Watershed Ecology: Implications of a Landscape Perspective

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The watershed embodies the 'human' scale. Of course, saying so immediately implies that both systems are hierarchical, and therefore of variable scale. But isn't this reflected in our experiences of the world around us? Our social spheres are nested within regional affiliations, which are in turn nested within larger political units; just as sub catchment is nested within catchment. Humans are impacting their environment throughout the world on a myriad of scales. Successfully managing a hierarchical system requires a hierarchical approach. Due to their connected nature and unidirectional flow, watersheds concentrate the distributed influences of man on his environment. They serve as a prime indicator of our status in the natural world, and require careful management in order to preserve the essential services they provide.

A characteristic shared by nearly all human impacted watersheds is a distinct urban-rural gradient. Urban areas tend to spawn in the fertile, level lowlands while the upland reaches of the watershed remain largely pristine. As the urban areas develop they expand outward, bringing a wave of land cover change with them. This is a perfect example of the interplay of pattern and process. The landscape's physical features shape the process of urbanization, which then alters the pattern in turn. However, when dealing with such a complex system it can be misleading to assume a linear relationship (Wear et al. 1998).

Another obvious pattern emerges in conjunction with the urban-rural gradient. Headwaters in the remote reaches of the watershed are relatively pristine and biologically healthy, but as the water moves down the landscape the matrix becomes increasingly interspersed with human induced land cover change. These new land covers alter the regime of inputs entering the network. In particular, agricultural lands increase nutrient loading and impervious surfaces alter storm hydrology, increasing sedimentation. As the streams converge the cumulative effects are concentrated, leading to extreme degradation of natural communities and processes.

Due to their interconnected nature, it is essential to disconnect hydrologic systems from undesirable land covers. Vegetated riparian zones are an essential buffer. They resemble a source-sink relationship, interrupting and absorbing the flow of pollutants. Riparian buffers may be the key to reducing man's impact on aquatic systems. However, their actual contribution to water quality remains poorly understood. This is largely due to the complexity of the natural bodies involved. In order to make reliable predictions about water quality, it's critical to accurately model the path of runoff through the landscape and integrate this data with detailed land cover information.

Indeed, the constraints of coarse data sets, in the face of such a complex system, obfuscate most attempts to model watersheds. There is an expansive body of studies that have attempted to predict water quality behavior by examining the landscapes composition. However, the majority of these investigations fail to sufficiently incorporate spatial configuration into their models. In many cases, the location of a cover type is much more important than its overall abundance. Studies that attempt to integrate configuration by assessing riparian buffers are frequently inhibited by the resolution of their data. It's not appropriate to characterize an entire riparian zone from the value of one pixel. Even the most ingenious model is useless if its data fail to reflect the world it describes.

Understandably, there has been great deal of frustration surrounding the struggle to wrest a functional science from the ponderings of landscape ecology. It seems such a tantalizing panacea for so many frightening environmental issues. I'm not convinced that it isn't, but there's only so much you can expect from a fledgling, hyper-disciplinary science that has only just hit technological puberty. Lammert and Allan (1999) are right to question whether a large-scale model actually explains variation more reliably than local conditions. However, a lower degree of accuracy in the face of exhaustively surveyed site characteristics does not discount a landscape approach. If we had those data for the entire watershed, we wouldn't be so desperate for a new method.

Biotic communities are shaped by their local conditions, which are in turn both shaped by conditions at the next hierarchical level. Add in the time lag for large-scale feedback loops and it's not very surprising that these systems aren't falling daintily into the boxes we've built. The intertwined nature of a dynamic, hierarchical system inherently leads to a great deal of correlation between its components. It's a staggering task to untangle the pieces. The ratio of forest to agriculture shifts, and nitrate levels shift along with them. But is the new level a result of increasing buffer, or decreasing input? Statistical tools like principle component analysis seem the best solution, but as their complexity increases so does their subjectivity. It becomes an exercise in database stroking wizardry; coaxing the analysis towards the results you're convinced are there.

