Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment

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[1] The literature contains contradictory conclusions regarding the relative effects of urbanization on peak flood flows due to increases in impervious area, drainage density and width function, and the addition of subsurface storm drains. We used data from an urbanized catchment, the 14.3 km^2 Dead Run watershed near Baltimore, Maryland, USA, and the physics-based gridded surface/subsurface hydrologic analysis (GSSHA) model to examine the relative effect of each of these factors on flood peaks, runoff volumes, and runoff production efficiencies. GSSHA was used because the model explicitly includes the spatial variability of land-surface and hydrodynamic parameters, including subsurface storm drains. Results indicate that increases in drainage density, particularly increases in density from low values, produce significant increases in the flood peaks. For a fixed land-use and rainfall input, the flood magnitude approaches an upper limit regardless of the increase in the channel drainage density. Changes in imperviousness can have a significant effect on flood peaks for both moderately extreme and extreme storms. For an extreme rainfall event with a recurrence interval in excess of 100 years, imperviousness is relatively unimportant in terms of runoff efficiency and volume, but can affect the peak flow depending on rainfall rate. Changes to the width function affect flood peaks much more than runoff efficiency, primarily in the case of lower density drainage networks with less impermeable area. Storm drains increase flood peaks, but are overwhelmed during extreme rainfall events when they have a negligible effect. Runoff in urbanized watersheds with considerable impervious area shows a marked sensitivity to rainfall rate. This sensitivity explains some of the contradictory findings in the literature.

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1. Introduction

[2] There is no dispute that flood magnitude and frequency increase as urban development spreads throughout a watershed. *Leopold* [1968] notes that hydrologic response to urbanization is typically characterized by increasing flood peak magnitudes, decreasing lag time, and increasing runoff volumes. The hydrologic processes affected by urbanization are primarily infiltration and surface runoff. *Leopold* [1968] presented an empirical analysis of impervious coverage that became a benchmark of urban watershed theory. *Leopold* [1968] assumed that the effect of urbanization can be described by the fraction of impervious area and argued that the most infrequent floods occur under conditions that are not appreciably affected by imperviousness of the basin. Early studies on the effects of urbanization on flood formation, such as that by *Leopold* [1968] focused largely on data analysis, because of the lack of a suitable model for hypothesis testing. *Hollis* [1975] suggested that small floods may increase 10 times by urbanization, and that floods with a return period of 100 years may be doubled in size by 30% impervious land cover. *Ogden et al.* [2000] showed that the flash flood on Spring Creek in Fort Collins, Colorado, 28 July 1997, which resulted from a series of small convective cells that produced 250 mm of rainfall in approximately 4 h, was slightly sensitive to impervious areas. *Graf* [1977] concluded that assessors of the hydrologic impact of suburban developments who only consider changes in impervious surfaces risk ignoring an equally serious problem associated with changes to drainage networks. Modifications to the channel network and channel conveyance characteristics also have significant effects on flooding in urbanized catchments [*Anderson*, 1970; *Smith et al.*, 2002; *Turner-Gillespie et al.*, 2003; *Wolff and Burges*, 1994]. *Ogden and Julien* [1993] tested the sensitivity of runoff to land-surface heterogeneities and found that sensitivity diminishes with increasing rain rate and duration, which tend toward equilibrium

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conditions, with high runoff efficiencies and outflow being approximately equal to rainfall rate times basin area. This is in contrast with *Javier et al.* [2007] who concluded that heterogeneities in the hydrologic response are in part responsible for the lack of predictability in urbanized basins less than 10 km^2 in size.

[3] The effects of drainage density on runoff from an urbanized catchment have long been hypothesized. An investigation into the nature of urbanizing stream networks with extensive historical data by *Graf* [1977] showed a drastic increase in the number, length, and density of man-made channels in an Iowa catchment. The density of reaches in a drainage network examined in that study can be described by the width function statistic. Generally, the width function is defined as a plot of the number of channel segments at a specified distance from the basin outlet [*Rodriguez-Iturbe and Rinaldo*, 1997]. The width function was used by *Smith et al.* [2002] during a study of the heavily urbanized Charlotte, North Carolina basin. Through diagnostic testing of multiple large flooding events, *Smith et al.* [2002] concluded that the rising trends of flood peaks are attributed to the expansion of the drainage network subsequent amplification of the width function. But, *Veitzer and Gupta* [2001] attempted to relate the width function to peak discharges and found that the width function alone does not produce a substantial correlation. The width function describes the network geomorphology by counting all stream links located at the same distance from the outlet without considering differences in flow conveyance. This averaging, however, prevents complete and accurate description of the spatial variability of hydrodynamic parameters.

[4] In the literature of hydrology of floods in urbanizing drainage basins, such as *Smith et al.* [2002] and *Turner-Gillespie et al.* [2003], catchment response is based on the digital elevation model (DEM) derived equivalent natural drainage network of the actual storm water drainage system. *Hsu et. al* [2000] simulated urban flooding in Taipei, Taiwan using the storm sewer module of the U.S. Environmental Protection Agency, Storm Water Management Model (SWMM) [*Rossman*, 2010] and a two-dimensional diffusive wave overland flow routine. *Hsu et al.* [2000] did not clearly explain the linkage of these models, and it appeared that the models were not run simultaneously. In a situation where channel interactions with storm drains are important, such as reverse flow, it is necessary that these model components operate simultaneously [*Schmitt et al.*, 2004]. *Javier et al.* [2007] concluded that storm water management infrastructure is a significant source of poorly known heterogeneity that has a significant effect on flood response.

[5] In this study, we used the gridded surface/subsurface hydrologic analysis (GSSHA) model [*Downer and Ogden*, 2004]. GSSHA is a distributed-parameter physics-based numerical model that is widely used by the US Army Corps of Engineers in engineering hydrology, erosion, contaminant/nutrient fate and transport, as well as storm surge studies. The spatially explicit nature of the GSSHA formulation allowed us to examine the influence of changes to the drainage network characteristics and imperviousness on flooding from urbanized catchments. GSSHA was used in this study because it has demonstrated abilities to simulate important runoff generation processes, and includes the ability to explicitly represent fully coupled channel and storm-drain hydrodynamics. The objective of this study was to examine the effects of these varying results of urbanization, namely, impervious area, drainage density and the distribution of drainage density as described by the width function, and subsurface storm drainage network on flood peaks, runoff volumes, and runoff generation efficiencies. These tests were performed using data from two storms with different degrees of extremity as defined by rain rate and storm-total rainfall, to allow detection of the sensitivity of land surface and drainage characteristics to storm severity.

