Watershed Land Cover / Water Resource Connections

Forecasting Future Land Use and Its Hydrologic Implications:
A Case Study of the Upper Delaware River Watershed

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Abstract

We mapped recent land use change patterns in an approximately 8,000-km^2 area encompassing the Upper Delaware River watershed with satellite imagery and used these data to calibrate a predictive spatial model of urban growth rates and patterns. With local stakeholders, we developed various future scenarios of growth to simulate the influence of different land use policies and land management practices, incorporating a variety of environmental, transportation, and other data sources. We generated forecasts of future urban growth patterns, including low-density residential development, under scenarios featuring current growth trends, increased growth, and increased conservation. These future scenarios form the basis for a number of environmental assessments of urbanization in the region. We incorporated the forecasts into a hydrologic model to examine the implications of urbanization on hydrologic factors—runoff, baseflow, and sediment loads—that are linked to water quality and aquatic biota management priorities for the watershed. The outcomes demonstrate how the spatial patterns of urbanization are likely to influence hydrologic dynamics in the future, notably by increasing runoff and sediment loads while decreasing baseflow under scenarios with greater development and associated impervious cover. The approaches, tools, and data sets employed here are useful not only because they produce forecasts in easily understood map form, but also because they are well documented and widely available to resource managers, policymakers, and a range of other stakeholders for diverse watershed applications, including mitigation, restoration, and adaptation objectives.

Introduction

Increased urbanization is well known to result in greater impervious cover, which modifies hydrologic processes such as the timing and magnitude of flow volume and peak discharge rates (e.g., "flashiness;" Ackerman and Stein 2008; Jacobson 2011; O'Driscoll et al. 2010; Schueler et al. 2009). These hydrologic changes, which occur even with low-density residential development, also modify water quality, instream habitat, and aquatic diversity (Booth et al. 2002; Goetz and Fiske 2008; King et al. 2005; Snyder et al. 2005). Estimating the magnitude of these changes and forecasting them into the future would allow land planners and managers to tailor development activities to effectively mitigate the negative consequences of urbanization, specifically those associated with commercial, industrial, and residential development.

Greater impervious cover hinders the infiltration of precipitation into the soil and ground water; thus, the overall expectation is one of reduced baseflow and increased overland flow (runoff). To better understand the various impacts of impervious cover, however, one may need to establish how the spatial distribution of new development influences hydrologic dynamics. For example, the placement of housing and commercial development will alter flow patterns within watersheds, changing both the timing and location of peak flows. Hydrologic models that incorporate spatial information (i.e., map data), particularly regarding land cover change, can be used to predict these dynamics (Beighley et al. 2009; Brabec et al. 2002), but future land cover information is not generally available for most areas.

This paper describes a unique case linking a spatially explicit urban land cover change model to a hydrologic model to investigate the expected future hydrologic impacts of impervious cover associated with exurban development in an environmentally sensitive landscape, the Upper Delaware River watershed. We first describe the land cover change component of the analysis, followed by the hydrologic modeling component that incorporated the land cover change results. For the land cover change predictions, we simulated several possible scenarios of development out to the year 2030 using version 3r of the Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade (SLEUTH) model (Jantz et al. 2010), a widely available model with an active group of users (Clarke et al. 2007; National Center for Geographic Information and Analysis n.d.). We used land cover change data, mapped by satellite imagery, to calibrate SLEUTH for the simulation of historic rates and patterns of development

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Table 1. Population growth rates in the four counties included in this study.

County	2010 Population	2000–2010 Growth Rate	Developed Area 2005 (km²)[a]	1984–2005 Growth Rate
Pike Co., PA	57,369	24.0%	23.75	191%
Wayne Co., PA	52,822	10.7%	32.80	260%
Sullivan Co., NY	77,547	4.9%	42.12	131%
Delaware Co., NY	47,980	−0.16%	33.02	206%

[a] *Does not include road area.*

and to create forecasts of future urban land cover change for a range of scenarios developed with a group of local stakeholders. We then used the Soil and Water Assessment Tool (SWAT2000), which is part of the Automated Geospatial Watershed Assessment (AGWA) program, to predict the impact of land use on water and sediment yields.

