data from the State of Maryland Office of Planning (1997).

Watershed	Residential	Agricultural	Forest	Other
Northwest Branch	48%	9%	28%	14%
Paint Branch	61%	9%	23%	7%
Hawlings	20%	41%	32%	6%
Cattail	14%	59%	25%	1%

amounts of land left in forest; however, Northwest Branch and Paint Branch have much more residential development whereas Hawlings and Cattail have more agricultural land (Figure 4, Table 1).

CURRENT WATERSHED CONDITIONS

In the summer of 2000, we began making field measurements to characterize the structure and functioning of each of the four study watersheds (Table 2). Our structural measurements include habitat assessments (diversity and amount of in stream habitat types, width and nature of the riparian vegetation, channel form), the abundance and diversity of aquatic invertebrates and fish, as well as, various measures of water quality (*e.g.*, dissolved oxygen, nutrient concentrations, etc.). We are also quantifying key ecological and geomorphic processes, including primary production, nutrient uptake rates, retentiveness, and streambed mobility.

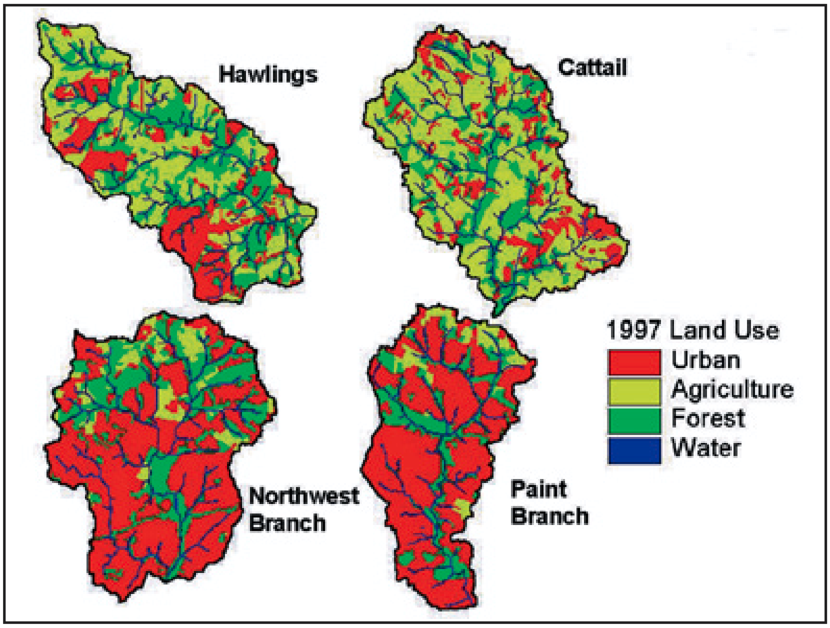

Figure 4 Land use distribution in the study watersheds as of 1997. Data are from the Maryland Department of Planning (http://www.op.state.md.us/data/mdview.htm).

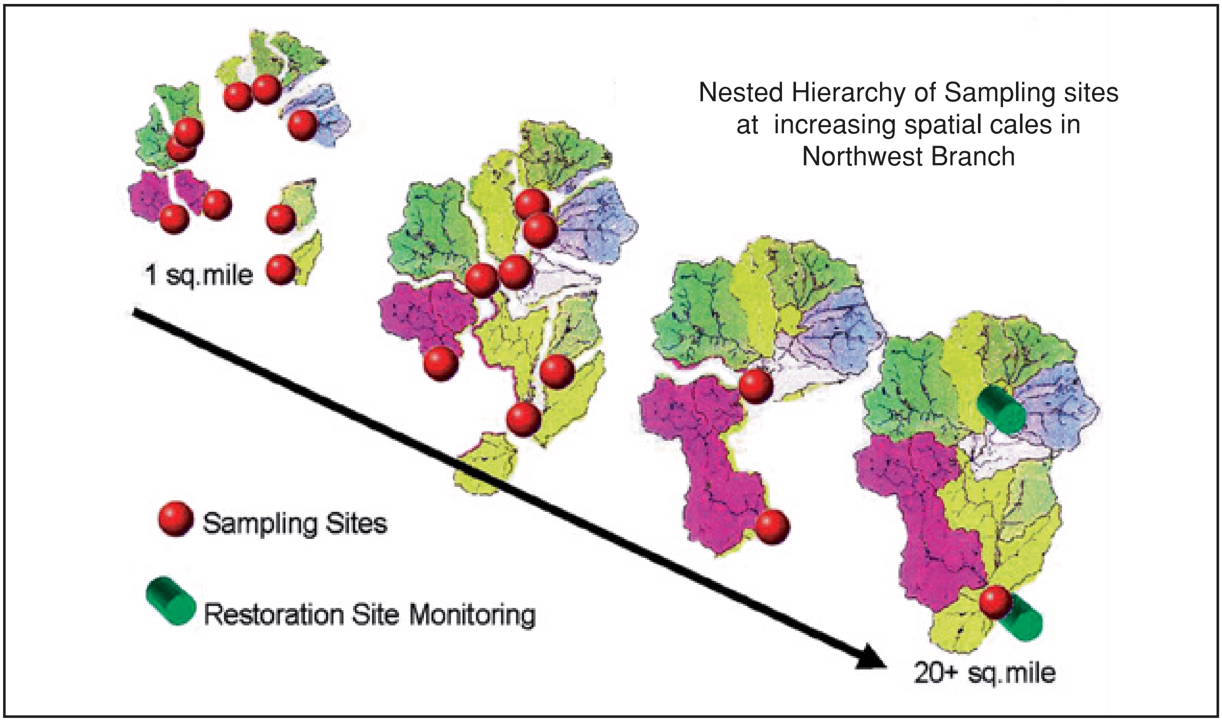

Figure 5 Illustration of nested hierarchy of sampling sites in Northwest Branch watershed. The smallest scale at which samples are collected are at sites that have small, primarily single-land use drainage areas of ca. 1 mi^2. The most downstream sampling sites are on the mainstem of the waterway and have drainage areas of 20 mi (or more in other watersheds) with mixed land use drainage areas. Sampling sites are located at the most major confluence points. Within this watershed a number of stream sites are targeted for restoration and these are also shown on the map since biological monitoring also focusing on these sites.