2. Methodology

2.1. Watershed Data

[6] The Dead Run watershed is located approximately 11.5 km west of central Baltimore, Maryland, and has an area of 14.3 km^2. It is intensely urbanized [*Nelson et al.* 2006] as shown in Figure 1(a). GIS layers of land use and drainage

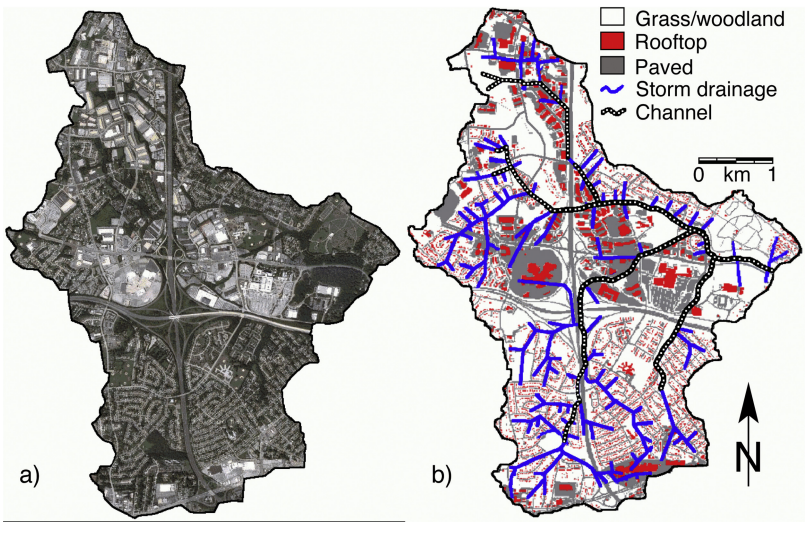

Figure 1. Dead Run catchment (a) aerial photograph and (b) GSSHA modeled land cover, channel, and subsurface storm drainage network.

were supplied by the county of Baltimore. Figure 1(b) shows the land use assigned into classes, as well as the location of channels and subsurface storm drains simulated in this study. The density of the drainage network shown in Figure 1(b) including subsurface storm drains is very nearly 3.5 km km^{-2}.

[7] Runoff data from a USGS stream gauge 01589330 at the outlet of the watershed (Dead Run at Franklintown, MD, 39:18:40.4N 76:42:59.9W), as well as rainfall data from a dense rain gauge network are available. Furthermore, maps exist that describe the subsurface storm drainage network, as shown in Figure 1(b). The Dead Run watershed is part of the Baltimore Ecosystem Study [*Welty et al.*, 2007]. The availability of high-quality rainfall-runoff data makes the Dead Run watershed an excellent site for examining urban flooding.

2.2. Storm Data

[8] For the purposes of our study, one important consideration is the magnitude of the storm total rainfall and rainfall intensity. We selected two well documented rainstorms for use in this study. One storm that we classify as a "moderately extreme" rainstorm due to the passage of Hurricane Isabel 18–19 September 2003. The second is an extreme thunderstorm rainfall event that produced the flood of record on the Dead Run at Franklintown on 7 July 2004. Both of these rainstorms exhibited spatial variability in rainfall. However, both were very large storms compared to the size of the Dead Run watershed and resulted in significant rainfall over the entire watershed.

2.3. Hurricane Isabel, 18–19 September 2003

[9] The passage of Hurricane Isabel resulted in about 8 h of light rainfall less than 10 mm h^{-1} followed by two pulses of intense rainfall, as is common in hurricane precipitation patterns. These two intense pulses of rainfall were about 150 min apart and approximately 50 and 30 min in duration, respectively. Basin averaged instantaneous rain rates peaked at 90 mm h^{-1}, but localized cells of precipitation produced instantaneous rainfall rates above 200 mm h^{-1} [*Smith et al.*, 2005]. Total basin-average rainfall for this storm was 88 mm (3.46 in.) with the southwestern portions receiving 70–80 mm, and northeastern receiving 90–105 mm. The peak discharge recorded by the USGS gauging station at the watershed outlet for this event was just under 40 m^3 s^{-1}. The return period for this event has not been quantified to the best knowledge of the authors because of the small sample size of hurricane events recorded at the gauging station. We consider this storm to be a "moderate-extreme" rainfall event. Hurricane Isabel rainfall data were derived from the WSR-88D radar in Sterling, Virginia, 75 km from watershed center. These radar-rainfall estimates were bias adjusted using data from 19 rain gauges [*Meierdiercks et al.*, 2010].

2.4. Extreme Thunderstorm of 7 July 2004

[10] The current flood of record on Dead Run occurred 7 July 2004, as the result of an intense thunderstorm that lasted approximately 2 h [*Javier et al.*, 2007]. The storm produced 124 mm (4.88 in.) basin-average storm-total rainfall, which was very uniformly distributed in space, varying only from 117 to 126 mm across the watershed. Rainfall intensities were over 60 mm h^{-1} (2.4 in. h^{-1}) for the duration of the entire storm, with peak rain rates measured at over 140 mm h^{-1}. Rainfall data for this event consist of quality-controlled rain gauge data from six gauges in the Dead Run watershed. *Ntelekos et al.* [2008] provide an excellent hydrometeorological analysis of this extreme event. This storm exceeded the 100 year return period at time scales of 1–2 h. The observed hydrograph for this storm is incomplete because of large uncertainty in the flow rating values above 70 m^3 s^{-1}. However, the peak discharge was measured indirectly to be 246 m^3 s^{-1} by the U.S. Geological Survey in a postevent analysis. For the watershed area of Dead Run at Franklintown (14.3 km^2), this peak discharge is on the upper limit of observed discharges in the eastern United States, the so-called "envelope curve" [*Meierdiercks et al.* 2010], which indicates that this was a truly extreme event.

2.5. Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) Model

[11] The GSSHA model [*Downer and Ogden,* 2004, 2006] was developed by university researchers and the U.S. Army Corps of Engineers to analyze hydrologic, sediment, and nutrient/contaminant transport problems where flow path is important. The GSSHA model, like its predecessor CASC2D [*Ogden and Julien* 2002], is formulated on a structured grid, and uses explicit finite-volume solutions of the diffusive-wave form of the de St-Venant equations of motion for two-dimensional overland and one-dimensional channel flow. Overland flow depth is modified each time step with the addition of rainfall and subtraction of infiltration, and updated to account for overland fluxes. Flow is then routed in the overland flow plane from regions of higher hydraulic head to those of lower hydraulic head. A smaller grid size more accurately represents the topography and simulations of urbanized areas are typically performed at grid sizes of 30 m or less.

[12] Infiltration can be simulated in GSSHA using a variety of optional methods including: multilayer Green and Ampt, Green and Ampt with redistribution [*Ogden and Saghafian*, 1997], and the *Richards* [1931] equation. When required, groundwater is simulated using a 2-D finite difference scheme [*Downer and Ogden*, 2004], allowing simulations of saturation excess overland flow and return flow. The groundwater solution is fully coupled to surface flows using a 1-D implicit finite difference solution of *Richards* [1931] equation. Groundwater was not simulated in the study reported in this paper. The GSSHA model can operate on individual events, or continuously with calculated evapotranspiration and soil-moisture accounting between rainfall events [*Senarath et al.* 2000]. GSSHA also has erosion/deposition simulation capabilities and can calculate the transport of sediments, nutrients, and other aquatic constituents. Those transport capabilities were not used in this study. A full description of the numerical solutions employed in the GSSHA model is provided by *Downer and Ogden* [2004] and the GSSHA wiki (GSSHAWIKI (2011), http://www.gsshawiki.com, accessed 29 August 2011).