The Study Area

The Upper Delaware River basin (Figure 1) is located at the intersection of New York, New Jersey, and Pennsylvania, within 161 km (100 miles) of the New York Metropolitan Area (some southern counties within the basin form the northwestern extent of the metropolitan area). The watershed contains some important natural, scenic, and recreational resources, including two National Park Service (NPS) units— the Upper Delaware Scenic and Recreational River (UPDE) and the Delaware Water Gap National Recreation Area. Along with watersheds in the adjacent Catskill Park and Catskill Forest Preserve, the Upper Delaware River watershed provides source water protection and reservoirs for New York City's water supply. The watershed also includes the New Jersey Highlands, an environmentally sensitive region of source water protection for millions of residents in New Jersey.

Despite the designation of UPDE as a scenic and recreational river, NPS has little direct control over land use in the river corridor and thus works closely with adjacent municipalities to encourage land preservation and land use practices that will not threaten the park's resources. Given the growth pressures that originate primarily from the New York Metropolitan Area, many of the counties in the southern and central part of the study area have experienced sustained exurbanization over the past few decades. Recent growth rates continue to be high; many counties in the study area are among the highest-ranked counties within their states in terms of growth rates between 2000 and 2010. The 2000–2010 growth

Upper Delaware
- Watershed Delineation
- Mongaup Basin
- Prompton Basin
- UPDE
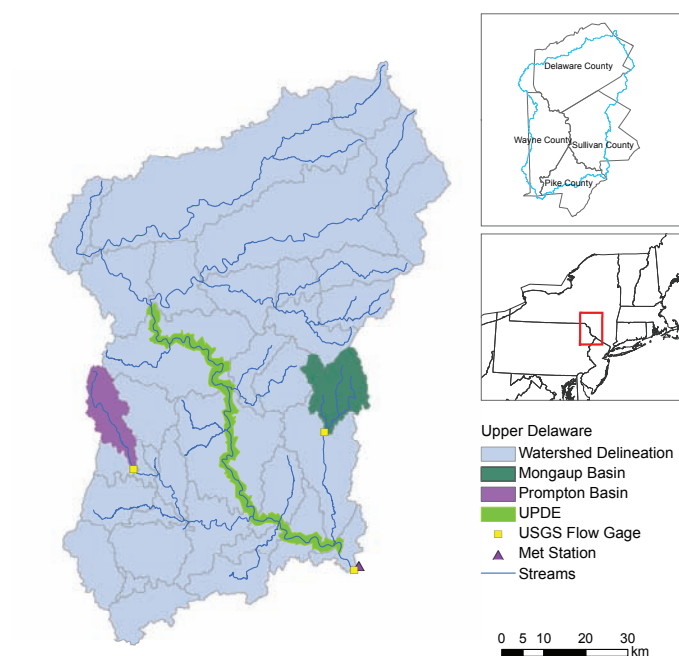- USGS Flow Gage
- Met Station
- Streams

0 5 10 20 30 km

Figure 1. The study area showing boundaries of the Upper Delaware River watershed, as defined by the 7,960-km² area draining to the US Geological Survey river gauge at Port Jervis. Sub-basins within the watershed (gray lines) were used as the basis for hydrologic modeling. The locations of the Prompton and Mongaup sub-basins, used for model testing, are shown for reference. The UPDE is also highlighted, and the location of the Port Jervis meteorological station is indicated.

rate in Pike County, Pennsylvania, was 24.0%, compared to a statewide growth rate of 3.4% (Table 1). Monroe County, Pennsylvania, grew at a rate of 22.5%; together Monroe and Pike Counties ranked second and third, respectively, of the 67 counties in Pennsylvania. The population in Orange County, New York, increased 9.2% compared to a statewide growth rate of 2.1%; this county ranks second of the 62 counties in the state. Thus, the question of how development in the surrounding communities might affect hydrology and other ecosystem processes in the Upper Delaware River basin has generated considerable interest.

To address these concerns, we coordinated an effort with NPS and the four counties that account for most of the land area within the Upper Delaware River basin (Pike and Wayne Counties in Pennsylvania and Sullivan and Delaware Counties in New York) to simulate and forecast urban land cover patterns. These stakeholder groups are now using the forecasts as a basis for ecosystem assessment studies, including the hydrology discussed here.