All measurements are being made on approximately twenty 75 meter-reaches per watershed. Many of these stations correspond to permanent Montgomery County stream monitoring stations. Selection of sites within each watershed was made to ensure that we sample in a hierarchical fashion from small (≈ 1 square mile) first-order subwatersheds to higher order tributaries at the main outlet of the watershed (Figure 5). With this design, we have ensured that sample sites at the "top" of our watersheds (*i.e.*, at the outlets from first-order subwatersheds) have drainage areas with fairly homogeneous land use (*i.e.*, primarily forested or primarily agricultural). We then sample at each major confluence where land use changes.

Table 2 Parameters being measured at study reaches within each of the four study watersheds in Maryland. The biotic parameters represent direct assessments of the fauna and ecological functioning of the streams; the physical parameters represent assessments of the habitat, flow, and geomorphic factors that influence the biota and ecological processes.

Structure	Function
Biotic	**Biotic**
Macroinvertebrate abundance, diversity, community structure	Whole reach primary production (Day-time 0_2 evolution)
Fish abundance, diversity, community structure	Whole reach community respiration (Night-time O_2 metabolic consumption)
Indices of Biotic Integrity (State and/or County Fish and Invertebrate IBIs)	NH_4, PO_4 Uptake rate
Physical	**Physical**
Cross-sectional morphology at riffles	Average Discharge
Channel bed slope	Average Transport Velocity
Riffle/pool ratio	Rate of water-atmosphere gas exchange
Particle size composition in riffles	Hydraulic Dispersion rate
Particle distribution (over 200-300m reaches)	Hydraulic Retention (Transient Storage)
Presence of man-made structures (e.g., pipe outfalls, bridges, culverts)	Riffle substrate particle stability
In-stream woody debris	
Aquatic and riparian vegetation, buffer width	
Canopy cover (shading)	
Undercut banks/overhanging vegetation	
Water quality (dissolved O_2, pH, temperature, conductivity)	

We will complete a full assessment of all sites within all four watersheds in winter 2001/2002. Using discharge data from gauges (USGS Streamflow gauges 01591500, 01591700, and 01650500) and existing models,[44] we will fully characterize the flow regime for each of our sites. We will then develop quantitative relationships between our ecological response variables and the hydrologic and geomorphic drivers that will allow us to understand how intensity, history, and spatial distribution of development influence ecological conditions at various scales. We will use these relationships to build models that will allow us to forecast and compare ecosystem condition using our different policy and growth scenarios.

In the remainder of this paper, we use the Northwest Branch watershed to illustrate the key issues we are addressing with respect to the influence of land use on stream ecosystems. Since we are in the first year (2001) of our field sampling, what we know now about the ecological conditions is based on past rapid bioassessment data for a subset of our sites that have been part of a monitoring program of the Montgomery County Department of the Environment. Their monitoring takes into account habitat conditions, invertebrate and fish diversity and results in a qualitative ranking of site conditions. In the Northwest Branch watershed, tributaries in the upper part of the watershed, particularly the headwaters, support the few remaining streams with excellent and good conditions (Figure 6). The fish community includes rosyside dace, northern hogsuckers, and five species of shiners. Although the same species can be found throughout the watershed, the community composition varies dramatically in response to habitat, flow, and pollutant stressors. In the middle section of Northwest Branch, the watershed contains a mix of low to higher density land uses along with large areas of forested parkland. Indeed, some of the widest stream buffers on the main stem in the entire county occur here but altered hydrology still prevails. The lower reaches of Northwest Branch contain more concentrated development, the hydrology has been altered significantly, and the stream conditions are generally poor to fair.

ALTERNATIVE WATERSHED FUTURES

Northwest Branch lies within Montgomery County, which is highly developed compared to many areas of the U.S., but still encompasses a large proportion of undeveloped land uses. As of 1997 about 32% of the county was in natural cover, 26% in agriculture, and 42% in developed uses. The Northwest Branch watershed has a somewhat higher proportion of developed area. Key pressures in the Northwest Branch watershed that have led to land use change include increases in real incomes in the region, increases in ex-urban populations (some of which is the result of flight from the city of Washington D.C.), and the provision of higher quality public services by the county. In the last 50 years, there has been a substantial shift in land use from primarily agricultural to residential (Figure 7). Of the 13,500 acres in the watershed, only about 1,300 acres of developable land of sufficient size to accommodate subdivisions of

[44] Soil Conservation Service. *Computer Program for Project Formulation*, Technical. Release 20, (Washington, D.C., 1984); See also, Donigan, A.S. and W.C. Huber. *Modeling of nonpoint source water quality in urban and non-urban areas.* EPA/600/3-91/039. U.S. EPA, Environmental Research Laboratory, Athens, GA, 1991; See also, Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigan and R.C. Johanson. *Hydrologic Simulation Program–Fortran, User's manual for version 11. EPA/600/R-97/080*. U.S. EPA, Ecosystems Research Division, Environmental Research Laboratory, Athens GA, 1997; See also, United States Geological Survey. http://water.usgs.gov/software/hspf.html Reston, VA, 2001.

