STORMWATER RUNOFF – MODELING IMPACTS OF URBANIZATION AND CLIMATE CHANGE

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Abstract. Urbanization and associated sprawl alters watershed hydrology. As land becomes covered with surfaces impervious to rain, stormwater runoff increases. Urbanized runoff is a leading cause of nonpoint source pollution and causes shallow flooding. Increased frequency and intensity of heavy storm events predicted by climate change models will amplify the impact of urbanization on stormwater runoff, further increasing the quantity of polluted runoff and the magnitude of flooding. We developed a method for modeling stormwater runoff for small coastal watersheds in the southeastern U.S. by using U.S. Department of Agriculture - Natural Resources Conservation Service's algorithms and flow curve number method. We calibrated model output and then validated with U.S. Geological Survey gaged flow and precipitation data from similar watersheds. The modeling method developed can be used to calculate runoff in watersheds at existing levels of urbanization, to project impact of urbanization on runoff for an undeveloped watershed, and to integrate climate change with urbanization impacts on runoff. Rainfall amount, storm duration, and runoff condition can be varied to present a range of urbanization and climate scenarios. Calculating watershed runoff and projecting runoff changes with urbanization and climate change will enable better-informed decisions related to minimizing the impacts of stormwater runoff.

INTRODUCTION

Development pressure throughout the coastal areas of the U.S. southeast continues to build (Allen and Lu 2003, Crossett et al. 2004). It is well known that development alters watershed hydrology: as land becomes covered with surfaces impervious to rain, water is redirected from groundwater recharge and evapotranspiration to stormwater runoff, and as the area of impervious cover increases, so does the volume and rate of runoff (Schueler 1994, Corbett et al. 1997).

Pollutants accumulate on impervious surfaces, and the increased runoff with urbanization is a leading cause of nonpoint source pollution (USEPA 2002). Sediment, chemicals, bacteria, nutrients, and other pollutants are carried into receiving water bodies, resulting in degraded water quality (Holland et al. 2004, Sanger et al. 2008).

Climate change will likely amplify the impact of urbanization on stormwater runoff, further increasing the quantity of polluted runoff. Climate change predictions point to scenarios for heavy precipitation events to increase in frequency and intensity (Bates et al. 2008, Gutowski et al. 2008). Semadeni-Davies et al. (2008) modeled the impacts of urbanization and climate change and found that increased rainfall intensity and increased impervious surfaces will cause flashier runoff periods, greater peak flows and heightened risk of flooding. Within this context, a science-based system for evaluating the relative impacts of both urbanization and climate change on stormwater runoff at the local scale was developed.

METHODS

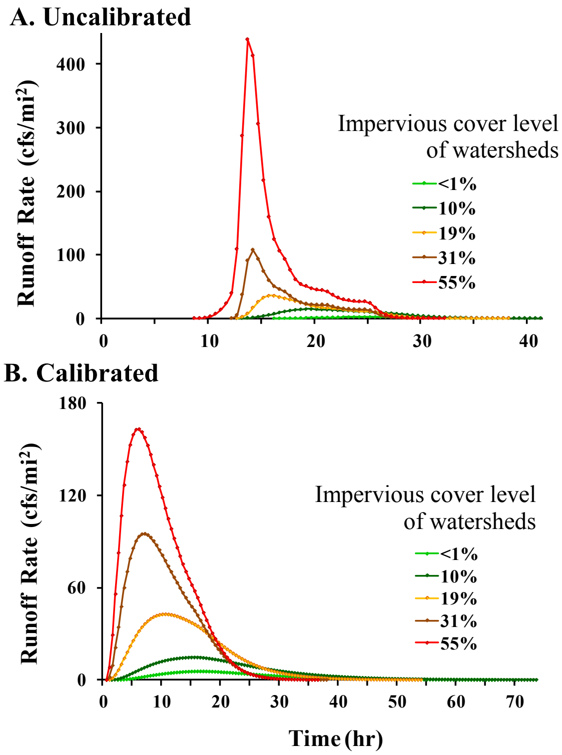
Methods are based on United States Department of Agriculture - Natural Resources Conservation Services (USDA-NRCS) algorithms and flow curve number method presented in Part 630 of the National Engineering Handbook and in NRCS Technical Release 55 (USDA-NRCS 1972, 1986, 2004a, 2004b, 2007). We used 13 headwater drainage areas in coastal South Carolina to develop and test the models. Area ranged from 61 to 2411 hectares.

Runoff volume was calculated using the flow curve number (CN) method. CN reflects the drainage characteristics of a watershed and is generally determined by identifying the proportional composition of land cover categories and hydrologic soil groups. Once the CN is established, it is converted to a value that can be used in the USDA-NRCS flow curve number runoff equation to calculate volume.