Mapping Current and Future Urbanization Patterns and Rates

We defined current land cover using the widely available National Land Cover Database (NLCD) combined with more detailed impervious cover maps derived specifically for the study area for 1986, 1996, and 2005 (Jantz and Goetz 2007; Jantz et al. 2009). The NLCD provides a nationwide impervious cover layer (circa 2001), but calibration of the urban change model requires a time series of maps that identify land cover change. This study used a time series of change derived from the Landsat series of satellites at a nominal spatial resolution (grain size) of 30 m (900 m^2). We assessed the products for accuracy using aerial photographs and corrected them for false positive change detections (e.g., bare agricultural fields, bare rock outcrops, quarries, and landfills) through visual editing of the digital maps (Jantz et al. 2009). We then used the land cover products to calibrate the urbanization model as described below; this permitted predictions into the future.

Scenario Development

We generated future urbanization predictions using SLEUTH, a probabilistic, cell-based model that we applied separately for each county in the study area. Inputs to SLEUTH include a slope layer derived from the US Geological Survey (USGS) 30-m National Elevation Dataset (NED), a transportation layer reflecting primary roads, and a layer describing areas that will either attract or not attract (or, one might say, *exclude*) development. The exclusion–attraction layer is particularly important for SLEUTH predictions because it provides what is essentially a weighted surface to guide the spatial allocation of growth. Here, exclusion and attraction refer to urbanization, specifically the urban land cover categories on which the model was calibrated (described in the next section), and various data layers developed for each county-specific future scenario.

We worked with county planners and other stakeholders within each county to (1) identify primary "attractors" of growth (e.g., proximity to the New York Metropolitan Area, proximity to natural amenities, and local land use policies), and (2) define future land use scenarios expressed through the exclusion–attraction layers. For forecasting, stakeholders from each county developed a county-specific set of narratives representing a range of relevant land use policy and land use change scenarios. We translated each narrative into a map representing the areas that would attract or repel development. Pike County stakeholders, for example, developed a total of six narratives ranging from a scenario with strict spatial controls on growth and high levels of protection for lands rich in natural resources, to a scenario that allowed dispersed growth patterns with minimal protection of natural lands. This resulted in scenarios that represented a range of realistic future policies and drivers (attractors) relevant for the specific planning needs of each county.

In addition to county-specific land use policy and land use change scenarios, which essentially enabled the application of spatial weights to areas where growth is more or less likely to occur, we also modeled different rates of growth for each scenario: a linear growth rate based on the 1984–2005 growth rate, a "boom" growth rate that was roughly 25% higher than the 1984–2005 trend, and a "bust" growth rate that was roughly 25% lower than that trend. In the case of Pike County, this resulted in a total of 18 different forecasts (3 growth rates for each of 6 land use change scenarios).

Even though the scenarios were county-specific, the emergence of common themes (e.g., "smart growth" vs. "sprawl") across counties allowed us to group common scenarios together. For this study, we were therefore able to combine results across counties to develop three watershed-wide scenarios that essentially reflect low, moderate, and high expectations for future urban growth (including low-density residential development). These scenarios include (1) a Conservation scenario reflecting land use policies that require strong protections on natural lands, spatially clustered development, and a low rate of growth; (2) a Trend scenario with policies reflecting the status quo of moderately focused development and moderate protection of natural lands with a linear growth rate; and (3) a Growth scenario reflecting limited protection of natural lands, dispersed development patterns, and a high growth rate. The spatial extent of the output simulations (probability maps) is 10,796 km^2 at a spatial resolution of 30 m, with each cell assigned a probability representing the likelihood that the cell will be transformed to impervious cover (i.e., developed) by 2030.

Table 2. Accuracy results for each county at the municipal scale and for the 1 km x 1 km array.