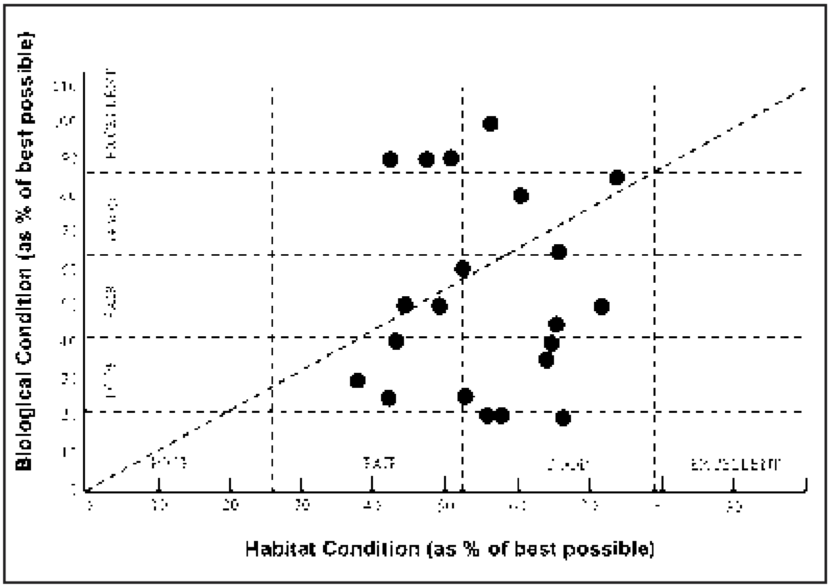

Figure 6 Relationship between habitat condition and biological condition in Northwest Branch watershed from the Montgomery County Department of the Environment's rapid bioassessment monitoring program.

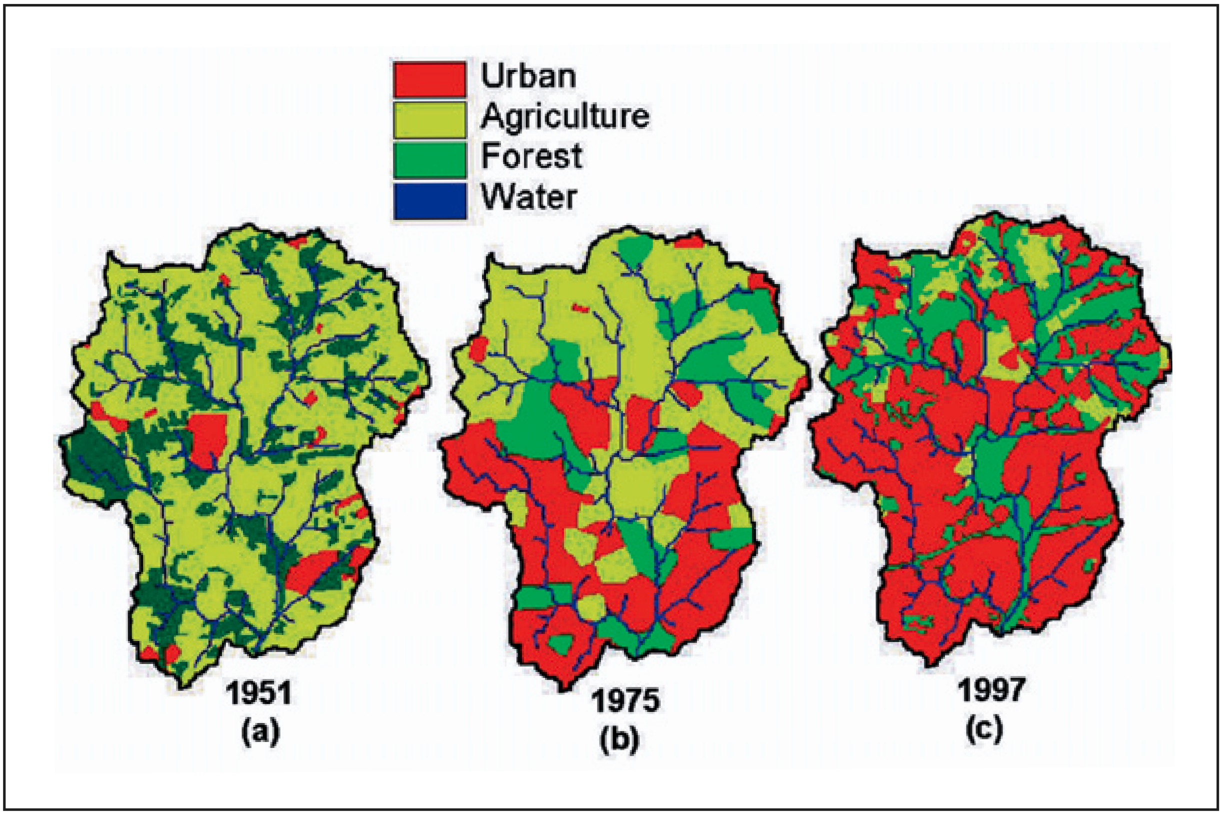

Figure 7 Evolution of land use in Northwest Branch watershed: 1951 (from aerial photography) (A), 1970's (from USGS GIRAS data) (B), 1997 (from Maryland Department of Planning) (C).

three or more housing units remain as of 2000. At current zoning densities, these 1300 acres could accommodate a bit less than 1000 new single-family dwelling units.

Land Use Change Forecasts Assuming Different Policies

To illustrate the forecasting process, we focus on the spatial dimension of the modeling approach and present preliminary results that capture the spirit of the forecasting exercise, but we do not yet take into account many of the particular features of Montgomery County and its policies that will ultimately be captured in our models. Here, we use Maryland Department of Planning projections for expected number of new households in the county over the next 20 years, which suggest the population will grow by about 860,000; this translates into about 70,000 new households by the year 2020. We present forecasting illustrations below by assuming that this growth is uniform over the next two decades and that the 70,000 new households induce an increase of about 20,000 new single family homes in the county. Not all new household formation results in new dwelling units, and not all new dwelling units are single-family houses.

How these new houses will be distributed spatially across the county and, as a result, how many will fall within the Northwest Branch watershed requires a spatial analysis. Different regulatory environments will generate different spatial patterns of development, depending on direct controls, such as changes in minimum lot size zoning, public acquisition of private lands, and incentives and disincentives for construction, such as provision of public utilities, roads, and schools, as well as changes in development fees. Some schemes will consume less land than others, while still providing the same number of new dwelling units. Some will accommodate a larger fraction of new homes on public water and sewer. Given the spatial heterogeneity in factors that affect profitability of development, a number of different spatial patterns could emerge.