[13] The SUPERLINK subsurface storm sewer model [*Ji*, 1998] was included in GSSHA by *Zahner* [2004] to simulate the subsurface storm drainage network and its interactions with the channel network in urbanized catchments. SUPERLINK is a general hydrodynamic model for storm sewer/channel networks [*Ji*, 1998]. It solves the full-

dynamic form of the de St-Venant equations in one dimension and employs the Preissmann slot [*Cunge et al.*, 1980] to extend the open channel flow assumptions to closed conduits flowing full and surcharged. Unlike many applications of the Preissman slot, SUPERLINK does not consider the area of the slot in the flow calculations or wetted perimeter, thus reducing the errors associated with this concept. Another significant benefit of this model is its staggered grid implicit solution to the full equations of motion, which enhances stability and computational speed, and allows for the simulation of transcritical flow, which the commonly used Preissmann four-point scheme cannot do [*Meselhe and Holly*, 1997]. Flow directions need not be specified a priori in the SUPERLINK scheme and it can simulate reverse flow and flow in looped networks. Several excellent examples of the performance of the method are shown by *Ji* [1998].

[14] SUPERLINK consists of junctions that represent culverts or manholes, nodes that represent grate/curb openings in a roadway, and links that connects nodes. In GSSHA, the flow of surface water into junctions and nodes is calculated using the overland flow depth. Depending upon the overland flow depth, curb-side grates either behave as weir-type inlets or as orifice-type inlets [*U.S. Department of Transportation*, 2009]. Flows from SUPERLINK can be discharged back onto the overland flow grid or into channels at predefined outlet points.

2.6. Important Urban Hydrologic Processes

[15] The importance of different hydrologic processes depends to some extent on the focus of the modeling effort. Long-term simulations are used when hydrologic response is influenced by groundwater contributions to streamflow or climatic factors such as evapotranspiration as it affects soil moisture. Single-event simulations targeting flood peaks and timing in urbanized catchments rely mainly on the short-term processes of infiltration, overland flow routing, and channel routing, at time scales where evapotranspiration is negligible relative to rainfall. As the focus of this study is the effect of drainage network modifications, we focused on processes fundamental to single events. Urbanization of the Dead Run watershed largely preceded the introduction of modern storm water control practices [*Beighly and Moglen*, 2003]. Storm water detention basins in the watershed do not have sufficient storage capacity to significantly affect large runoff events, so they were not simulated.

[16] One significant advantage of the physics-based hydrologic modeling approach is that published values can be used to constrain certain model parameters. Estimation of GSSHA parameters relied upon on both literature values and parameter estimation through calibration. A 30 m grid size was selected as a compromise between the number of computational grids, and the ability to describe relevant land-surface details. This grid size resulted in 16,033 computational grids within the catchment. Land-use classification is important in the analysis of flooding events in urbanized catchments [*Crooks and Davies*, 2001]. Soil saturated hydraulic conductivity, initial soil moisture content, overland flow and channel roughness coefficients, and impervious areas are the key parameters that describe runoff generation processes in a single-event simulations of urbanized catchments [*Ogden et al.*, 2000]. A land-use classification index was assigned to each grid cell based on the majority coverage as shown in Figure 1(b). Parameter values for roughness coefficients, soil saturated hydraulic conductivity, capillary head, porosity, and initial soil moisture content were assigned based on the land-use classification index. The use of land use in assigning soil parameters is justified by the assumption that soil structural modifications due to urbanization overwhelm the influence of soil texture. For nonpaved surfaces one soil index was used throughout the watershed because the surface soils in the catchment have been heavily modified by urbanization through the importation of fill, placement of sod, compaction, etc.

[17] The standard *Green and Ampt* [1911] model has proven effective for modeling infiltration into soils for single events in well-drained uniform soils, but several important common natural and man-made phenomena can invalidate the assumption of vertically uniform soils. Soil layering, nonuniform initial soil moisture, surface crusts, lenses, and high water tables all violate the conditions necessary to apply the traditional *Green and Ampt* [1911] method. Site investigations in the watershed have revealed that many grassy areas in the catchment consist of an imported upper layer of topsoil, with compacted soils beneath (J. Smith, personal communication). For these reasons, the three-layer Green and Ampt infiltration option in GSSHA [*Downer*, 2002; GSSHAWIKI (2011), http://www.gsshawiki.com, accessed 29 August 2011] was used to simulate infiltration in the Dead Run catchment.

[18] Channel cross sections were simulated as trapezoidal, and were generally assumed to increase in size in the flow direction. We did not use detailed cross-section surveys. Rather, areal photographs were used to estimate channel bottom widths. Trapezoidal cross sections had 2:1 (H:V) side slopes and bottom widths varied from 8 m in first order channels to 12 m at the watershed outlet.

2.7. Model Calibration

[19] Ordinarily, calibration uniqueness in distributed-parameter physics-based hydrologic models is enhanced by calibration on an extended period of record with continuous soil moisture accounting [*Javier et al.*, 2007], which improves the ability of a model such as GSSHA to better simulate a range of event magnitudes [*Senarath et al.*, 2000]. In urbanized catchments, calculation of evapotranspiration is complicated by uncertain aerodynamic roughness, radiation shading, irrigation, etc. However, in the case of moderate to extreme rainfall events, model sensitivity to heterogeneous parameters is diminished [*Ogden and Julien*, 1993], which enables use of event-based calibration [*Ogden et al.*, 2000].

[20] Calibration of the GSSHA model in urbanized catchments is simplified by assignment of soils and hydraulic parameters based on a land-use index, which limits the number of parameter values that must be estimated. Parameter values were adjusted manually to achieve an acceptable fit to the observed hydrograph, with parameter values bounded by physical understanding and our experience with the model. The existence of physical limits on parameter values is one of the strengths of the physics-based approach, which significantly reduces uncertainty in parameter values.