County	Municipal-scale accuracy		1 km x 1 km–scale accuracy	
	Municipalities (N)	r^2	Cells (N)	r^2
Pike	13	0.99	1,464	0.83
Wayne	28	0.98	1,938	0.82
Delaware	19	0.90	3,802	0.88
Sullivan	15	0.95	2,579	0.92

Calibrating the SLEUTH Model

The calibration phase used an expert-weighting approach in which county planners identified a set of factors that had acted to either exclude or attract development between 1986 and 2005 (Jantz et al. 2009). For example, stakeholders in both Pike County, Pennsylvania, and Sullivan County, New York, identified their proximity to the New York urban core as a driver for growth pressure, so we weighted factors to reflect higher growth pressure in the southeastern part of the watershed and lower growth pressure in the northwestern part (our assumption is that this growth pressure will persist through the 2030 forecast period). In contrast, in central and southeastern Delaware County, New York, growth is largely restricted to reflect the protection of watersheds that supply water to the New York Metropolitan Area. For each county, we assigned each factor a weight and combined all factors into a single map that reflected growth pressures over the time period used for calibration. Based on tests of the model's performance both with and without the use of the expert-weighted exclusion–attraction layer, we note that the exclusion–attraction map developed in conjunction with county planners significantly improved model performance (Jantz et al. 2009).

While the exclusion–attraction layer weights areas differentially for potential development, whether an area undergoes nonurban-to-urban change is determined through the application of five growth rules, each of which is associated with a parameter value that can range from 0 to 100 (see Jantz et al. [2010] for specifics). These rules include *diffusion* (the development of single cells), *breed* (the development of a group of cells), *spread* (edge growth around existing urban areas), *slope* (resistance to development on steep slopes), and *road-oriented growth*. During model calibration, we tested multiple possible combinations of growth parameter values over a range of randomized trials, resulting in an optimized parameter set. The particular value derived for a growth parameter describes its influence in generating

a particular pattern of development (e.g., dispersed vs. clustered) and also controls the overall amount of growth. Because of this, the SLEUTH model can be adapted to growth rates and patterns that are specific to a study area. By optimizing the model's ability to simulate the amount of development and the patterns of development, we were able to match the amount of growth and the number of urban clusters (a pattern metric) within 5% for all counties.

We measured model fits by comparing rate and pattern metrics for simulated urban growth (averaged over a set of trials) with observed urban growth (mapped from Landsat imagery); this allows one to discern the amount and direction of over- or underestimation produced for each metric and for each set of parameter values being considered and thus to "train" the model. This calibration phase of the SLEUTH modeling showed high accuracy across all scales for simulating rates and patterns of development that occurred between 1984 and 2005 (Table 2). For each county, we matched to within 5% the fractional difference in total urban area between the modeled and observed urban land cover maps and the fractional difference in urban clusters, indicating good performance of the model at the county scale. At the municipal scale, a regression analysis comparing modeled and observed urban extent explained 95% of observed urbanization in Sullivan County, New York, and 99% in Pike County, Pennsylvania (see r^2 values in Table 2). While accuracy declined at the finer scale of 1 km x 1 km cells, explained variance was still high and ranged from 82% to 92%.

Generating Forecasts of Development with SLEUTH

As described above, we developed a set of forecast scenarios that reflect different land use policies, using the same stakeholder-based approach that we used for model calibration. The scenarios essentially modify the exclusion–attraction surfaces to reflect various possible land use objectives or contingencies. These scenarios form the basis for
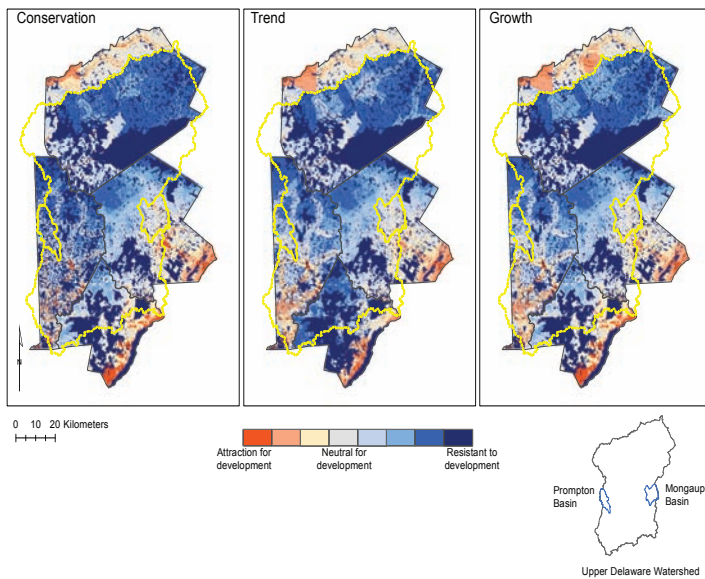
Figure 2. Scenarios depicting the probability of development, as derived from multiple data sources in collaboration with a wide range of stakeholders from four counties within the Upper Delaware River watershed. Areas in blue indicate resistance to development, gray areas are neutral for development, and shades of red indicate areas that are likely to attract development.

