MODELING CHANGES IN THE SPATIAL DISTRIBUTION OF SOIL SATURATION IN URBANIZING WATERSHEDS

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Abstract. The focus of urban hydrology has traditionally been upon flood-event runoff and the management of storm water. However, the impervious cover that is an element of urbanization can also cause diminished soil moisture levels and lower base flows due to less recharge to a watershed's near-surface groundwater system. Presented here is a modeling approach for examining urbanization-related changes in soil moisture levels. This approach employs a TOPMODEL-like topographic index that is implemented using a spatially distributed watershed representation within a geographic information system. Using the model, the changes resulting from urban development upon the extent of the saturation zone in a small, north Georgia watershed are simulated. Based upon model results, residential development of a forested watershed is shown to result in a 15 percent decrease in saturated watershed area.

INTRODUCTION

Much of the Atlanta metropolitan area is undergoing rapid urban growth. Unfortunately, a common consequence of urban growth is degradation of water resources and environmental conditions. In forested watersheds, most rainfall infiltrates into forest soils and is delivered to a stream hours, days, or even months after a slow transit through the shallow groundwater system. Urbanization changes the fundamental hydrological processes of a watershed causing rapid runoff from impervious areas to be delivered to streams within minutes. Consequently, peak streamflows dramatically increase.

At the other end of the hydrological cycle, impervious areas also prevent infiltration and recharge of the groundwater system. This disruption in hydrological processes can manifest as less groundwater recharge, fewer saturated areas in a watershed, and lower base flows in a watershed's streams. Streamflow characteristics of Peachtree Creek in DeKalb County tend to support the hypothesis of less infiltration and lower base flows in an urban watershed compared with similar non-urban watersheds (Rose and Peters, 2001). However, a confounding factor is that forest removal due to urbanization can result in increased soil moisture levels due to lowered evapotranspiration and therefore result in increased stream base flows.

The manifestation of reduced recharge to the groundwater system is less saturated area and lowered base flows in a watershed's drainage network. Flow reductions in 1st order reaches can convert perennial reaches to intermittent or ephemeral flow. A reduction in stream length in low-order tributaries might not only have adverse consequences upon the aquatic ecosystem, but it also could affect the associated riparian-wetlands that occur in these saturated areas. The objective of this paper is to present a modeling approach for assessing potential changes in the spatial extent of saturated areas and perennial stream length in urbanizing watersheds.

BACKGROUND

In forested watersheds, very little watershed area produces direct overland flow runoff during rain events. Rain falling on stream channels and completely saturated areas adjacent to stream channels is the primary source of contribution to the storm hydrograph (Dunne and Black, 1970). However, this "saturation excess" runoff generation is limited to a fairly small area of a watershed. Over most of a forested watershed's area, nearly all precipitation infiltrates and becomes part of the soil water or groundwater systems. In areas with shallow bedrock, this infiltrated water will first percolate downward through the soil and then be forced to move laterally when it hits the more impervious bedrock below. This lateral groundwater movement is directed down the hillslope following the bedrock surface, which can be approximately related to surface topography.

Field observations by many scientists indicate that higher soil moisture and areas of surface saturation tend to occur with increasing watershed area, decreasing local slope, thin soils, and an increased rate of watershed recharge (precipitation input minus losses). Ridge tops and upper hillslopes are relatively dry but points farther downstream, particularly where topography converges, become wetter until soil saturation and possibly overland flow occurs. These saturated areas with overland flow become locations of perennial streams in forested watersheds if the saturated condition remains year-round. These saturated areas are typically occupied by wetland plant species.

Beven and Kirkby (1979) implemented this idea of topographically defined areas of saturation into a simple relative wetness index based upon the topographic structure of a watershed. They devised a topographic index, *ln (a/tan b)*, where α (specific catchment area) is the upslope area draining through a point and β is the local land slope. Locations where the index is higher (lower slope or larger specific catchment area) are parts of a watershed more likely to be saturated. A number of assumptions are implicit in the index. It assumes a steady state soil moisture condition, flow parallel to a shallow bedrock surface, and transmissivity decreasing exponentially with depth. Although one can find many faults with such a simple model structure and the steady state and other assumptions, the index does provide an uncomplicated mechanism for modeling forested environments.