[21] Table 1 lists the parameters used to simulate infiltration in vegetated areas using the multilayered Green and Ampt infiltration scheme in GSSHA. Note that not all

Table 1. Parameter Values for the Multilayered Green and Ampt Infiltration Scheme in the GSSHA Model for Simulating Infiltration in Grass/Woodlands Areas

Infiltration Parameter	Soil Layer		
	Top	Middle	Lower
Saturated hydraulic conductivity (cm h^{-1})[a]	1.1	0.0017	0.001
Pore size distribution index (−)[b]	0.165	0.165	0.165
Wetting front suction head (cm)[b]	12.0	12.0	20.0
Saturated soil moisture content (−)[b]	0.5	0.4	0.35
Residual soil moisture content (−)[b]	0.09	0.09	0.09
Soil layer thickness (cm)[a]	18.35	27.0	–
Initial soil moisture content Isabel (−)[c]	0.177	0.215	0.185
Initial soil moisture content 7 July 2005 storm[c]	0.44	0.37	0.225

[a]Indicates calibrated parameter.
[b]Indicates literature or otherwise assigned value based on modeler experience.
[c]An estimated state variable.

parameters listed in Table 1 were calibrated. In fact, soil hydraulic parameter calibration was limited to a total of five parameters, namely three values of saturated hydraulic conductivity, and the thickness of the upper two soil layers. Initial soil moistures were estimated for each of the three soil layers in vegetated areas based on cumulative rainfall 7 days prior to the event before manual calibration of the soil parameters.

[22] Roughness coefficients influence overland and channel flow travel times. Literature values were applied without calibration. Overland flow Manning's roughness coefficients used were: 0.16 for vegetated areas, 0.014 for rooftops, roadways, and parking lots. The Manning roughness coefficient for all channel segments was set equal to 0.035, which is representative of clean and winding channels [*Chow et al.*, 1988]. The Manning roughness coefficient of subsurface storm drains was assumed constant and uniform, equal to 0.024. The retention depth for all land uses was assumed to be 5 mm. Rainfall interception was neglected.

[23] The calibrated outflow hydrograph for Hurricane Isabel (18–19 September 2003) was compared to the observed discharge at the basin outlet as displayed in Figure 2(a). The model Nash-Sutcliffe [*Nash and Sutcliffe*, 1970] efficiency for this calibration event was 91% with subsurface storm drainage included, and 89% without. Figure 2(a) also shows the hydrograph predicted by the calibrated model with the storm-drain simulator de-activated, as well as the flows from the storm drainage network to the channels when activated.

2.8. Calibration Verification

[24] The extreme thunderstorm of 7 July 2004, was simulated with GSSHA to verify the model calibration for an extreme event. The hydrograph for the calibration verification simulation is shown in Figure 2(b). It is important to note that the model parameters used in this verification were the same as those identified through model calibration. Initial soil moisture for grass/woodlands soils were increased as shown in Table 1 because the preceding 7 days saw a number of rain storms. Calculation of the Nash-Sutcliffe efficiency was not possible because there is no complete observed hydrograph for this event. The GSSHA simulated peak discharge with subsurface storm drainage was 247 $m^3 s^{-1}$, which is essentially the same as the indirect peak discharge measurement by the U.S. Geological Survey. This result indicates that our calibration is plausible, but does not demonstrate that it is unique. However, for GSSHA and similar models, the model sensitivity to parameter uncertainty diminishes as event magnitude increases [*Senarath et al.* 2000], which provides confidence that errors in the parameter set will not significantly effect the conclusions in this paper.

2.9. Generation of Channel Networks

[25] The distributed GSSHA model allows simulation of different channel networks to evaluate their relative hydrologic response. To test the effect of channel dendritic structure we used the drainage density D_d, which is defined as the length of channel per unit watershed area (km km^{-2}),

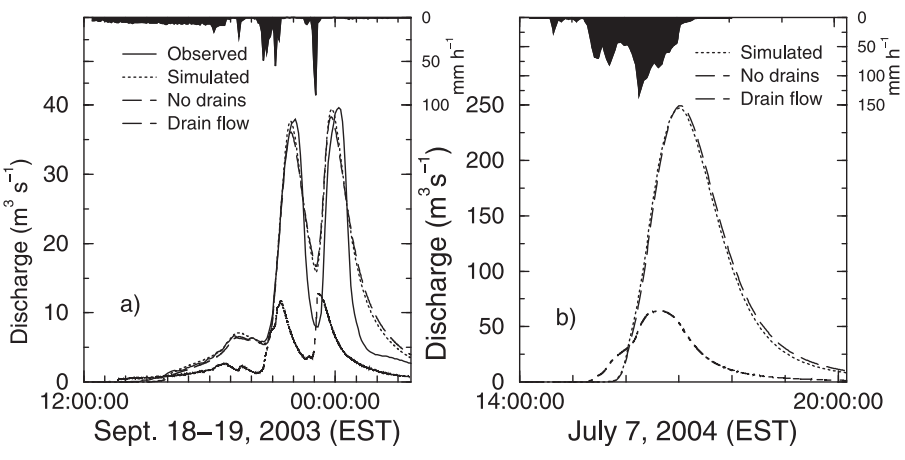

Figure 2. Rainfall hyetographs, observed and simulated hydrographs for (a) calibration and (b) calibration-verification events in the Dead Run catchment. In (a) "Simulated" denotes calibrated model with storm drains simulated, "No drains" denotes the calibrated simulation with the subsurface storm drainage not simulated, and "Drain flow" is the discharge from the storm drainage network to the channels with the subsurface storm drains simulated. Note there is no observed hydrograph for the 7 July 2004, event. The U.S. Geological Survey indirect peak discharge measurement was 246 $m^3 s^{-1}$.

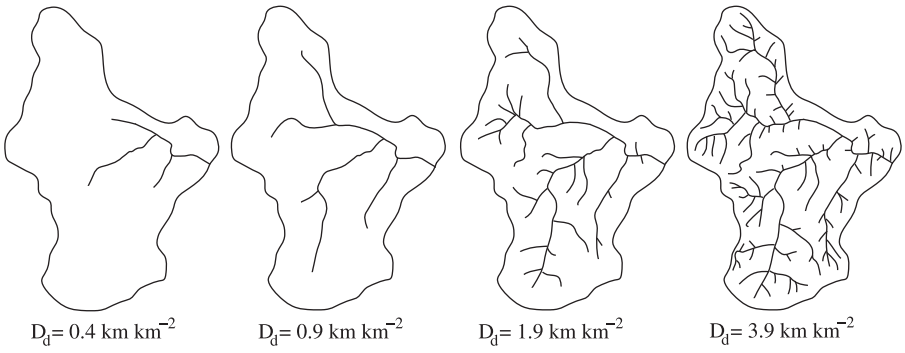

Figure 3. Four different channel realizations with different drainage densities.

and the width function $W(s)$, which is defined as the number of channel segments at a given distance s from the watershed outlet. A flow segment was defined as a 10 m length of either channel of subsurface storm drain.

[26] The TOPAZ program [*Garbrecht and Martz* 1993] running as part of the watershed modeling system (WMS) [*Nelson* 2001] model interface by Aquaveo LLC was used to generate different drainage networks based upon a flow accumulation threshold parameter. Given an input threshold value, TOPAZ identified channel locations, and the WMS interface was used to generate stream arcs for input to the GSSHA model. Figure 3 shows four idealized channel drainage networks generated applying TOPAZ that have drainage densities of 0.4, 0.9, 1.9, and 3.9 km km^{-2}. The width functions for these four different channel networks are shown in Figure 4. Figures 5(a) and 5(b) shows two other channel networks with identical drainage density equal to 1.5 km km^{-2} that were developed to test the effect of the width function on hydrologic response. The width functions for these two networks are shown in Figure 6.