Runoff rate and time were calculated by determining watershed time-of-concentration (i.e., time required for water to travel to the creek outlet from the most distant point on the watershed boundary), and then constructing a direct runoff hydrograph from a unit hydrograph based upon a dimensionless unit hydrograph. A direct runoff hydrograph represents a watershed's drainage response to a rain event by graphically presenting stormwater runoff discharge rates over time. The hydrograph shows runoff volume (area under the curve) and also additional information including peak rate and runoff duration.

The model was calibrated (Figure 1). NRCS temporal rainfall distribution ratios were replaced with NOAA ratios (NOAA 2004), NRCS sheet flow equation used in time-of-concentration calculations was replaced by one developed for flatlands (Zomorodi 2005). For the peak rate equation, peak rate factor (a reflection of slope) was lowered from 484 to 200 (Sheridan et al. 2002, USDA-NRCS 2007). For the flow curve runoff equation, the ratio of initial abstraction to maximum potential storage was changed from 0.2 to 0.05 (Woodward et al. 2003, Lim et al. 2006). Watershed CNs were increased for the developed land cover categories by increasing soil imperviousness by two grades to reflect soil compaction effects (Lim et al. 2006).

The calibrated models were validated using U.S. Geological Survey (USGS) gaged precipitation and discharge measurements (Table 1). USGS gaged data were recorded at 15-minute intervals from August 2002 through September 2003 in three South Carolina creeks with watersheds similar to test sites (Smith 2005).


A. Uncalibrated

B. Calibrated

Figure 1. Runoff hydrographs from 5 of the 13 test watersheds at different levels of development (based on impervious cover). Y-axis shows runoff rate, and x-axis shows time. Curves are based on a 24-hour 4.5-inch storm event.

A. Hydrographs generated by uncalibrated USDA-NRCS models.

B. Hydrographs generated by calibrated models.

RESULTS & APPLICATIONS

Model output consistently showed higher runoff volume, higher peak rate, and shorter runoff duration with increasing urbanization. Peak runoff rate was found to be at least 19 times greater in developed watersheds than in the undeveloped watershed, runoff volume is at least 10 times greater, and hydrograph curves show that total runoff time is almost 50% less in the developed watersheds (Figure 2A). Integrating climate change into the model amplified impacts of urbanization with runoff volume generally doubling in developed watersheds (Figure 2B). Results are what would be expected, indicating that relative impact of urbanization on stormwater runoff in southeastern coastal watersheds can be quantified Validation results support the suitability of using the model to calculate runoff.

Applications include calculating and projecting runoff changes in various urbanization and climate change scenarios. This allows us to examine relative differences in runoff among watersheds at existing development

Table 1. Validation results for six storm events in undeveloped and developed watersheds similar to test watersheds.

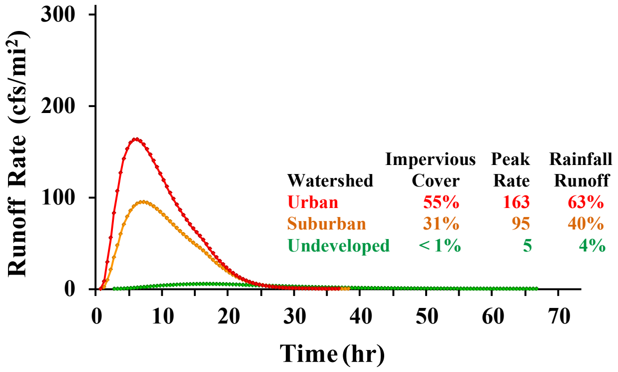
Watershed	Storm	Rain - in.	Runoff - in.		Rain to Runoff	Peak Rate - cfs		Curves r^2	Antecedent
			Gaged	Modeled	Difference	Gaged	Modeled	Hydrograph	Conditions
Old House	4/8/2003	2.6	1.17	0.92	-9.5%	40.6	25.3	0.93	ave
Old House	4/7-8/2003	4.6	2.20	2.14	-1.2%	46.0	52.7	0.97	ave/wet
Parrot	4/8/2003	2.2	0.57	0.62	2.5%	3.0	2.7	0.41	ave
Parrot	5/22/2003	2.4	0.90	0.77	-5.3%	2.8	3.4	0.81	ave
Shem-filtered	5/22/2003	2.6	1.17	1.22	1.8%	14.0	19.3	0.88	wet
Shem-filtered	8/30/2002	4.4	3.50	2.51	-22.4%	41.4	39.3	0.88	wet

levels (Figure 2A). In addition, we can project the impact of development within undeveloped watersheds by modeling increases in the percent of impervious cover. The percents used here are <1% (undeveloped), 10% (light development), 30% (developed-suburban), and 50% (developed-urban) (Figure 3A). Different rainfall amounts, storm durations, and runoff conditions can be used to integrate the impact of climate change with urbanization (Figures 2B, 3B). The climate change illustrated here involves increasing rain amount by 15%, decreasing duration by 50%, and modeling semi-saturated runoff conditions.