In forested areas that become urbanized, hydrological processes change due to the addition of impervious cover (e.g., buildings, streets, parking lots) and the removal of forest vegetation. Runoff production by the saturation excess mechanism is replaced by the “infiltration excess” mechanism devised by Horton (1933). For impervious areas, nearly all precipitation may be converted to runoff, and there is little infiltration. In essence, recharge to the groundwater system is reduced because rainfall is transformed into overland flow runoff that rapidly exits the watershed. Less groundwater recharge will result in lower soil moisture levels, less extensive areas of saturation, and lower base flows in watershed streams. Alternatively, forest removal can reduce evapotranspiration rates and soil moisture losses to the atmosphere. In subtropical areas, evapotranspiration is generally radiation-limited, and evapotranspiration frequently exceeds runoff in the water budget. Thus, urbanization may result in either increases or decreases to groundwater recharge.

MODEL DESCRIPTION

The TOPMODEL concepts conceptualized by Beven and Kirkby (1979) are implemented here using a grid-based approach within a geographic information system (GIS). A grid digital elevation model (DEM) is used as the base grid to describe watershed topography. Grid DEMs consist of a matrix data structure with the topographic elevation of each grid cell stored in a matrix node. Grid DEMs are readily available and simple to use and hence have seen widespread application to the analysis of hydrologic problems (Moore et al., 1991).

The TOPMODEL concepts can be modified to generate a wetness index that can be applied at each grid cell in a grid based GIS:

$$W = R\ a / T \sin q$$

where:

W = is a wetness index,
R = steady-state recharge rate (m/hr), a function of rainfall and evapotranspiration rates,
a = specific catchment area (m) obtained by dividing contributing drainage area by flow path width,
T = soil transmissivity (m^2/hr), and
$\sin q$ = land slope

The index and four input parameters are either specified or calculated for each grid cell. The W parameter is an index of soil wetness. When its value is less than 1, soil moisture levels are at a less-than-saturated condition. Values less than 0.1 are expected on the higher parts of hillslopes and represent very low moisture conditions. Values near 1 will typically occur on lower hillslopes and valley floors. Where W reaches 1, usually farther downstream in valley floors, the ground is saturated. At values of W greater than 1, runoff can be expected to occur. Many factors that may affect soil moisture distribution across the landscape are ignored by this simple conceptualization, but the W index provides a first approximation to specifying soil moisture level and possible perennial stream locations.

In the above equation, $a/\sin q$ is a modification of the TOPMODEL topographic index. Both of these parameters can be automatically calculated from a DEM using GIS methods. In fact, using a DEM and GIS algorithms not discussed here, slope, specific catchment area, flow direction, and delineation of the drainage network and watershed can all be accomplished (e.g., Marks et al., 1984; Jenson and Domingue, 1988; Quinn et al., 1991; Tarboton, 1997).

In this model conceptualization, transmissivity (T) is assumed uniform with depth. Transmissivity can frequently be approximated from soil survey information, and soil maps can be used as the basis for deriving a grid of spatially variable transmissivity.

Recharge to the groundwater system (R) is a function of rainfall and evapotranspiration. In urban landscapes, R can be considered to be near zero for impervious areas. As with the other parameters, R can be varied across a watershed by input of a grid of spatially variable recharge values. Because transmissivity and recharge values - particularly their spatial distribution - can be difficult to determine, they (in combination) are frequently determined through model calibration. Calibration of recharge and transmissivity are done using stream gauging data or by adjusting model parameters until the model spatial distribution of springs and wetlands matches those determined from field studies. Note that the steady state recharge (R) is not necessarily total annual recharge to the groundwater system but may be the amount of recharge during a shorter (or longer) interval that is also dependent upon watershed soil and topographic characteristics.