3. Results and Discussion

3.1. Changes in Impervious Area

[27] The effect of impervious area was examined by simulating the calibration and verification storms with three different realizations of watershed imperviousness: actual conditions (34% impervious), roof tops only (11% impervious), and no impervious areas. Removed impervious areas were assumed to have the same soil hydraulic properties as the grass/woodlands shown on Figure 1(b) and in Table 1. The resulting hydrographs are shown in Figures 7(a) and 7(b) for the Hurricane Isabel and 7 July 2004, extreme storm, respectively.

[28] The results in Figure 7 show that the magnitude of the storm changes the effect of impervious area on the runoff hydrograph. The respective peak flows, runoff volumes, and runoff efficiencies for these three different degrees of imperviousness for both storms are listed in Table 2. In the case of the moderately extreme Hurricane Isabel, both peak flows and runoff ratios increase significantly with increases in imperviousness. The effect of imperviousness on peak discharge is much more pronounced in the first peak of the Hurricane Isabel runoff hydrograph. The second peak is much less sensitive to the degree of imperviousness, due to the decrease in soil infiltration capacity during the second pulse of intense rainfall.

[29] However, in the case of the extreme storm of 7 July 2004, imperviousness was observed to have a less pronounced effect on runoff volume and runoff generation efficiency. Increasing the impervious area from 0% to 11%

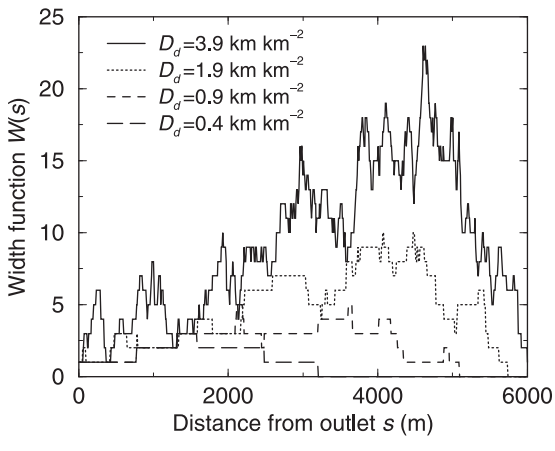

Figure 4. Width functions $W(s)$ for the channel network realizations shown in Figure 3.

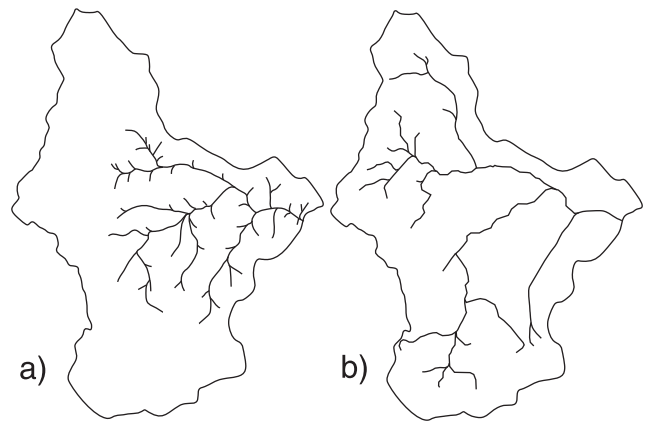

Figure 5. Two channel realizations with identical drainage density (1.5 km km^{-2}). Network (a) has drainage density concentrated near the watershed outlet, while network (b) has drainage density far from the outlet.

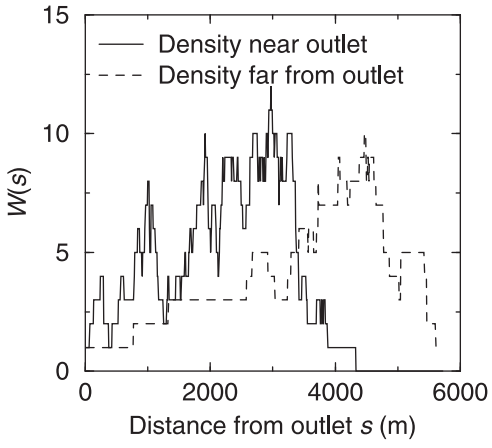

Figure 6. Width functions $W(s)$ for the channel network realizations shown in Figure 5.

and 0% to 34% of the watershed area increased the runoff volume and runoff production efficiency only 2.2% and 3.4%, respectively. This result supports the hypothesis by *Leopold* [1968] that the most infrequent floods occur under conditions that are not appreciably affected by imperviousness of the basin. This is particularly true when the rainfall intensity greatly exceeds the infiltration capacity of the soil, which was clearly the case during the storm of 7 July 2004. That said, the peak flow was found to be sensitive to impervious area during this event, increasing from 188 to 212 and 247 $m^3 s^{-1}$ as impervious area increased from none to 11% and 34% of the catchment area. This represents increases in peak discharge of 16% and 31%. Clearly in the case of extreme events on Dead Run, peak discharge remains sensitive to impervious areas. This finding is contradictory to *Leopold* [1968].

[30] Compared with the calibration event, results in Table 2 show that the runoff efficiencies for the fully impervious case during the 7 July 2004, event is very high, 88% versus 55% for Hurricane Isabel. For the hurricane event, runoff efficiency increased substantially from 32% to 55% with the addition of 34.4% impervious area. For the verification event, the runoff production efficiency increases only from 82% to 88% for the same scenario. For this extreme event the amount of rainfall overwhelmed the soil infiltration capacity. For comparison, the peak rainfall rate from this storm was over 140 mm h^{-1} while the calibrated saturated hydraulic conductivity of the upper soil layer is 11 mm h^{-1}. Therefore, covering a portion of these soils with impervious cover has limited effect on the runoff generation efficiency during the extreme event of 7 July 2004. This condition should result in simple scaling of flood peaks as a function of subcatchment area [*Ogden and Dawdy* 2003].

3.2. Changes in Drainage Density

[31] Hydrologic response based on geomorphologic network properties [*Rodriguez-Iturbe and Valdes,* 1979; *Gupta et al.*, 1980] has been analyzed using a number of different drainage network geomorphology classification systems [e.g., *Horton,* 1945; *Strahler,* 1952; *Kirkby,* 1976; *Naden*, 1992]. Each idealized drainage network shown in Figure 3 was simulated with GSSHA to examine the effect of network drainage density and width function on the catchment runoff response. These simulations were conducted with identical distributed land use, overland roughness values, and without storm drains. The channel networks shown in Figure 3 were simulated with Manning n equal to 0.035. The width functions shown in Figure 4 correspond to the channel networks shown in Figure 3.