Drawing on spatially explicit data on land use/land cover made available by the Maryland Department of Planning,[45] we determined that about 48% of the land use in the Northwest Branch is in residential use, 28% is in forest, and 9% is in agriculture. About 20% of the watershed is impervious. Using historic data on neighboring counties (Montgomery County historical data is not yet available), parameters were estimated for a model that explained how different characteristics affect the value of parcels in residential use. A second model was estimated, also using data on neighboring counties, that captured the likelihood that a parcel was developed, depending on its predicted residential value and factors that affected its value in other uses and conversion costs. We employed the parameters estimated for neighboring counties and projected the order in which parcels in Montgomery County that could be developed into subdivisions of three or more houses would likely be converted. A limitation of this forecasting illustration is that it does not model the alternative terminal decision of preserving land in permanent conservation easements. Nonethe-

[45] Maryland Department of Planning (2000). "Land Use / Land Cover in Maryland by Political Jurisdiction". Planning Data Services Division, GIS Section, Baltimore, MD.

less, the illustration points out qualitatively how we can approach explicit spatial modeling of land conversion and how differing policies can have effects on the spatial outcome.

In the estimated model, important factors found to affect the value of parcels in residential use included the commuting distance between the parcel and major employment centers, proximity of the parcel to the coastline, the size of the buildable lot, whether the lot was served by public utilities, the sociodemographics of the already established surrounding residential areas, and the general nature of the surrounding landscape (*i.e.*, type of land uses in close proximity). The factors that affect the cost of acquisition and conversion include the opportunity lost in agricultural use as captured by soil quality, the availability of public utilities, the size of the overall parcel and number of buildable lots, quality of soils for excavation, and type of vegetative cover. Estimation of the parameters of the hazard (or duration) model that explains the timing of past conversion produces the information needed to make preliminary forecasts of the timing of future changes.

Assuming that growth (development) occurs at the hypothetically projected rate and in this projected pattern without any major changes in policies, the "business as usual" illustration projects that the Northwest Branch will see major development occurring first in the headwater areas of the watershed (See Figure 8A.) There are many reasons for this, but prime among them is the profitability of developing large lot subdivisions in areas accessible to the city, but close to open space, either privately or publicly held. There are two simple scenarios that offer a considerable contrast to the business as usual forecast presented above. The State of Maryland is in the process of instituting a program under the rubric of "Smart Growth." As key features of this program, the state, in conjunction with counties, has designated two types of areas: "Priority Funding Areas" (PFAs) and "Rural Legacy Areas" (RLAs).

"Priority Funding Areas" (PFAs) are designated areas within which public infrastructure will be subsidized by the state and outside of which state subsidies will be denied. PFAs tend to be areas of in-fill-areas where capacity for new housing exists and where public utilities have already been provided – areas usually zoned for relatively small lot sizes. More than half of the Northwest Branch watershed falls within a PFA. Ironically, the order of development we predict in our first scenario under "business as usual" is just the reverse of what is being encouraged within the Priority Funding Areas program, as the PFA covers the lower part of the watershed. We have no way of knowing at this time how successful this feature of Smart Growth will be at redirecting development. If we assume that it is effective, then Montgomery County parcels will be developed in the order forecasted in our business as usual scenario except that any parcel within a PFA takes precedence over parcels outside PFAs. The result for the Northwest Branch is depicted in Figure 8B.

"Rural Legacy Areas" are large contiguous tracts of agricultural, forest, and natural areas designated as receiving top priority for outright public purchase