These model concepts have been implemented into the ArcView® GIS. A DEM and estimates of recharge and soil transmissivity are required to apply the model. Output of the model is a grid of wetness index (W) values. Comparison of the wetness index grids for alternative scenarios (e.g., forested versus urban) allows for assessment of potential land use effects upon watershed hydrological conditions.

MODEL APPLICATION

To demonstrate the potential for using the wetness index concept, the Wildcat Creek watershed in Gwinnett County, Georgia was used for model testing. This 336 hectare watershed was continuously gauged by the U.S. Geological Survey (gage no. 02205000) for water years 1954 to 1982, during which time the watershed was mostly undeveloped. Mean annual unit discharge from the watershed was 452 mm during the period of record. During this time period, mean annual precipitation at the nearby Norcross weather station was 1,343 mm. Annual watershed runoff is therefore about 34 percent of precipitation.

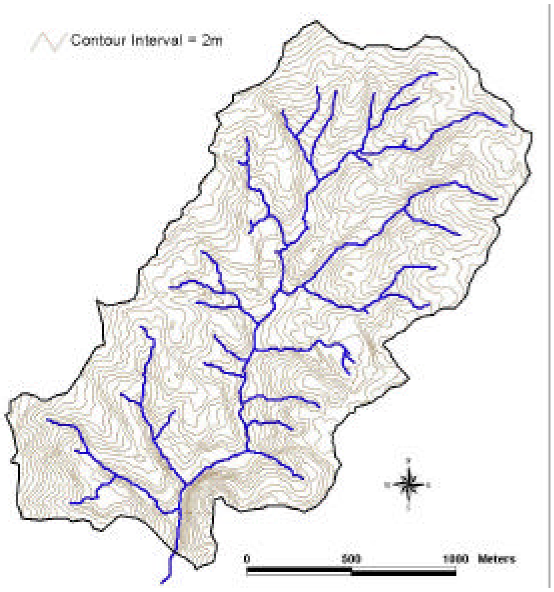

Figure 1. Stream network and topography of the Wildcat Creek watershed.

A 6.1-meter grid DEM of the watershed was used for deriving topographic attributes. Using a curvature based approach (Peuker and Douglas, 1975), the stream network was extracted from the DEM grid (Figure 1). Based upon the DEM-extracted stream network, Wildcat Creek watershed is of 4th order (Horton-Strahler ordering) and has 38 1st order tributaries. Mean hillslope length is 102 m.

The watershed has developed primarily with single family residences, and the current level of impervious cover within the watershed is approximately 19 percent. Figure 2 illustrates the distribution of impervious cover and the cumulative impervious cover percentage for

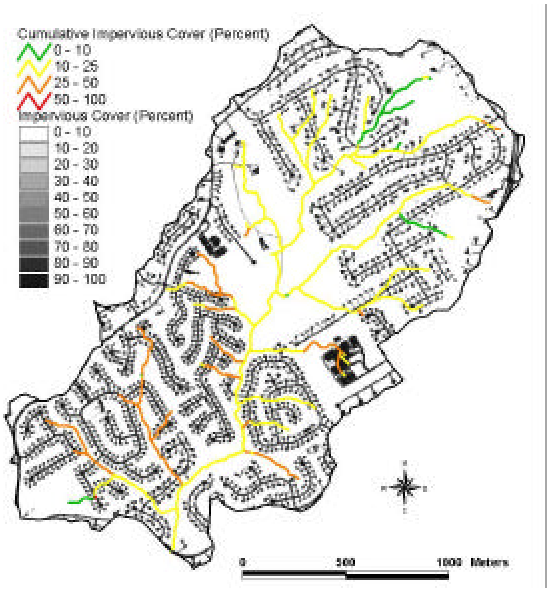

Figure 2. Impervious cover and cumulative impervious cover along the stream network.

each of the GIS-defined streams in the drainage network.