Luckily, landscape ecology is amidst a surge of development. High-resolution imagery for land use delineation, LIDAR for vegetative structure and elevation models, and a flood of other emerging technologies will revolutionize the precision and efficiency with which we monitor the natural world. As we carefully sift through new tools and sophisticated metrics, theory evolves in sporadic leaps and bounds. The new landscape perspective paradigm is not going away; they way we view natural systems has changed at a fundamental level. Nature is not a collection of distinct systems operating within well defined temporal and spatial scales. Rather, it is a slippery chaos of hierarchically linked components. The influences and mechanisms of these components slip and out of focus as we adjust the domain under which we consider them. Understanding and mastering the landscape perspective is integral to managing the processes and resources humanity relies so heavily upon.

Baker ME, Weller DE, Jordan TE (2006a) Improved methods for quantifying potential nutrient interception by riparian buffers. Landscape Ecology 21:1327–1345

Baker criticizes riparian buffer metrics that use a fixed distance approach. There is a contradiction in the scales at which buffers are defined in the field and how they are quantified on a landscape level. Buffer metrics must be designed to incorporate the connectivity and retention of the land pattern. Fixed distance measurements also correlate far too strongly to add predictive power to a model. They design two new metrics: an unconstrained method that measures contiguous buffer patches and a flow path model that incorporates elevation data to model surface transport. This seems to be an excellent way to improve buffer models, is supported by a comprehensive statistical analysis, and is easily adaptable to multiple scenarios.

Baker ME, Weller DE, Jordan TE (2007) Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential. Landscape Ecology 22:973-992

Baker et al. take the next logical step after introducing their flow path buffer analysis method and evaluate how stream resolution affects riparian metrics. Unsurprisingly, the predictive power of the model plummets as resolution decreases. This is an inherent complication when using a flow path model; they demand a greater level of detail than a fixed distance measure. The paper is precisely worded, statistically sound, and applied over a variety of regions. I think Baker's work is exceptional, but clearly comes from an American perspective of landscape ecology.

Goetz SJ (2006) Remote Sensing of Riparian Buffers: Past progress and future prospects. Journal of American Water Resources Association 42:133-143

Goetz reviews typical remote sensing applications from the past and then addresses several rapidly emerging technologies that will dramatically improve the quantification of riparian buffers. Of particular interest was the ability to use proportional cover estimation in conjunction with a single scene of high-resolution data to extract more information from a large set of moderately detailed imagery. Even more exciting is the emergence of LIDAR. While widespread implementation is currently unrealistic, it is clear that the technology will revolutionize the way we quantify overland flow and vegetative structure, and therefore the predictive power of watershed nutrient models.

Hunsaker CT, Levine DA (1995) Hierarchical Approaches to the Study of Water Quality in Rivers. BioScience 45:193-203

This paper compares two very different efforts to model land cover's effect on nutrient inputs. The Illinois study used relatively coarse elevation data, land cover proportions, and several pattern metrics to construct a linear regression model. The resolution of this data was inappropriate for the riparian buffer model, resulting in a much more accurate landscape level predictions. The Texas study combined a model of nutrient and sediment delivery with a hydrologic flow path model. The data used in the Texas data was drastically finer grained, allowing for a much more reasonable estimate of riparian mechanisms. They conclude that the lumped, coarse approach can be used to screen regions for trouble watersheds, which are then assessed by the finer model to direct management decisions.

This paper was interesting, in that it consciously compared two drastically different studies, and still drew significant conclusions. It's clear that a blend of modeling techniques is needed to assess a watershed due to their hierarchical and spatially dependent nature. This is the first time I've seen the phrase hydrologically active area, the area in a watershed that produces surface runoff, and it seems to be an excellent way to define a buffer zone. The COUNT model they used to predict flow paths in combination with nutrient removal coefficients based on land cover seems like a solid direction for these types of models, and I'm surprised it doesn't appear more often. While complex, this article was very clearly written.