[32] Figures 8(a) and 8(b) show the simulated hydrographs from the calibration and verification events, respectively, for the four different drainage densities tested. Table 3 lists the peak discharges, runoff volumes, and runoff efficiencies from each of the four density scenarios. There was a significant change in peak discharge and runoff volume seen by increasing D_d from 0.4 to 0.9 km km^{-2}. Increases in D_d beyond 0.9, however, had a lesser effect. As shown in Table 3, runoff efficiency appears to approach an asymptote with increasing drainage density. In the case of the extreme thunderstorm of 7 July 2004, increasing drainage density from 1.9 to 3.9 km km^{-2} actually decreased the peak discharge by about 3%. This is likely due to more efficient interception of overland flow near the watershed outlet by the denser channel network. Runoff volumes and runoff generation efficiencies were seen to be less sensitive to changes in drainage density above 0.9 km km^{-2}.

[33] From the observed large change in peak discharge between 0.4 and 0.9 km km^{-2}, it appears that flood peaks are most affected by drainage density up to a point, beyond

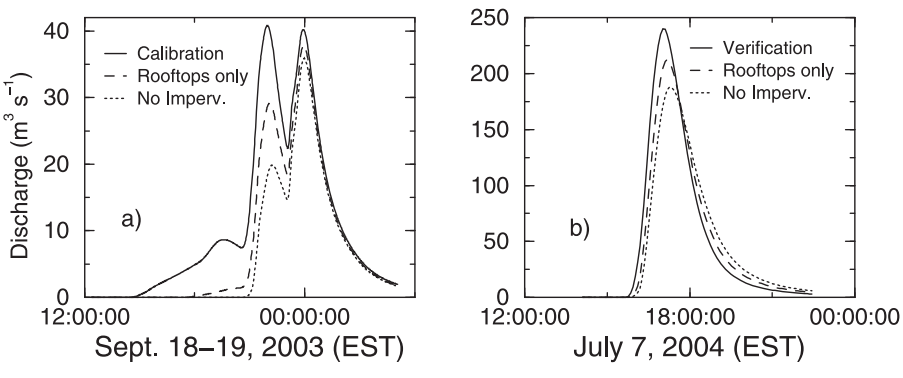

Figure 7. Effect of degree of imperviousness in the Dead Run catchment on runoff hydrographs for (a) Hurricane Isabel (18–19 September 2003) and (b) the >100 year convective storm of 7 July 2004. Calibration and verification simulations include all impervious area.

Table 2. Results of Simulations With Variable Degrees of Imperviousness

Case	Imperv. Area (%)	Hurricane Isabel Calibration Event (Rainfall: 1.255×10^6 m^3)			Extreme Thunderstorm Verification Event (Rainfall: 1.769×10^6 m^3)		
		Peak Flow (m^3 s^{-1})	Runoff Volume (m$^3 \times 10^6$)	Runoff Efficiency (%)	Peak Flow (m^3 s^{-1})	Runoff Volume (m$^3 \times 10^6$)	Runoff Efficiency (%)
No imperv. area	0	35.9	0.392	32.0	188	1.448	81.9
Rooftops only	11	37.9	0.477	38.9	212	1.487	84.1
Rooftops, streets and parking lots	34	40.8	0.670	54.7	240	1.548	87.5

which the effect of significant changes in drainage density on peak flows is considerably diminished. This could be particularly important in the case of a suburban watershed without major modifications to the natural drainage network. If drainage density values are on the lower end of the sensitive range, minor drainage improvements that cause relatively small increases in drainage density could significantly increase flood peaks. Conversely, further modifications to a dense drainage network will affect flood peaks to a lesser extent. In watersheds with D_d above 1.9 km km^{-2}, further increases in drainage density will have a small effect on runoff for large events.

3.3. Changes in Width Function

[34] This test involved the two drainage networks shown in Figure 5, both of which have $D_d = 1.5$ km km^{-2}. These networks were simulated as open channels with variable cross section as previously described. Given the significant differences between the width functions shown in Figure 6 for these two networks, one would expect a significant difference between the hydrographs produced by the model. We tested these two drainage networks with and without impervious areas using the rainfall data from Hurricane Isabel to examine the influence of width function in the case of constant drainage density. The idea behind this experiment was to see if the network shown in Figure 5(b), which had more density far from the outlet better connecting to the impervious areas, showed an increased sensitivity to the presence of those impervious areas.

[35] Results of these model simulations are shown in Figures 9(a) and 9(b). Similarly to the result shown in Figure 7(a), impervious area (Figure 9a) increased flood peaks in both drainage networks compared to no impervious area, Figure 7(b). Drainage density far from the outlet produced significantly higher flood peaks for simulations with and without impervious areas. Results shown in Table 4 indicate that the width function has a much larger effect on runoff volumes and efficiencies than imperviousness.

[36] For Hurricane Isabel rainfall and the same degree of imperviousness, drainage density located far from the catchment outlet resulted in 44% to 50% higher peak flows in the first hydrograph peak, and 64% to 90% higher second peak compared to drainage density concentrated nearer to the watershed outlet. For the same impervious area, differences in runoff volume and runoff efficiency were less than 8% for the two different width functions. The extreme storm of 7 July 2004, was also tested. The hydrographs with and without impervious area had the same peak discharge within a few percent. The peak discharge in the case of increased drainage density near the watershed outlet was 170 m^3 s^{-1}, while for drainage density far from the outlet, the peak was 287 m^3 s^{-1}, an increase of 69%. Runoff volumes varied by less than 6% in all cases tested. This result indicates that for extreme rainfall, the width function controls peak discharge, and the degree of imperviousness does not play as significant a role in determining the peak discharge or runoff volume an urbanized watershed with calibrated soil hydraulic parameters given in Table 1.

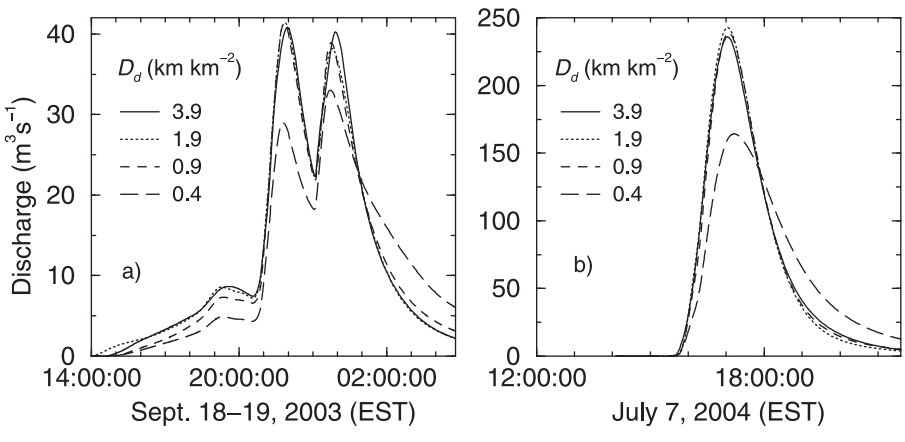

Figure 8. Effect of drainage density on GSSHA simulated runoff hydrographs for (a) calibration event and (b) calibration-verification event in the Dead Run catchment. All simulations include full impervious area as shown in Figure 1.