Natural Resources Conservation Service soils mapping and soils characteristics were used to estimate transmissivity. Eight soil classes were defined with transmissivities ranging from about 0.02 to 0.08 m^2/hr. Areas disturbed by impervious cover were given a transmissivity of 0.02 m^2/hr.

Recharge to the watershed was estimated by assuming that recharge is equal to base flow at the outlet gauging station. An annual critical low recharge period of 3 months was selected because hillslope drainage should occur in about that length of time based upon typical hillslope lengths and average soil transmissivities. The months of July through September were used for this analysis because they represent a period of low discharge and precipitation. Base flow was considered to be discharge of less than 0.028 cms. This base flow discharge was chosen from a visual inspection of the daily flow duration curve for the July through September period. A break in the curve to a steeper slope occurred at a frequency of 86 percent at a discharge of 0.076 cms. This break is interpreted as separating base flow from quick storm flow. Using this methodology, watershed recharge during July through September is estimated at 26 mm. For the urban scenario, impervious areas derived from aerial photography were given a recharge of 1 mm. Although disturbed areas would be expected to have altered recharge rates due to soil compaction and changes in vegetation types, we did not attempt to account for these possible changes.

RESULTS AND DISCUSSION

Figure 3 illustrates model-predicted soil moisture conditions for the non-urban forested watershed condition. The darkest areas of the map are those most likely to be saturated (W 1) and to experience perennial flow. Ridge tops and the upper parts of hillslopes have low levels of soil moisture, have W values of less than 0.1, and are depicted by light-colored areas in Figure 3. The drainage area influence upon soil moisture can be seen by comparing Figure 3 with the topographic map in Figure 1. Approximately 11.9 percent of the watershed's area is saturated under this scenario (Table 1).

Under the present-day urban condition, approximately 19 percent of the watershed has impervious cover (Figure 2). This effectively results in a 19 percent reduction in base flow at the outlet, reduced from a unit discharge of 145 mm/year to 117

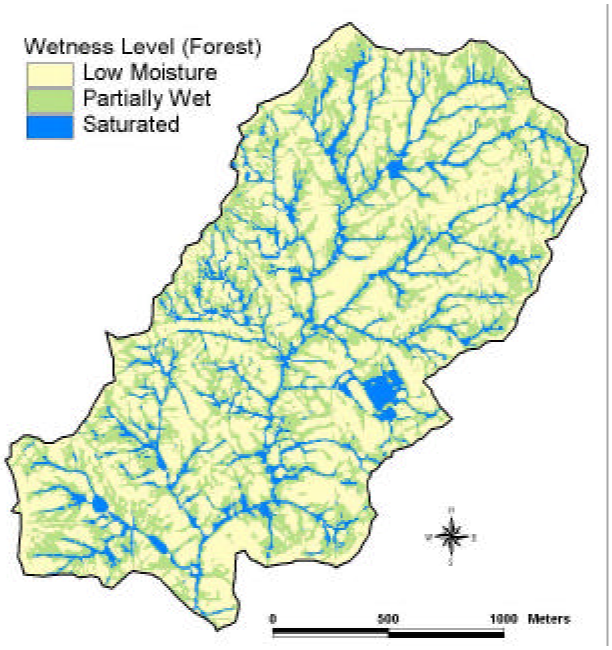

Figure 3. Predicted soil moisture levels for non-urban forested condition.

Table 1. Percentage of watershed area in given soil moisture class for forest and urban scenarios

Moisture Level	Forest	Urban
Low Moisture	51.5	59.3
Partially Wet	36.6	30.6
Saturated	11.9	10.1