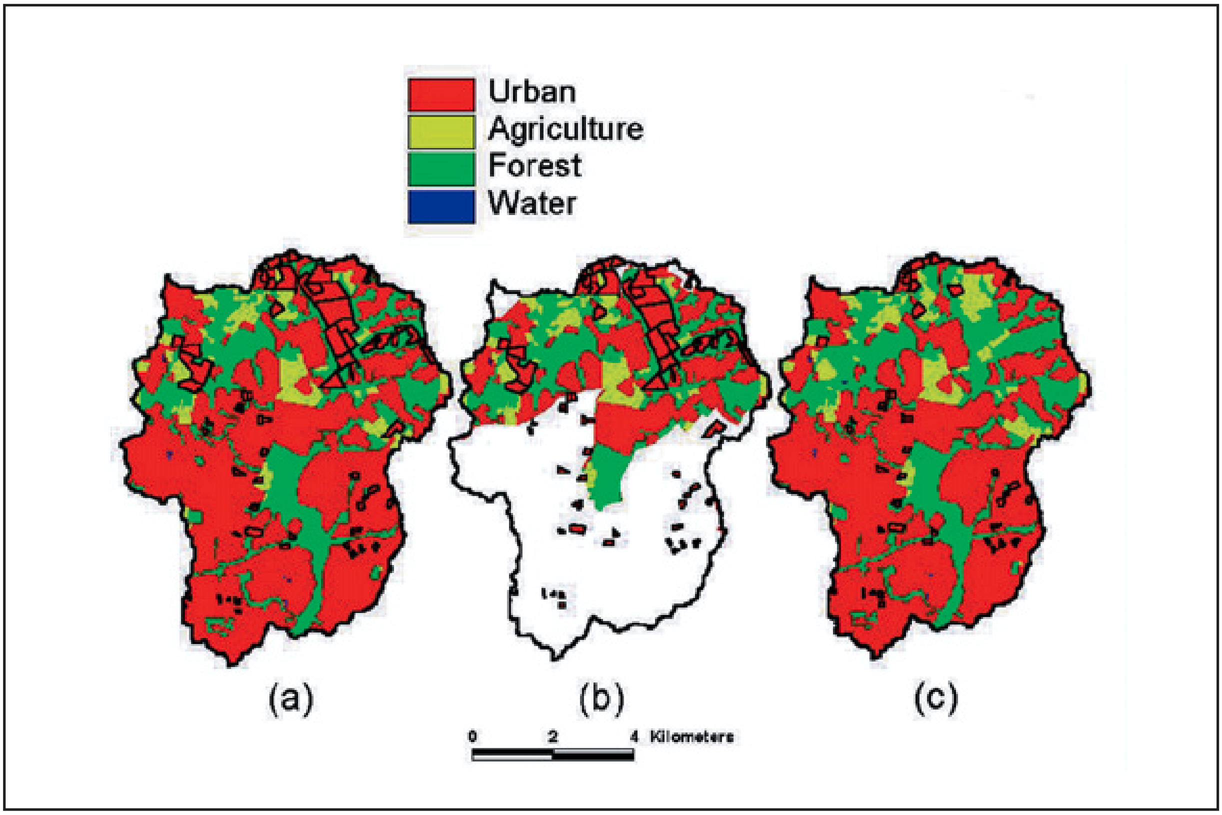

Figure 8A, B, C Alternative 2020 land use distributions in Northwest Branch: "business as usual" (A), "Priority Funding Areas" (B), and "Rural Legacy Areas" (C). Black outlines indicate developable parcels. White areas in (B) indicate location of PFA's. Notice smaller size and fewer number of developable parcels in (C).

or public purchase of development rights, as funds for such purposes become available. While some areas have already been identified as potential candidates, local governments and private land trusts will be encouraged to identify Rural Legacy Areas to be approved or denied by the Maryland Department of Natural Resources. Currently there are no Rural Legacy Areas identified within the Northwest Branch watershed. That does not mean that this feature of the program will not affect this watershed. For one thing, development could well be deflected from other areas that are preserved. For another, the creation of preserved open space affects residential values in the surrounding area and thus alters the relative appeal of remaining developable parcels. To provide further contrast to the "business as usual" and PFA examples above, we propose a hypothetical RLA example in which conservation easements are purchased on all developable parcels exceeding 0.1 km2 within the Northwest Branch, thus fixing the land use on these parcels to remain as it is under current (1997) conditions. This development scenario is shown in Figure 8C. Notice that the developable parcels shown in 8A and 8B are more numerous, and that in 8C the land use where the "missing" parcels would be tends to remain in agricultural or forested land uses.

The land use distributions under these alternative futures are also presented in Table 3. It is interesting to note that by the year 2020, both the "business as usual" and the "PFA" scenarios reach the same endpoint with all parcels being developed. We interpret this to indicate that, although the timing of development differs between these two scenarios, the ultimate hydrologic, geomorphic, and ecological consequences are likely to be the same, being perhaps somewhat delayed in the PFA scenario relative to the "business as usual" case. In contrast, the RLA scenario, because it removes some of the largest parcels from potential development, has a smaller residential fraction and level of imperviousness than do the other two cases and would be expected to have fewer associated deleterious environmental consequences.

Hydrological, Geomorphic and Ecological Implications

Since the quantitative relationships between our empirical measurements will not be made until our sampling is complete in late 2001/early 2002, at this point we can only speculate on the geomorphic and ecological implications of the alternative land use futures of Northwest Branch. In the upper reaches of this watershed, low-density land uses will still predominate in 2020, but the landscape will increasingly be in transition from some agricultural land with mixed forest to a more suburban landscape. The streams will also be in a state of transition, from carrying sediment loads and nutrients associated with past farming activities to a watershed condition that has higher imperviousness. As this area develops and the imperviousness increases, changes in watershed hydrology and ecology are inevitable. Increasing the impervious surface has well known negative consequences for stream ecosystems, caused by increased scour and channel erosion, thermal pollution generated by runoff from hot paved surfaces, and organic and heavy metal pollution largely from roads and car parks.[46] It is also common for the amount of riparian buffer to decline with such urbanization pressures; however, it is possible that there may be a shift towards more riparian forest along Northwest Branch because of the many buffer reclamation projects in this watershed.[47]

In general, we expect the land use change depicted in (Figure 7) to have produced increases in peak flows (the 2- through 100 year-flood events).[48] A change in flow behavior as this watershed has become urbanized over the last 50 years has already occurred, but changes over the next 20 years may further continue this trend (see Table 4). While peak discharges across all magnitude storm events are expected to increase under the urbanization illustrations depicted in Figures 7 and 8, changes in streamflow are likely to be more pronounced at smaller scales (*i.e.*, in the smaller first and second-order watersheds) and to be increasingly damped as the size of the watershed increases. In other words, measurements taken at the outlet of the watershed (*i.e.*, at the southern extreme of the overall watershed) represent an integration of all the incremental sub-watersheds within. Locally the changes are expected to be significant, so one should be careful not to view small predicted changes

[46] Van Buren, M., W. Watt, J. Marsalek and B. Anderson, 2000; See also, EPA. (Orlando, Florida, 1980); See also, Karr, J.R. and E.W. Chu. *Restoring life in running waters: better biological monitoring*. Island Press, Washington, D.C., 1999; See also, Tucker, K.A. and G.A. Burton. 1999. Assessment of nonpoint-source runoff in a stream using in situ and laboratory approaches. *Environmental Toxicology* 18, 2797-2803.

[47] Moglen, G.E. 2000. Urbanization, Stream Buffers, and Stewardship in Maryland. *Watershed Protection Techniques* 3, 676-680.

[48] Moglen, G.E. and R.E. Beighley. Spatially Explicit Hydrologic Modeling of Land Use Change. *Journal of the American Water Resources Association* (2002.).

Table 3 Comparison of land use evolution under three alternative futures in Northwest Branch watershed (see text for full explanation).

Condition or Scenario	Year	Percent Residential	Percent Agriculture	Percent Forest	Percent Impervious
Current	1997	47.2	9.2	28.4	20.1
Business as Usual	2005	53.4	7.1	24.4	21.6
	2010	53.5	7.1	24.4	21.6
	2015	53.6	7.1	24.3	21.7
	2020	53.6	7.1	24.3	21.7
Priority Funding Areas	2005	47.6	9.1	28.1	20.2
	2010	49.5	8.9	26.5	20.7
	2015	53.6	7.1	24.3	21.7
	2020	53.6	7.1	24.3	21.7
Rural Legacy Program	2020	48.0	8.8	28.0	20.3

at the overall watershed outlet as necessarily indicative of uniformly small changes throughout the smaller sub-watersheds nested within.