forecasts of urban development from 2005 to 2030. The forecasts are the combined result of 100 randomized trials for each scenario, with each cell assigned a probability of development by 2030. While each county generated a unique set of forecasts, they had common elements that allowed us to combine results for all four counties to represent the three watershed-wide scenarios described previously. In Figure 2, areas that are likely to attract growth are shown in shades of red, areas that are likely to repel growth are shown in shades of blue, and areas considered neutral for development are gray. Note that, in general, the Conservation scenario tends to have more areas shaded blue, whereas the Growth scenario tends to have more areas in red.

As noted above, SLEUTH generates maps that show the probability of development. We translated the probability maps into impervious cover maps by classifying any grid cell with a probability of development greater than 50% as developed land. We chose the 50% threshold on the basis of past work calibrating satellite imagery to aerial photos (Goetz and Jantz 2006; Jantz et al. 2005), but variations on this threshold are possible depending upon the user's desired application. We overlaid these development predictions on the 2001 NLCD land cover map and designated all areas that were either "developed" according to the model or

"urban" in the NLCD map as developed areas. All other areas maintained their current land cover, as defined by the NLCD. We applied this approach to each of the three future land use scenarios (Table 3).

Figure 3 shows basin-wide forecasts of future urbanization for each scenario compared to current conditions (2005). As expected, the Conservation scenario shows the least overall growth compared to the other two scenarios (Table 2). Under the Trend scenario, low-density development expands significantly across the central watershed, and this outcome is enhanced under the Growth scenario. The Conservation scenario shows urbanization mostly intensifying in and around existing developed areas but also shows some dispersed, low-density development.

We then used each of these scenarios, and the differences between them, to explore the hydrologic implications of increasing urbanization and associated potential land management policies.

Hydrologic Modeling and Outcomes

We incorporated the land cover change forecasts described above into the SWAT model (within AGWA). SWAT is a quasi-spatial (distributed) model developed by the US Department of Agriculture Agricultural Research Service to predict the impact of land management practices on water, sediment, and agricultural
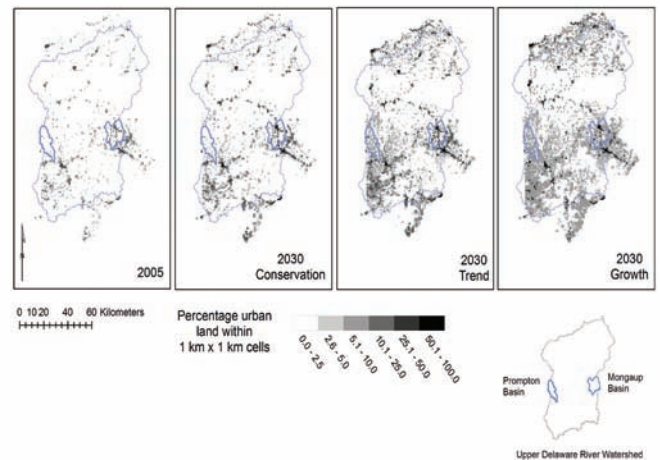

Figure 3. Forecasts of future impervious cover associated with different scenarios of urban development (three right panels) compared to impervious cover mapped in 2005 (left panel). The original 30-m resolution data have been rescaled to a 1-km resolution so that basin-wide patterns can be discerned.

Table 3. Area of land (in km²) devoted to each land cover type for current (2005) conditions and under each development scenario. Although the percentage of developed land in the entire basin increased from 4.5% currently to 6% for the Growth scenario, forest was the predominant land cover for every scenario.

Land Use	Current	Conservation	Trend	Growth
Developed	363	422	448	479
% Change from Current	—	16	23	32
Undeveloped	7,423	7,365	7,339	7,308
Forest	6,212	6,181	6,168	6,152
Agricultural	927	904	892	880
Wetlands	189	187	186	185
Other	95	93	93	92
% Change from Current	—	−0.8	−1.1	−1.5

chemical yields in complex watersheds with varying soils, land uses, and management conditions (Gassman et al. 2007). It is a widely used model, partly because it was designed to operate within commonly available geographic information system (GIS) software. SWAT is simpler than fully spatial hydrologic routing models, but it requires fewer, less detailed inputs to produce results useful for assessing general hydrologic trends resulting from land use change.