Table 3. Results From Simulations With Variable Drainage Density Using the Rainfall Volumes of Hurricane Isabel on 18–19 September 2003 and the Extreme Thunderstorm on 7 July 2004

Drainage Density D_d (m km^{-2})	Distance to $W(s)$ Mean (m)	Hurricane Isabel Rainfall: 1.255×10^6 m^3				Extreme Thunderstorm Rainfall: 1.769×10^6 m^3		
		First Peak Flow (m^3 s^{-1})	Second Peak Flow (m^3 s^{-1})	Runoff Volume (m$^3 \times 10^6$)	Runoff Efficiency (%)	Peak Flow (m^3 s^{-1})	Runoff Volume (m$^3 \times 10^6$)	Runoff Efficiency (%)
0.4	1710	28.9	32.9	0.468	38.2	164	1.535	86.7
0.9	2870	41.1	38.0	0.572	46.7	239	1.606	90.8
1.9	3720	41.4	38.8	0.604	49.3	243	1.618	91.5
3.9	4460	40.7	40.8	0.605	49.4	236	1.628	92.0

3.4. Effect of Subsurface Storm Drainage

[37] Subsurface storm drainage networks have the potential to significantly alter the runoff from watersheds as the storm drainage network effectively increases drainage density and transports water to streams without infiltration losses. The subsurface storm drainage network shown in Figure 1b was simulated using the SUPERLINK numerical storm drain code fully coupled within the GSSHA model for both the Hurricane Isabel and extreme thunderstorm events. As Figure 1(b) shows, most of the storm drains are distal to the outlet of the watershed, and their effect is to increase delivery of water to the channel network, not directly to the gauging station.

[38] Discharge from the subsurface drainage network to the channels shown in Figure 2(a) shows that the peak flow through the storm drainage network during Hurricane Isabel was about 25% of the peak discharge, and it was nearly the same during both pulses of heavy rainfall. The subsurface storm drainage network increase the magnitude of the first hydrograph peak by 1.4 m^3 s^{-1} or 4%. The effect of storm drains on the second peak in Figure 2(a) was to increase the peak discharge by 3 m^3 s^{-1} or 7.5%. The storm drain flow hydrograph in Figure 2(a) shows that at the beginning the second pulse of heavy rain, the subsurface drainage network was partly filled and discharging 3.3 m^3 s^{-1} to the channels. At this time the channel network was partially filled and flowing. In this condition, the 1.2 m^3 s^{-1} increase in storm drain discharge to the channel network during the second intense rain pulse had a smaller effect on the second peak. In Figure 2(b) the effect of storm drains on the hydrograph peak for the 7 July 2004 extreme thunderstorm is not discernible. This is despite that the peak flow through the storm drainage network during this storm was about 61 m^3 s^{-1}.

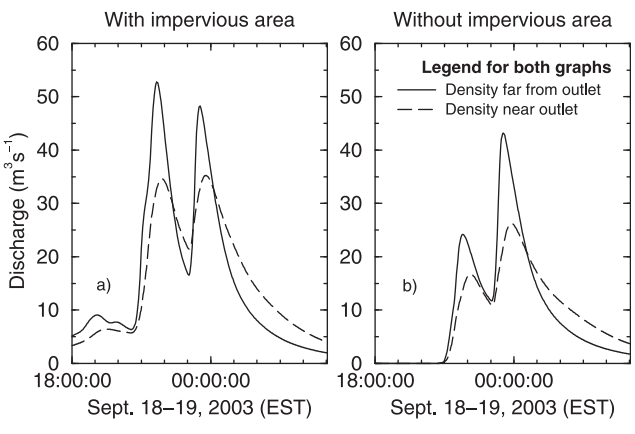

Figure 9. Effect of the location of drainage density on GSSHA simulated runoff hydrographs from the Dead Run catchment for Hurricane Isabel (a) with and (b) without impervious areas simulated. Both drainage networks shown in Figure 5 have drainage densities $D_d = 1.5$ km km^{-2}.

[39] Figure 10(a) shows the width function of the drainage network shown in Figure 1(b) together with the width function of the $D_d = 3.9$ km km^{-2} idealized open channel drainage network shown in Figure 3. Notice that they are very similar. However, when one considers differences in conveyance between storm drains and open channels, the picture becomes much different.

[40] Assuming the Manning equation is valid, the conveyance K was calculated as

$$K = \frac{1}{n} A R^{2/3}. \tag{1}$$

In equation (1), n is Manning's roughness coefficient, A is the bankfull or full pipe flow cross-sectional area, and R is the bankfull hydraulic radius in the case of open channels, or 1/4th of the pipe diameter in the case of pipes flowing full. The conveyance-weighted width function shown in Figure 10(b) is considerably different than the width function that considers network topology alone in Figure 10(a), showing considerably less conveyance in the upper watershed. Conveyance-weighting more accurately describes the ability of flow segments to transport water, and is a more accurate hydrologic description of network capacity.

[41] Buried storm drains rarely exceed 1 m diameter, so generally the conveyance of a pipe is generally far less than an open channel. The capacity of subsurface storm drains is not only limited by conveyance. The slope of the hydraulic grade line in storm drains is limited to the land-surface slope. Furthermore, extreme rainfall can and does result in situations where storm drains flow in the opposite direction intended, distributing water away from channels by reverse flow with unanticipated consequences [*Schmitt et al.*, 2004]. Depending on the existing stream network, watershed topographic relief, intensity, and magnitude of the storm event, the addition of storm drains may have only a limited effect on the peak discharge at a point in the watershed as was the case in this study.

4. Summary and Conclusions

[42] Flood magnitude and frequency increase as urban development spreads throughout a watershed. The literature

Table 4. Results From Simulations With the Two Channel Networks Shown in Figure 5, Having Very Different Width Functions But Identical Drainage Density (1.5 km km^{-2})[a]

Case	Distance to $W(s)$ Mean (m)	First Peak Discharge (m^3 s^{-1})	Second Peak Discharge (m^3 s^{-1})	Runoff Volume (m^3 × 10^6)	Runoff Efficiency (%)
Figure 5(a) with impervious area	2220	34.6	25.3	0.635	51
Figure 5(b) with impervious area	3480	52.7	48.2	0.664	53
Figure 5(a) with no impervious area	2220	16.7	26.2	0.358	29
Figure 5(b) with no impervious area	3480	24.1	43.2	0.386	31

[a]Using the Hurricane Isabel rain storm of 18–19 September 2003 (rainfall volume 1.255 × 10^6 m^3).

contains contradictory hypothesis regarding the influence of imperviousness, geomorphological features such as drainage density and width function, and subsurface storm drainage on catchment runoff and flood peaks. This study was undertaken to examine the influence of these geomorphological factors on flooding in an urbanized catchment, the 14.3 km^2 Dead Run watershed near Baltimore, Maryland, USA.