Johnson BL et al. (1995) Past, Present, and Future Concepts in Large River Ecology. BioScience 45:134-141

This is an introductory article to an issue of BioScience focusing on flowing water systems. It reviews the paradigms that shape how we view lotic systems, and where these concepts fail us. The river-continuum theory is contrasted against the flood-pulse theory, and then both are criticized for their reliance on linear rather than hierarchical organization and assumption of physical rather than biological controls. Furthermore, our perceptions of lotic systems need to acknowledge the inherently disturbed and nature of systems within a developed world. Lotic systems are not in a state of equilibrium, but are constantly changing under the influence of mechanisms with long temporal lags and may have alternative stable states. There needs to be an effort to produce mechanistic rather than descriptive hypotheses. Finally, due to the temporal and spatial scale of these systems a new set of tools must be developed to study them.

This article lays the foundation for many of the concepts underlying watershed studies. It is well worded, easily accessible, and comprehensive. The dichotomies they construct forced me to reevaluate the way I view these systems. The message is pervasively clear that a landscape ecology approach is required to understand these systems.

> Kearns FR et al. (2005) A method for the use of landscape metrics in freshwater research and management. Landscape Ecology 23:113-125

This study strove to define a set of landscape pattern metrics that can be applied over multiple scales and regions, particularly in urban areas. They stress the importance of pattern over compositional metrics for characterizing watersheds. Beginning with an initial group of 26 metrics, they eliminate those with low variation, high standard error, and high sensitivity to extent. Using a factor analysis they further simplify the metrics down to two axis, patch density/distribution and patch shape/landscape subdivision. They then select the four most appropriate metrics: patch density, contagion, interspersion, and mean shape index.

Integrating landscape configuration into watershed assessments requires a method for quantitative assessment. Therefore, analyses like this are vital for discerning the most descriptive and accurate metrics from the sea of calculations available. This study does an excellent job of defining which characteristics inhibit the effectiveness of a metric, and a principal components analysis is a very appropriate way to uncover the factors that actually define a landscape. There was a high level awareness of the intricacies of dealing with geospatial data apparent throughout the paper, such as the effects of combining raster and vector datasets. They also touch on an interesting concept, that pattern metrics may reflect the socioeconomic functioning of an urban area, which deserves greater exploration. Finally, there is a call to move away from the dichotomy of an urban-rural gradient and accept a more complicated model of urban growth.

> Lammert M, Allan JD (1999) Assessing Biotic Integrity of Streams: Effects of Scale in Measuring the Influence of Land Use/Cover and Habitat

Structure on Fish and Macroinvertebrates. Environmental Management 23:257-270

This study was a response to Roth et. al. 1996. It covered the same watershed but used fewer subcatchments. The results contradicted Roth's findings, stating that site conditions and local scale buffers more accurately predicted biotic variation than catchment wide composition.

Lammert raises a good point, that on site investigations will almost always yield superior assessments of their conditions. They also have a point that it's more appropriate to draw comparisons from a dataset with less variation (ie fewer catchments.) However, the spatial configuration of land cover patches remains unaddressed. In fact, they seem to use pattern and composition interchangeably. Furthermore, they collect very precise on site metrics and compare them against coarse landscape data. Of course the less accurate data predicts less, if there were stream morphology of that resolution for the entire watershed there'd be little need for further metrics. There was a clear contrast in the style of the two articles, and I feel Lammert constructed a more coherent and focused picture of his analysis.

O'Neill RV et al (1997) Monitoring Environmental Quality at the Landscape Scale. BioScience 47:513-519

This review provides a basic introduction to the potentials of a landscape level approach, with sections discussing watershed integrity and water quality. O'Neill et al provide a clear, eloquent, and exciting picture of the emerging science of landscape ecology, and their predictions of where and how the science will progress have rung true over the past twelve years.