As noted above, we delineated the Upper Delaware River watershed into sub-basins (shown in Figure 1), each parameterized by its hydraulic geometry, flow length, land cover, and soil properties. We ran the SWAT model to include each of these small watersheds, which experienced different rates of urbanization (shown in Figure 3). We used the Prompton sub-basin (1,954 km²), located near the southwestern corner of the greater watershed, and the Mongaup sub-basin (2,576 km²), located toward the southeastern corner of the basin, to assess the model calibration based on USGS river gauge measurements. The hydrologic model used daily meteorological data, specifically minimum and maximum temperature and precipitation. We assumed homogeneous climatic conditions throughout the study area, based on the meteorological station data collected at Liberty, New York, about 50 km from the Port Jervis river gauge in Pennsylvania. Although one could produce a more accurate model calibration using meteorological data from multiple stations, the present study instead focused primarily on the effects of land use change rather than, for example, spatial variability in precipitation. Additional model inputs were based on data sets freely available to any user, including 30-m NED data, a national hydrologic database of the stream network (flowlines), State Soil Geographic Database soils data, NLCD 2001 land cover data, and roads.

Hydrologic Model Calibration and Assessment

For model calibration, we refined the curve numbers for land cover parameterization to determine the best match between the modeled flow volume and the observed river gauge measurements. We parameterized each land cover class within SWAT using a number of factors (the curve numbers for each hydrologic group, percentage impervious cover, interception, and Manning's N), with impervious cover as a particularly important calibration parameter. We ran the model calibration using precipitation data from the Port Jervis gauge (downloaded from the USGS website, station 01434000) for the three-year period 2000–2002 at a monthly time step. The calibrated parameters produced a match (Nash–Sutcliffe coefficient) of 0.4, which is considered good (Moriasi et al. 2007). Although the model tended to slightly underpredict water yield in periods of low flow and slightly overpredict it in periods of high flow, the timing of the minima and maxima were close to the gauge-measured values.

Using the calibrated parameters, we then ran a 25-year simulation for the entire watershed, obtaining monthly averages for baseflow, runoff, and total water yield. In repeating this process for each future land use scenario we captured changes in impervious cover associated with development. We used the same parameter set for all model runs for each scenario to ensure that results would be consistent and comparable.
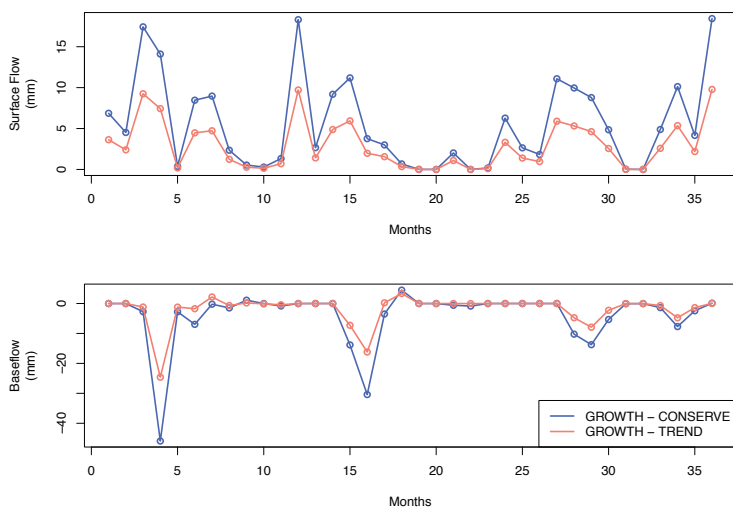
Figure 4a. A comparison of differences in monthly surface flow (top) and baseflow (bottom) for the Growth scenario relative to the Conservation scenario (blue line) and the Growth scenario relative to the Trend scenario (red line). The values reflect the differences between the Growth scenario values for surface flow and baseflow and the values from the other two scenarios. Results show greater amounts of surface flow and reduced amounts of baseflow when and where urban development increases._

