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Impact of urbanization on stormwater runoff in tidal creek headwaters

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Urbanization alters the hydrologic cycle of watersheds: as land becomes covered with surfaces impervious to rain, water is redirected from groundwater recharge and evapotranspiration to stormwater runoff. This is a critical issue considering that nonpoint source (NPS) pollution is the leading cause of water quality degradation, and stormwater runoff accounts for most NPS pollution (USEPA 2002). The human population in South Carolina coastal counties has increased by 30% since 1990, and growth is expected to continue at this rate. The urban sprawl type of development that characterizes most of South Carolina consumes land 3 to 6 times faster than the rate of population growth (Allen and Lu 2003). Within this context, researchers at NOAA's Hollings Marine Laboratory have adapted well-established methods for calculating stormwater runoff in order to quantify and to predict changes in runoff as urbanization increases. The resulting method is non-field based and leverages existing federal and state data sources.

The flow curve number (CN) and dimensionless unit hydrograph (DUH) methods developed by the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS) were used to quantify stormwater runoff volume and rate in thirteen small (61 to 2400 hectares) watersheds of primary tidal creeks in South Carolina. Watersheds were delineated using U.S. Geological Survey (USGS) topographic maps with elevation contours, at a scale of 1:24,000.

Runoff volume was calculated using the CN method (USDA-NRCS 1986, 2004). The CN reflects the drainage characteristics of a watershed's soil and land cover, and is determined by identifying the proportional composition of land cover categories and hydrologic soil groups within a watershed. CNs were derived by using ArcGIS 9 and digitized watershed boundary data to clip data layers from U.S. Geological Survey (USGS) & Multi-Resolution Land Characteristics Consortium (MRLC) 2001 National Land Cover Database (NLCD). Watershed land cover data were determined from this layer and then matched to the applicable NRCS land cover categories. Then, for each land cover category, the NRCS-provided CN number was modified by the proportion of hydrologic soil groups in the watershed, as determined by spatial soil data layers provided by NRCS National Cooperative Soil Survey. Finally, the derived CN for each watershed was used in the NRCS runoff equation to calculate runoff volume as follows:

$$S = \frac{1000}{CN} - 10$$ S = maximum potential retention after runoff begins

$$Q_d = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Q_d = depth of runoff, inches
P = depth of rainfall (inches)
I_a = initial abstraction (rainfall lost to infiltration and surface depressions before runoff occurs (in.)

Runoff rate was calculated using the DUH method (USDA-NRCS 1972, 2007). Watershed-specific data for time of concentration (T_c) and area (A) were required to solve two equations:

$$T_p = \frac{\Delta D}{2} + L$$

T_p = time from beginning of runoff to peak rate of runoff (hr.)
ΔD = time of unit excess rainfall = $0.133T_c$
L = watershed lag time = $0.6T_c$
T_c = time of concentration = travel time of stormwater from watershed boundary to channel outlet

DUH time and discharge ratios provided by NRCS were used to calculate the watershed unit hydrograph by multiplying each time ratio by 'time to peak' (T_p) and each discharge ratio by 'peak rate' (q_p). Unit hydrograph time increments and associated discharges were interpolated to 0.5 hour time increments. Temporal rain distribution ratios (Type III-1st quartile-30%, NOAA 2004) were set to 0.5 hour time increments using the Michaelis-Menten equation and then were used to calculate cumlative rainfall. Next, cumulative runoff per time increment was calculated using the NRCS runoff equation, and incremental runoff was determined from the cumulative runoff. Finally, the runoff hydrograph was calculated by convolution: multiplying each unit hydrograph flow by each incremental runoff value, then summing to obtain runoff at 0.5 hour time increments. A framework within Microsoft Excel was designed to generate hydrographs for watersheds of varying sizes and degrees of urbanization and for storm events of varying duration and rain depth.

$$q_p = \frac{PRF \times A \times Q}{T_p}$$

q_p = peak rate of runoff
PRF = peak rate factor
A = watershed area
Q = runoff volume
T_p = time to peak

Five modifications were applied generally based upon the flat topography of the southeastern US coastal watersheds and upon usage described in current literature. One of the modifications affected runoff volume calculations: watershed CN was increased for the developed land cover categories by increasing soil imperviousness by two grades to reflect soil compaction effects (Lim et al. 2006). Three of the modifications affected runoff rate calculations: NRCS temporal rainfall distribution ratios were replaced with NOAA ratios, the NRCS sheet flow equation used for T_c calculations was replaced by one developed for flatlands (Zomorodi 2005), and the PRF (a reflection of slope) was lowered from 484 to 200 (Sheridan et al. 2002, USDA-NRCS 2007). One modification affected both volume and rate: the I_a ratio was changed from 0.2 to 0.05 (Woodward et al. 2003, Lim et al. 2006).

Anticipated results of greater runoff volume, higher peak discharge, and shorter runoff duration with increasing urbanization were found, indicating that the relative impact of urbanization on stormwater runoff in SC coastal watersheds can be quantified. Initial method validation using USGS gaged flow and rain data from SC headwater creeks during 2002-2003 indicates that model hydrographs track fairly well with gaged hydrographs suggesting that the conceptual model and our modifications are reasonable. Modeled hydrograph curves for runoff followed gaged curves best when gaged rainfall distributions were used in hydrograph generation. Calibration and validation are ongoing. Results for predicted impacts of urbanization on stormwater runoff also showed greater runoff volume, higher peak discharge, and shorter runoff duration with increasing urbanization.

The capability to model stormwater runoff facilitates the development of forecasting tools to better manage urbanization's impact on coastal ecosystems. Additionally, the flexibility of the hydrograph worksheet makes the template a useful tool for graphically conveying the effect of urbanization on stormwater runoff.

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