Roth NE, Allan JD, Erickson DL (1996) Landscape influences on stream biotic integrity assessed at multiple spatial scales. Landscape Ecology 11:141-156

This study examined the impact of land cover on a Midwestern watershed dominated by agriculture. An Index of Biotic Integrity and a Habitat Index rated stream conditions. Vegetative cover and land use were measured at several scales. The results indicated that agricultural cover on a catchment scale was a much more powerful predictor of stream condition than local site conditions.

Interestingly, this study attempts to quantify the landscape with a variety of alternative techniques, in addition to the methods typically found elsewhere. There as an in depth discussion on the various combinations of buffer width, length, and analysis extent. Several alternative IBIs are evaluated for their predictive power as well. None of these techniques were as informative as those found in the majority of other studies, which I believe strengthens the findings of other researchers. However, a considerable amount of paper was wasted for the sake of this discussion. There was a significant lack of independent variables, but that's an inherent characteristic of the system being studied. Land cover shapes habitat quality shapes biotic community. It was surprising that vegetative buffers were such a secondary factor compared to agricultural inputs, and therefore irrelevant to conservation. However, there is no attempt to examine what is adjacent to the buffer. Pattern relations are crucial.

Strayer DL et al (2003) Effects of Land Cover on Stream Ecosystems: Roles of Empirical Models and Scaling Issues. Ecosystems 6:407-423

This study used preexisting databases to create empirical models based on a variety of predictive and response variables, as well over several spatial extents. Despite several emerging relationships, such as total agricultural lands to nitrate output and wetland to native species, the model lacked significant explanatory power. It's likely this resulted from a small sample size and shortcomings in the selected variables. However, the lackluster results are softened by a wealth of insightful discussion. Some topics included the roles of mechanistic and empirical models, the implications of technological advances for modeling, the necessity of incorporating the temporal scale, and the appropriate domain of a model. The lack of consistency within the results was due to the varied mechanisms influencing the response variables. As a result, the spatial scale that best captures the extent of controlling mechanisms will have the greatest explanatory power.

Van Sickle J et al (2004) Projecting the Biological Condition of Streams under Alternative Scenarios of Human Land Use. Ecological Applications 14:368-380

This study created regression models to predict the response of five separate biological indicators under four different alternative land use scenarios. Data collected circa 1990 for the Willamette River Basin served as a baseline for stream health. Each reach was modeled using the upstream composition of the watershed, both within its entirety, along a 120 m riparian buffer, and along a narrower local buffer. The study found current and accelerated development trends resulted in no significant change in biological condition, and a conservative trend slightly restored stream health. None of these trends approached the dramatic shift from pre-colonial to current development.

Any model dealing with a system this complex inevitably convoluted. The attempt to incorporate error propagation when scaling the reach level results to a basin wide scale seemed crucial for this kind of study. Furthermore, there is an extensive discussion of the highly correlated models from which the 'best fit' was selected. Nevertheless, the esoteric modeling process obfuscates the results of this study, and therefore its practical application to decision making. I was surprised that there was little further degradation predicted if current trends continue. It's not clear to me whether this is due to the nature of ag-urban shifts or a lack of predictive power within the model.

Wear DN, Turner MG, Naiman RJ (1998) Land Cover Along an Urban-Rural Gradient: Implications for Water Quality. Ecological Applications 8:619-630

This study examined the influence of position along an urban-rural gradient to land cover along the Little Tennessee River, and the implications for water quality. Several statistical models for land cover change were created using variables for distance to urban center, distance to road, population density, and slope. The best-fit model was then incorporated into a land change simulation for a hypothetical forested landscape and analyzed at incremental distances from an urban center.
The results found a strong correlation between position and composition in private lands, but not in public forests.

While its conclusions are intuitive, this study does a great job of generating a simple, flexible model from real world data, which can be modified and applied by land stewards to make critical conservation decisions. The biggest implication from a management standpoint is that change is concentrated at the edge of urban expansion and at the most remote portion of the landscape, facilitating more effective management efforts.