Hydrologic Implications of Future Urbanization

The model for the land use change scenario forecasts out to 2030, baseflow would decrease and surface runoff would increase as the level of development intensified, with the Growth scenario showing the greatest changes and the Conservation scenario the least. These contrasts were emphasized when we examined the difference between the possible future land use scenarios, that is, the difference between the Conservation and Growth scenarios or between the Trend and Growth scenarios (Figure 4). The hydrologic implications of these comparisons were most pronounced for high-runoff events (Figure 4a), indicating that peak flows would be much greater if the stakeholder-identified conservation measures were not considered. Conversely, baseflows would be substantially reduced without conservation-oriented land management policies, meaning that headwater streams would be more likely to "run dry" or flow at very low levels at some point during the year. Changes of this magnitude would thus not only negatively impact stream biota (including native trout populations), but would also increase the likelihood of potentially damaging and expensive flood events in downstream communities. Spatially, sub-basins with more highly developed areas, particularly those in the northern and southwestern parts of the greater watershed, would experience the greatest changes (Figure 4b).

We also simulated erosion from the watershed (Figure 5) using the Modified Universal Soil Loss Equation, which is part of the SWAT model. We derived sediment yield using some of the other

hydrologic variables produced by the model, such as surface runoff volume (Figure 4b) and the peak runoff rate, but also including soil type erodibility and factors related to management and topography that influence the sediment lag time in surface runoff. As with runoff and baseflow, changes in sediment load were clearly associated with the differences between the land use forecast scenarios. Sediment loading was greater where impervious cover and associated surface flows increased. We expected this since greater flow volumes from more impervious areas would have greater capacity to produce erosion and to transport greater loads and larger particle sizes. Sediment loading could be reduced in some areas of greater impervious cover if the associated urbanization process replaced agricultural lands, as opposed to, for example, forested lands. The results shown in Figure 5 thus represent the net effect of changes in urbanization among multiple land cover type transitions.
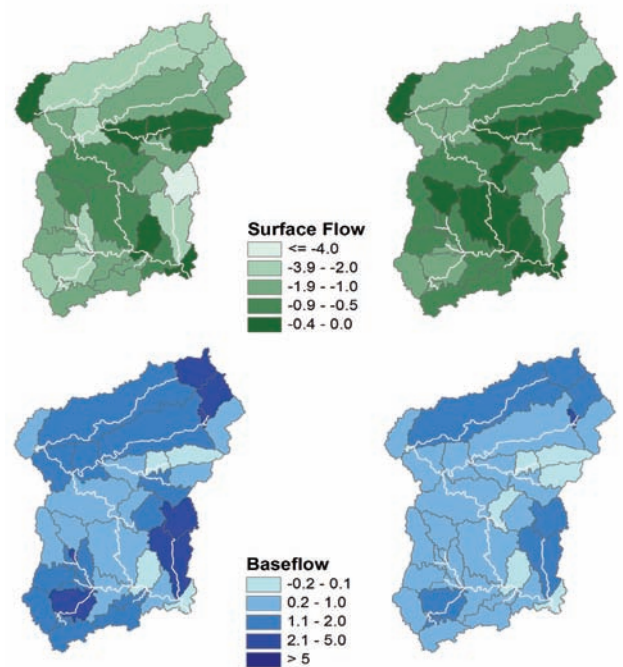

Figure 4b. Map depiction of the results from Figure 4a, showing differences in average annual surface streamflow (top) and baseflow (bottom) for the Conservation (left) and Trend (right) scenarios. As in Figure 4a, each is differenced with (subtracted from) the Growth scenario. These SWAT model outcomes are for a 25-year simulation period (2005 to 2030) but do not incorporate future climate (i.e., they are based on 1981–2006 precipitation records). Results clearly show reduced surface runoff and greater baseflow when and where increases in impervious cover are constrained._