Table 4 illustrates the integrative nature of the watershed. Notice that the extremes, in terms of minimum and maximum discharge ratios, generally tend toward ratios of 1 with increasing stream order. For example, the minimum ratio in peak discharge, Q_p, at a given 1st order sub-watershed outlet is 0.08 between 1951 and 1997. In other words, for this particular sub-watershed, the 1951 discharge is 8% of the 1997 discharge. In contrast, the minimum ratio increases to 13 and 35% for the 2nd and 3rd order sub-watersheds, respectively. This same pattern can be observed elsewhere in the table.

Table 4 also illustrates the magnitude of change from past land use to the present in comparison to anticipated future changes. Observed at the outlet, the 2-year peak discharge in 1951 was only 73% of what it is currently. Depending on the future scenario being considered, the 2-year peak is only likely to increase 1 (in the RLA scenario) to 5% (in either the "business as usual" or PFA scenarios).

In the middle section of the watershed, there are more stormwater controls than in the lower reaches; however, the stormwater management technologies used are of older designs that are believed to be not as effective as methods used today. The lower reaches of Northwest Branch contain older and more concentrated development, where communities developed long before there were requirements for stream valley protection or stormwater management. The hydrology in these areas has been significantly altered and the stream condition is generally poor or fair. We anticipate that without significant changes in the expected development patterns in this region, increased variance in peak and low flows will occur.

Baseflows are also typically expected to decline with urbanization; however, leaky water distribution systems and homeowner watering patterns in highly residential areas make it difficult to predict how baseflow will respond. This is a research area that needs active investigation and requires a full understanding of not only the stream network and groundwater flows, but also the water supply network, stormwater drainage network, and landowner water use patterns.

For any development scenario, the areas within the watershed where human impacts would cause the most ecological damage will depend on the specific land use, but as a rule of thumb, it is probably safe to say that these areas would mostly be the headwater regions. Deforestation in headwater areas will affect the patterns of sediment transport and carbon cycling in the entire stream. Introduction of impervious surfaces in headwater regions will increase the variability of water discharge in the stream, and this will increase scouring of riparian areas[49] and probably pave the way for invasion of alien plants, etc. There are also cases where impacts in downstream parts of the watershed will affect upstream regions, especially when dams stop upstream migration of anadromous fish and associated patterns of nutrient cycling.

Geomorphologically, we anticipate a spatially and temporally complex pattern of changes that vary with changes in discharge and sediment supply. Channels should increase in size with increasing urbanization,[50] except where sediment eroded from upstream is accumulating in a particular reach.[51] The frequency and extent of bed mobilization should also tend to increase with increasing urbanization, although these variables are complex functions of

[49] Leopold, L.B. *Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Land Use.* U.S. Geological Survey Circular 554 (1968).

[50] Hammer, T.R., Stream channel enlargement due to urbanization. Water Resources Res 8:1530-1540. 1972; See also, Pizzuto, J.E., W.C. Hession and M. McBride, Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania 2000. Geology 28:79-82

[51] Clark, J.J. and P.R. Wilcock. 2000. Effects of land-use change on channel morphology in northeastern Puerto Rico. *Geological Society of America Bulletin* 112, 1763-1777.

Table 4 Statistics for modeled 2-year peak discharge in Northwest Branch by stream order.

Condition or Scenario	Statistic	Order 1	Order 2	Order 3	Outlet
1997	Q_p mean (m^3/s)	2.35	5.35	12.24	29.4
	Q_p min (m^3/s)	0.40	2.00	8.46	-
	Q_p max (m^3/s)	7.95	9.97	16.62	-
1951:1997	Q_p ratio mean	0.84	0.77	0.79	0.73
	Q_p ratio min	0.08	0.13	0.35	-
	Q_p ratio max	1.00	1.00	1.00	-
2020:1997 (business as usual or PFA)	Q_p ratio mean	1.03	1.05	1.06	1.05
	Q_p ratio min	1.00	1.00	1.00	-
	Q_p ratio max	1.37	1.28	1.12	-
2020:1997 (RLA)	Q_p ratio mean	1.01	1.01	1.01	1.01
	Q_p ratio min	1.00	1.00	1.00	-
	Q_p ratio max	1.11	1.05	1.01	-

channel morphology, flow frequency, and sediment characteristics, and cannot be readily forecasted without detailed analysis. Channel morphology, sediment properties, and hence bed mobility, will also vary with differences in riparian vegetation.[52] Changes in riparian vegetation are only loosely correlated with changes in land use, so, although we can empirically document how riparian vegetation influences present channels, we may not be able to include this variable in our predictive models.

Ecological impacts expected under the future conditions scenario of higher peak flows, lower base flows, less stable beds, and potentially higher sediment loads (at least during the construction phase of development) include loss of species – particularly intolerant invertebrates (mayflies, stoneflies, caddisflies) and fish. We expect poorer water quality, primarily through additions of nitrogen from run-off from fertilized lawns, and an increase in the number of septic fields. With increased impervious area and increased population, we expect an increase in organic and heavy metal pollutants. Increased flow rates and nutrient addition may be ameliorated to some extent if buffer reclamation and stormwater retention projects are successful. With respect to the ecosystem functions, we predict a decrease in retentiveness (due to loss of habitat complexity) that would cause an increase in nutrient spiraling length, *i.e.*, nutrients moving rapidly downstream with little biological uptake locally. However, low nutrient uptake may be countered to some extent if development involves clearing of riparian vegetation that results in higher streambed light levels and thus elevated algal uptake of nutrients.[53] Such compensatory uptake is likely to be small if Montgomery County's current levels of riparian protection and reclamation are maintained.[54] Low nutrient uptake may also be countered if development leads to an increase in the concentration of suspended particulates. Nutrients may adsorb to these particulates and thus nutrient uptake may be seemingly high but for nonbiological reasons. Finally, with more impervious land area, reduced groundwater recharge will lower the contribution of heterotrophic metabolism in the hyporheic zone to the surface waters, thereby increasing the production/respiration (P/R) ratio.[55] Larger channel sizes provide more surface area to be colonized by algae, further amplifying P/R.