[43] We coupled the physically based distributed hydrological model GSSHA [*Downer and Ogden*, 2004] with the SUPERLINK [*Ji*, 1998] hydrodynamic numerical solution of subsurface storm drainage to consider all the hydrodynamically distributed physical processes that contribute to flood peaks. The GSSHA model was calibrated using rainfall-runoff data from a moderate-extreme event, Hurricane Isabel, which occurred 18–19 September 2003. This storm consisted of approximately 8 h of moderate rain rates between 5 and 10 mm h^{-1}, followed by two high intensity pulses of rainfall separated by approximately 150 min, with peak rainfall rates in excess of 200 mm h^{-1} for a 5 min period. Storm total rainfall for Hurricane Isabel was 88 mm. The model calibration was verified using data from an extreme thunderstorm event that occurred on 7 July 2004, which had a recurrence interval in excess of 100 years, and produced the flood of record on the Dead Run. This storm resulted in 124 mm of rainfall over the watershed in about 2 h, with peak rainfall rates exceeding 140 mm h^{-1}. The extreme thunderstorm of 7 July 2004 resulted in a unit discharge from the Dead Run that is on the envelope curve of maximum runoff in the eastern United States. Nash-Sutcliffe model efficiency for the calibration event was 91%, and the error in peak discharge during the verification event less than 1%.

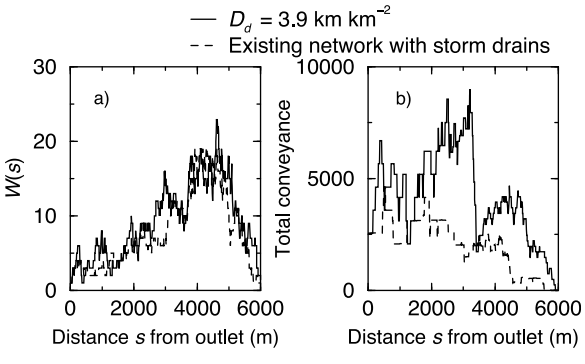

Figure 10. (a) Width function for existing network with storm drains and idealized drainage network with D_d = 3.9 km km^{-2} and (b) conveyance-weighted width function for the same two drainage networks.

[44] With reference to the objectives set forth in this research and analysis of the simulation results, the following conclusions were drawn from this modeling study:

[45] 1. Changes in imperviousness can have a significant effect on flood peaks as shown in Figure 7. The influence of imperviousness on runoff generation efficiency and runoff volume decreases with increasing storm intensity. In the case of rainfall from Hurricane Isabel, simulations with varying degrees of imperviousness showed a large effect on peak discharge during the first peak, and much less effect during the second peak. In the case of the extreme storm of 7 July 2004, imperviousness was found to have an effect on the peak flow rate. Simulation with 34% impervious area resulted in peak flow of 247 m^3 s^{-1}. Compared to 188 m^3 s^{-1} with no impervious area. The hypothesis by *Leopold* [1968] that the most infrequent floods occur under conditions that are not appreciably affected by imperviousness of the basin is not generally supported by this finding with respect to flood peaks. Imperviousness had a significantly reduced effect on runoff volume and runoff generation efficiency for the 7 July 2004 event.

[46] 2. For the moderately extreme Hurricane Isabel rainstorm, increasing drainage density had a large effect on flood peaks and runoff production efficiency within a relatively small range of drainage densities tested. A large change in flood peaks and runoff production efficiency was observed when the drainage density was increased from 0.4 to 0.9 km km^{-2}. Further increases in drainage density above 0.9 km km^{-2} had a negligible effect. This result indicates that small increases in drainage density in low density networks can have a pronounced effect on flood peaks and runoff ratios for moderate-extreme events. In the case of a truly extreme storm such as the event of 7 July 2004, where exceedingly high rainfall rates resulted in runoff production efficiencies in excess of 80%, the same result was observed. Changes in drainage density above 0.9 km km^{-2} have virtually no effect on peak flows, runoff volumes, or runoff ratios for moderately extreme and extreme events.

[47] 3. The spatial distribution of channel drainage density as described using the width function affected peak flows much more than runoff volumes or runoff generation efficiencies given the same degree of imperviousness. Increasing distance from watershed outlet to width function mean resulted in increasing peak flows with or without impervious areas simulated.

[48] 4. The Dead Run subsurface storm drainage network increased the magnitude of the first peak during Hurricane

Isabel by 5%. The second peak was increased by subsurface drains only 3%. The influence of subsurface storm drains is diminished when the subsurface storm drainage network is flowing water at the beginning of a rainfall event. During the extreme storm of 7 July 2004, the subsurface storm drainage network had no discernable effect on the runoff hydrograph, despite the fact that about 25% of the peak flow was moving through the network at one point.

[49] 5. The conveyance of open channels far surpasses closed conduits. Simulating subsurface storm drains as open channels is not a sound approximation. Width function alone does not adequately describe the drainage network when subsurface storm drains are considered. A conveyance-weighted width function is suggested as a superior alternative.

[50] The conclusions of this study were drawn from a 14.3 km^2 urbanized watershed using rainfall data from large two storms that produced rather uniform distribution of rainfall in space. These conclusions is limited to watersheds the size of Dead Run or smaller, with relatively uniform, high intensity rainfall.

[51] Runoff in urbanized watersheds shows a marked sensitivity to rainfall rate. The relative importance of the factors considered in this study was found to be a function of rainfall intensity. Inconsistencies in the literature with regard to the relative roles of imperviousness, drainage density, and width function, as well as the role of subsurface storm drainage, largely arise from the effects of rainfall intensity. The use of models that can accurately simulate the effect of rainfall rate on runoff production, as well as the use of appropriate drainage density and imperviousness is indicated for modeling extreme storms in urbanized watersheds.

[52] **Acknowledgments.** This study was initiated in the M.S. Thesis work of Jon Zahner [*Zahner* 2004]. Since that time significant improvements were made to the GSSHA and SUPERLINK code and an entire reanalysis was performed. Radar-rainfall and rain gauge data were for the Dead Run catchment were provided by James A. Smith of Princeton University. Data for the Dead Run storm drainage network were provided by Katherine Meierdierks while a student at Princeton. Streamflow data were provided by the USGS. This study was funded in part by U.S. Army Research Office through grants DAAD19-03-l-0355, DAAD19-01-l-0629, DAAG55-98-l-0069 (DURIP) and the U.S. National Science Foundation through grant EAR-0003408 while the lead author was at the University of CT. GSSHA development is funded by the U.S. Army Corps of Engineers, Engineer Research and Development Center. We acknowledge constructive review comments by Daniel Wright, Ph.D. student at Princeton University, two anonymous reviewers, and Associate Editor Graham Sander.

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