The outcomes of the hydrologic analyses highlight the importance of spatial information in modeling the implications of impervious cover changes associated with urbanization. That said, we recognize that this analysis could be improved in a number of ways. For example, one could illuminate mechanisms of flow through areas of varying impervious cover by using more specific and detailed information on flow connectivity, or perhaps by distinguishing among different types of development (industrial, commercial, or residential). Similarly, available data did not allow for a consideration of the location of retention ponds or for the use of specific low-impact development techniques or best management practices that may mitigate some of the negative impacts of increased urbanization and associated impervious cover on hydrologic dynamics, such as peak runoff volume and increased flashiness of streams (Booth et al. 2002; Dietz 2007). This is not to say that site design can be expected to fully mitigate the impacts of land use change, but rather simply to note that, where the effectiveness of such efforts has been quantified, it may be possible to incorporate those outcomes into spatial scenarios, such as the ones presented here. Notably, the location and situation of new development, such as proximity to stream networks and surrounding topology, could be incorporated, via spatial distance–weighting schemes to assess the influence on streamflow patterns associated with flow routing across areas of interest (e.g., where mitigation efforts are planned). Related efforts may include simple metrics of housing density per square kilometer (Jacob and Lopez 2009) or other spatial metrics capturing more dispersed or clustered development (Steuer et al. 2010).

Even without explicitly modeling flow paths, the statistical averages for each sub-basin used in our SWAT modeling were able to capture the hydrologic implications of changing urbanization and how spatial changes in impervious cover accumulate across watersheds (see Figures 4a, 4b, and 5). The model captured significant changes in hydrologic dynamics and demonstrated the potential implications of urbanization associated with the various forecast land use change scenarios.

Conclusion

The findings presented here underscore the relevance of policies that broadly support growth strategies emphasizing resource protection and the positive benefits of reducing impervious cover at the landscape scale. Clearly lower growth levels, specifically in terms of minimizing impervious cover associated with development, will also minimize impacts on water resources. These results are perhaps not
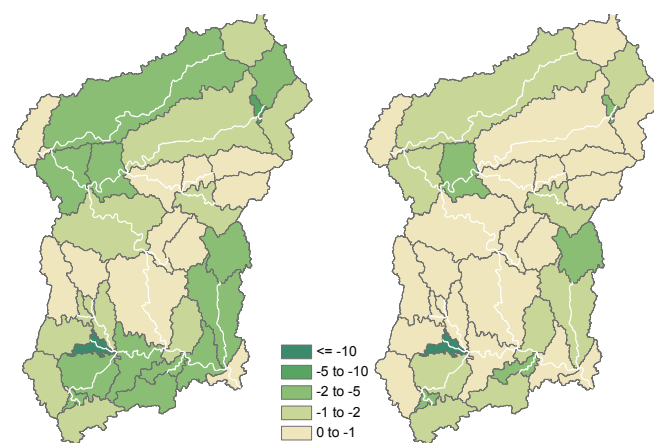

Figure 5. Percentage differences in average annual sediment yields for Conservation (left) and Trend (right) scenarios. As in Figures 4a and 4b, each map illustrates values that represent differences from the Growth scenario. Under the Conservation scenario, sediment loading was lower than under the Trend scenario, and sediment loading in both of these scenarios were lower than that under the Growth scenario.

surprising, but they highlight the importance of limiting the footprint of urban land cover if protection of water resources is a priority, and they demonstrate that this can be accomplished in a readily conveyed map form incorporating future land development and conservation scenarios. This case study of the Upper Delaware River watershed did not incorporate population or employment forecasts, so one should keep in mind that the three development levels we forecast might accommodate similar levels of population and employment growth, assuming a higher density (smart growth) in the Conservation scenario and a lower density (sprawl) in the Growth scenario. Proactive land use planning therefore remains paramount in this, and undoubtedly other, environmentally sensitive regions.

The involvement of stakeholders, especially county planners, in both the model calibration phase and the development of forecast scenarios greatly enhanced this modeling effort. First, the local knowledge of the study area provided by stakeholders improved the performance of the land use change model. Second, the forecast scenarios reflect what planners perceived to be realistic future alternatives. Our findings regarding the importance of land use policies that encourage spatially clustered development, higher densities, and the protection of natural lands provide support for the adoption of such policies.

All analyses and outcomes reported here were based on tools and data sets available to the land planning and watershed management communities, among other stakeholders.

They reflect the fact that most development routes surface flow across impervious surfaces to storm drain systems that effectively connect development to the hydrologic network (i.e., streams and rivers). To the extent necessary, different types of hydrologic models may allow one to incorporate various types of impervious cover and explicitly route flow by coupling them to realistic representations of storm drain networks, but our results show that users can reasonably and realistically predict the hydrologic implications of future development using an approach like the one we describe, which is intuitive, effective, and readily available.

Acknowledgments

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