POLICY TO PROTECT WATERSHEDS

When watersheds are threatened by development, a frequent recommendation from environmentalists is to identify set-aside areas and protect them from further development. Ecologists would argue that these set-aside areas should be tracks of land that have been identified as environmentally sensitive or of particular ecological importance. The underlying conception is that this strategy will ensure a sustained ecological functioning of the streams and their riparian zones even under the pressure of an increasing human population density. The goals of this strategy are to avoid diffusive disturbance of the watershed and local disturbance of critical areas. These goals are consistent in principle with

[52] Sweeney, B.W. 1992. Stream forests and the physical, chemical, and trophic characteristics of Piedmont streams in Eastern North America. *Water Science Technology* 26, 2653-2673; See also, Reed, J.E. 133 (University of Delaware, Newark, DE, 1999).

[53] Sabater, F, A. Butturini, E. Marti, I. Muñoz, A. Romani, J. Wray, S. Sabater. 2000. Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream. *Journal of the North American Benthological Society.* 19: 609-620.

[54] Moglen, G.E., 2000. "Urbanization, Stream Buffers, and Stewardship in Maryland." *Watershed Protection Techniques*, 3(2): 676-680.

[55] Findlay, S. 1995. Importance of surface-subsurface exchange in stream ecosystems: the hyporheic zone. *Limnology and Oceanography* 40, 159-164.

the goals of the Smart Growth policies being adopted by Maryland, but because the development decision is a complex one, it is not obvious that such policies will achieve this end.

Critical areas are generally divided into two types: (1) areas that meet certain evaluation criteria, and (2) areas that are valuable for ecosystem functioning or integrity. Four of the most frequently used and useful criteria for selecting areas to preserve are diversity, rarity (*e.g.*, endangered species), naturalness, and size. The identification and conservation of species-rich (diverse) areas have intuitive appeal particularly if they harbor rare or endangered species. Preservation of undeveloped land, particularly large tracks of "natural" lands, represents an obvious target for conservationists, particularly if these are situated in a matrix where development is fairly significant. We suggest that it is important to answer two questions: (1) Is there scientific evidence that setting aside areas for protection in watersheds, and clustering development in other areas, will improve the ecological condition of freshwaters? and (2) even if this is attractive from an environmental perspective, can we identify policies we know with confidence will lead to this type of Smart Growth?

THE NEED TO CONSIDER THE UNINTENDED CONSEQUENCES OF POLICIES

In our case study, we began with a story in which a certain number of new dwelling units are expected to be built each year. Can we restrict the number that are being added and divert those homes from critical or undeveloped areas to areas already developed? For legal reasons, most land use policies are quite indirect. Local governments in Maryland have historically adopted large lot zoning and withheld public utilities in order to discourage development in largely rural areas. However, this has resulted in unintended consequences. In an attempt to make development less profitable in these areas, the counties have produced a situation in which, if development happens, it involves the addition of septic fields and wells, making previously undeveloped areas more environmentally vulnerable. Further, the developed land is fragmented and low density, making it expensive to provide other public services. In Maryland and many other places, the prices people are willing to pay for land at the rural-urban fringe more than makes up for the added costs to developers of developing in this way.

Since local governments set most land use policy, some counties have discouraged diffuse development (*e.g.*, by setting extremely large minimum lot sizes). The problem is that housing markets often transcend individual jurisdictional boundaries, so the development is simply shifted to the next county that may be within the same sub-watershed.[56] Thus, policies may be needed at much larger (*e.g.*, statewide or regional) scales. Maryland's two "Smart Growth" initiatives, Priority Funding Areas and the Rural Legacy Program,[57] are both designed to be effective at statewide or regional scales.

Whether policies such as Smart Growth will have the intended effects – to identify critical areas, halt further development in these areas, and shift

[56] Bockstael, N. and K. Bell. 1997. "Land Use Patterns and Water Quality: The Effect of Differential Land Management Controls". In *International Water and Resource Economics Consortium, Conflict and Cooperation on Trans-Boundary Water Resources*, Richard Just and Sinaia Netanyahu, editors. Kluwer Publishing.

[57] Maryland Department of Planning (2000). "Land Use / Land Cover in Maryland by Political Jurisdiction". Planning Data Services Division, GIS Section, Baltimore, MD.

development patterns to infill – is an empirical question; however, it would be incorrect to assume that all further development will occur in the target zones. If the policy is effective in targeting growth, we still need to determine the environmental effects of higher intensity development in areas already partially developed. Is it necessarily better from an ecological perspective to have large contiguous areas that are almost completely impervious? If it isn't effective, where will the development occur and at what densities?

The Need for Outreach Efforts

While much more research is needed on the environmental effects of the *pattern* of development as well as when policy instruments may or may not be effective, efforts to involve the public should not be delayed. Educating the public about the environmental effects of an individual's actions in particular and urban sprawl in general should be considered key ingredients to successful watershed management and stream protection plans. As the waste recycling movement has clearly shown, aggressive and focused public outreach and education can do wonders to change public behavior to reduce impacts on the environment. Aggressive enforcement of pollution laws is also critical, but likely to fail or be less successful without an initial and sustained public education effort to make people aware of their personal stewardship responsibilities and related legal requirements and penalties for noncompliance.

Jurisdictions need to pursue public outreach activities much more aggressively. However, since the research we argued for will take years to complete, for now, they must rely on what science is available *and* their intuitive sense of what will do some good. There are certainly examples around where well-designed and funded public outreach programs have been very effective despite the fact that public outreach is generally one of the first things to be cut in budgets, particularly in difficult economic times.