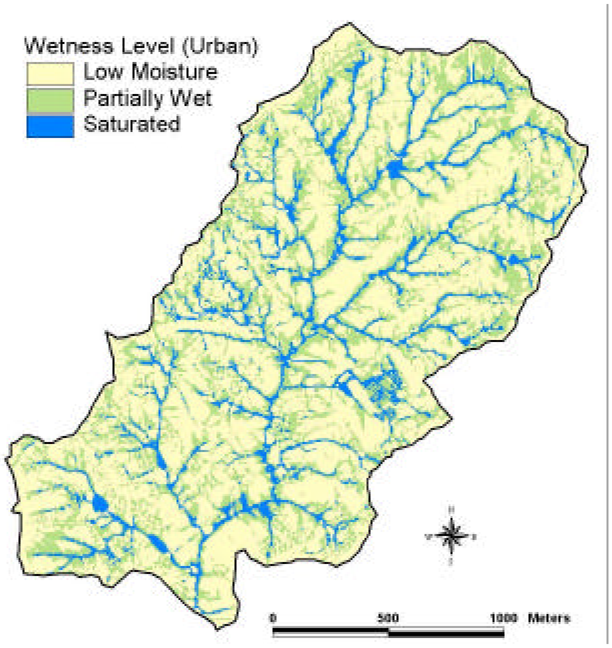

Figure 4. Predicted soil moisture levels for urban condition.

mm/year. The effect of urban cover upon the spatial distribution of saturated soil conditions is illustrated in Figure 4. Although differences in saturation levels between Figures 3 and 4 are barely perceptible here, saturated grid cells account for only 10.1 percent of watershed grid cells in the urban scenario. Based upon model results from the two scenarios, urbanization of the watershed has reduced the extent of saturated area by about 15 percent. The length of perennial streams within the watershed should be similarly reduced.

Detailed field studies have not been performed in the watershed to verify the extent of saturated versus unsaturated area, and an assessment of pre-urban conditions is not possible. Therefore, results here are based solely upon model analyses. Model results suggest that the extent of saturated area, the extent of perennial stream, and base flows have been reduced by urbanization in the Wildcat Creek watershed. The effect of impervious cover on reducing groundwater recharge therefore appears to be greater than the effect of removing forest vegetation upon evapotranspiration reduction. However, no accounting has been made for potential effects of disturbed non-impervious areas upon either recharge or evapotranspiration losses. The gauging station on Wildcat Creek has been reactivated, so data collected for current urban conditions should enable future model testing.

SUMMARY AND CONCLUSIONS

Urbanization is considered to be changing hydrological conditions of Georgia's forested watersheds. A wetness index that incorporates TOPMODEL concepts (Beven and Kirby, 1979) into a grid-based GIS model offers the potential to simulate the effects of these changes. For a small urban watershed in the metro Atlanta area, model simulation indicates that urbanization has probably decreased the extent of saturated area and perennial stream length by nearly 15 percent from pre-urban forest conditions.

LITERATURE CITED

Band, L. E., 1986. Topographic partition of watersheds with digital elevation models. *Water Resources Research* 22: 15-24.

Beven, K., and M. J. Kirkby, 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletin* 24: 43-69.

Dune, T. and R. D. Black, 1970. Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research* 6: 1296-1311.

Horton, R. E., 1933. The role of infiltration in the hydrologic cycle. *Transactions - American Geophysical Union* 14: 446-460.

Jenson, S. K. and J. O. Domingue, 1988. Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing* 54: 1593-1600.

Marks, D., J. Dozier, and J. Frew, 1984. Automated basin delineation from digital elevation data, *Geo. Processing* 2: 299-311.

Moore, I. D., R. B. Grayson, and A. R. Ladson, 1991. Digital Terrain Modelling: A Review of Hydrological, Geomorphological, and Biological Applications. *Hydrological Processes* 5: 3-30.

Peuker, T. K. and D. H. Douglas, 1975. Detection of surface-specific points by local parallel processing of discrete terrain elevation data. *Computer Graphics and Image Processing* 4: 375-387.

Quinn, P., K. Beven, P. Chevallier, and O. Planchon, 1991. The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. *Hydrological Processes* 5: 59-80.

Rose, S., and N. E. Peters, 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* 15: 1441-1457.

Tarboton, D. G., 1997. A new method for the determination of flow directions and contributing areas in grid digital elevation models. *Water Resources Research* 33: 309-319.