CONCLUSIONS

This modeling method provides a way to quantify stormwater runoff for southeastern coastal plain watersheds at the local level. Output can be used to explore and explain relative impacts of urbanization and climate change. Peak runoff rate and volume are shown to be much greater in developed watersheds than in undeveloped watersheds. Hydrograph curves provide a visual image of relative differences and show shorter runoff time for developed watersheds. The integrated climate scenario illustrates that the effect on runoff rate and volume greatly exceeds the proportional rainfall increase and that impact of urbanization is amplified. Conditions leading to sedimentation, erosion, and flashiness in streams and creeks in urbanized watersheds and the need to consider the impact on runoff of increased intensity and frequency of heavy storms predicted with changing climate are evident.

A. Impact of Urbanization



B. Impact of Urbanization & Climate Change

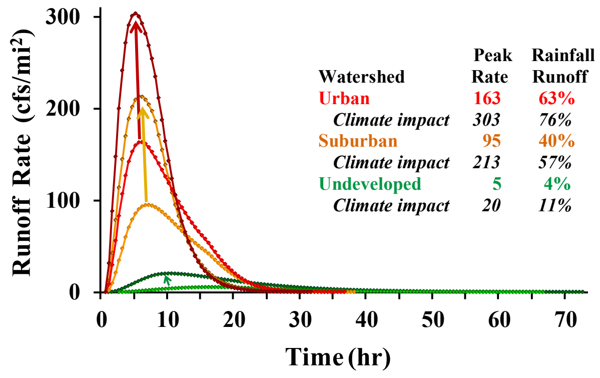
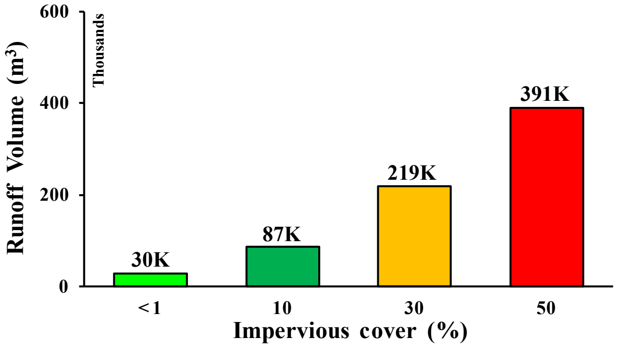


Figure 2. Modeled runoff from 3 test watersheds at different levels of impervious cover. Y-axis shows runoff rate which is expressed in cubic feet per second per square mile to account for differences in watershed area, and x-axis shows time in hours. Peak Rate is maximum rate attained. Rainfall Runoff is percent of rainfall converted to runoff.

A. Hydrographs illustrate impact of urbanization on runoff. Curves are based on a 24-hour 4.5-inch storm, average runoff conditions.

B. Hydrographs illustrate the impact of urbanization and climate change on runoff. Climate impact curves are based on a 12-hour 5.175-inch storm, semi-saturated runoff conditions.

A. Impact of Urbanization



B. Impact of Urbanization & Climate Change

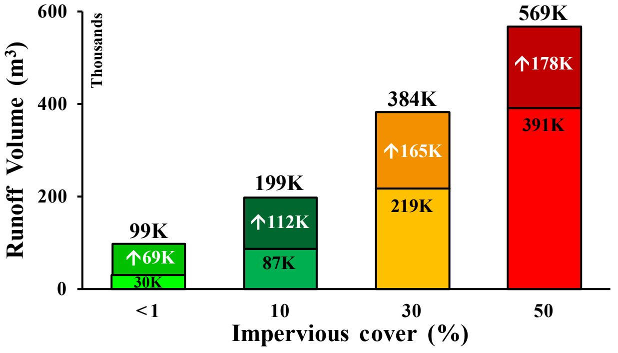


Figure 3. Modeled runoff volume for undeveloped watershed at current development level and also at levels reflecting increasing urbanization. Volume is shown on the y-axis in thousands of cubic meters. Percent of impervious cover is shown on the x-axis.

A. Bar charts illustrate the impact of urbanization on runoff, and volumes are based on a 4.5 inch storm event, average runoff conditions.

B. Bar charts illustrate the impact of urbanization and climate change on runoff volume, and climate impact is based on a 12-hour 5.175-inch storm, semi-saturated runoff conditions.

Calculating runoff at current levels of development and projecting impacts of urbanization and climate change will enable better-informed decisions related to minimizing the impacts of stormwater runoff. This modeling method can be developed into tools designed for use by research scientists, coastal managers, educators, and outreach professionals.

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