In this paper, we have focused on addressing the ecological impacts of land use change by integrating diverse scientific and economic principles. But our focus has been primarily on the physical and ecological effects of different spatial configurations and densities of development. Models can also be developed to consider how the behavior of people in these places can significantly influence the actual versus predicted impact. For example, the Center for Watershed Protection has recently developed desk top models for estimating the effects of residential education in reducing nutrients from lawn overfertilization, inadequately maintained septic tanks, and pet wastes not picked up and properly disposed by pet owners.[58] This work often involves research in the form of public surveys and monitoring studies of targeted populations to judge the effectiveness that sustained public outreach may have when combined with legislation aimed at directing growth away from or to certain areas.

No matter what land use patterns emerge (*e.g.,* Smart Growth vs. sprawl), the habits, traditions, and behavior of people and businesses who populate the

[58] Caraco, D. *The Watershed Treatment Model,* Version 3.0. Center for Watershed Protection, Ellicott City, MD, 2001.

land will dramatically affect the final impacts on fresh waters. For example, nutrient loading scenarios are generally modeled based purely on empirical data of nutrient levels washing off different land use types. How do we adjust these models to account for people's varying behavior in fertilizing their lawns? In their efforts to achieve that artificially perfect and uniform green monoculture lawn, the Center for Watershed Protection estimates that 78% of individuals fertilize their lawns and that 65% of these overfertilize (more than twice/year). Conversely, some people never fertilize their lawns once they're originally established. The CWP estimates that 70% of the "overfertilizers" can be induced to voluntarily change their behavior. What if one jurisdiction pursued a major, continuing, multi-media, multi-cultural public outreach effort and actually succeeded in reducing use of lawn fertilizers by 50% or more? What if another jurisdiction judged nutrient loading problems to be so bad that it actually banned the fertilization of established lawns? This approach would be no more radical than the very successful ban on phosphate-based laundry detergents adopted to protect the Great Lakes and the Chesapeake Bay. Nor is it much different from the idea of banning of lawn watering in times of drought.

Using Policy, Science-Based Tools, and Public Outreach for Watershed Protection: The Case of Montgomery County

In 1998, Montgomery County, MD developed its *Countywide Stream Protection Strategy* (CSPS)[59] to enhance public understanding of why a quantitative, science-based understanding of local stream conditions and watershed management strategies was needed. Prior to this, watershed protection investments in stream buffers, stream restoration, and remedial stormwater management controls were uncoordinated among agencies and scattered geographically resulting in costly and relatively ineffective use of limited resources for environmental protection.

The Montgomery County Department of Environmental Protection (DEP) designed a program: (1) to develop science-based water quality information which would serve as the basic building block for reaching out to and educating the general public on watershed protection issues; (2) to explain how the county was addressing water quality problems with capital projects, education, and enforcement programs to reduce pollution sources; and (3) to help the public better understand and contribute to problem resolution by personally serving as stream protection stewards in their own watersheds.

To provide a framework for pursuing these objectives, DEP decided to collect biological and habitat data to evaluate stream conditions in its subwatersheds. To build consensus for this undertaking and later acceptance of results, DEP convened a Biological Monitoring Workgroup representing local and state monitoring agencies, environmental consultants, and environmental groups. This diverse group of scientists, engineers, citizens, and environmental community representatives quickly and remarkably reached consensus on sampling and analytical methods and data sharing protocols.

[59] Montgomery County Department of Environmental Protection. Countywide Stream Protection Strategy. http://www.co.mo.md.us/services/dep/Watershed/csps/csps.html. 1998.

DEP and partner agencies and volunteers collected biological information, and these data served as primary indicators to rank stream conditions in familiar, easy to comprehend "excellent, good, fair, or poor" terms (*e.g.*, see Figure 6). This type of information was useful to citizens in their own neighborhoods, but also allowed the county to use extensive GIS applications to identify and integrate land cover, zoning, and impervious area information by subwatershed and relate it directly to observed stream rankings. The county was then able to classify subwatersheds into management categories and designate priority subwatersheds based upon analysis of observed stream conditions and impacts from existing or planned development. Specific management tools were identified to address typical stream impacts found within with each management category.

What Montgomery County has done with CSPS represents an unusually proactive and focused effort by a local government, not only to develop stream and watershed protection goals, but also to involve and engage the public and elected officials in the process. The CSPS guides interagency cooperation in watershed monitoring and in the targeting of management programs. It stimulates citizen and business awareness and activism as essential components of subwatershed protection initiatives to protect neighborhood streams. It is used by the County Planning Agency to integrate consideration of stream resources directly into decision processes on land use alternatives and into legal land use master plan documents. County funding is now directed and scheduled to achieve specific stream protection goals in designated CSPS priority subwatersheds. The Montgomery County Executive and County Council have backed up their endorsement of the CSPS with budget actions authorizing a $26 million capital improvements program to support targeted stream restoration initiatives in 99 designated CSPS priority subwatersheds. Thus far, 22 projects have been completed and another 83 are in design or construction. Projects implemented thus far in the highly urbanized, 35% impervious Sligo Creek watershed have helped improve the stream's biological community from a "poor" to a "fair" rating. The creek now successfully supports 13 native fish species where once only 3 species were found. Amphibian populations were also restored to areas where new wetland habitats were created to help slow down and clean up storm drain discharges that had previously entered directly into the creek

Montgomery County has also used the scientific underpinning of the CSPS as a powerful educational and guidance tool to gain and sustain public awareness and interest in water quality management programs. The CSPS document has been widely disseminated for public review. The final CSPS report is easily accessed on the Internet (www.askDEP.com). This web site also contains many other creative and interactive data presentations and brochures on all aspects of watershed management roles that citizens can play in personal pollution prevention and stream stewardship. Recently, the National Association of County Officials (NACO) gave the county its 1999 Achievement Award for its efforts to develop and implement the CSPS, and neighboring jurisdictions are now developing stream protection strategies using the CSPS as its model.

We close with this final focus on the Montgomery County efforts because they illustrate that, while we need a great deal more scientific research to understand and forecast how land use change will influence the flow, morphology, and ecological integrity of rivers and streams, successful and proactive watershed protection is possible. The merger of state-of-the-art science, proactive policies, and creative outreach can make a difference.

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