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Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude

Yang Yang[b,*], Theodore A. Endreny[c], David J. Nowak[a]

[a] USDA Forest Service Northern Research Station, Syracuse, NY 13210, United States
[b] The Davey Institute, Syracuse, NY 13210, United States
[c] Environmental Resource Engineering, SUNY ESF, Syracuse, NY 13210, United States

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ABSTRACT

Impervious land cover was the choice for many urban development projects in order to accelerate runoff and reduce the depth and duration of local flooding, however this led to increases in downstream runoff characterized by large, flashy peak flows. Urban ecosystem restoration now involves slowing down urban runoff to restore local hydrology with green infrastructure, which can be installed as single parcels along runoff flow paths; green infrastructure essentially increases the surface roughness, delaying the speed of runoff compared with relatively smooth impervious surfaces. In this study, we present a runoff routing model that inter-compares runoff from different land parcel surfaces with different roughness to help communities quantify how land parcel restoration impacts runoff timing and peak magnitude. Our modeling experiments contrast the timing and magnitude of floods for discrete runoff pathways composed of parcels with different cover types, converting rough rural land cover to smooth impervious cover as well as the restorative impact of relocating impervious area further from the water body or installing green infrastructure along the flow path. We demonstrate how the model is calibrated to match observed runoff for an entire watershed, and how the model can then be used to estimate how land cover changes will affect runoff timing and magnitude. This study introduces how a simple model to represent land parcel surface roughness and stormwater runoff timing and magnitude, allowing for informed watershed restoration planning, urban planning and placement of green infrastructure.

Introduction

The conversion of rural land to urban land has been the trend as urban populations grow, and with urban populations nearing 80% of all citizens worldwide (Heilig, 2012) it is strategic to examine how we can improve the quality of life in urban areas. The process of urbanization has significant land cover impacts known to result in serious and profound long term environmental problems (Goudie, 2013; Pickett et al., 2001). The conversion of pervious land (i.e., soil) and vegetated land parcels to impervious cover such as asphalt and concrete leads to greater heat storage and higher urban nighttime temperatures than surrounding rural areas, adversely impacting human health (Oke, 1982), as well as harder, smoother surfaces that stop infiltration and speed up stormwater runoff and lead to rapid downstream flooding as well as water quality pollution (Endreny et al., 2003; Hollis, 1975; Leopold, 1968a,b). As more urban areas reconsider the disruptive impact of impervious surfaces (Shuster et al., 2005; Lee and Heaney, 2003; Niehoff et al., 2002; Harbor, 1994), there have been calls to use low impact development (LID) to restore pre-development hydrological functions (Dietz, 2007). Green infrastructure (Benedict and Mcmahon, 2002a,b), considered a LID practice, uses permeable soils with bioretention as well as permeable concrete or pavement (Brattebo and Booth, 2003) to increase stormwater infiltration and increase parcel roughness such that runoff is similar to pre-development hydrology. Urban areas are designing with green infrastructure retrofits and in new construction as a watershed structure that serves to naturalize urban hydrology and ecosystem functions (Ahern, 2007; Benedict and Mcmahon, 2002a,b).

Simulating the effective of green infrastructure on urban hydrology has recently become a feature in several hydrological models. Most models have been run to analyze the impact of green infrastructure to the water budget, determining how much rainfall is converted to infiltration or detention, and not the impact to parcel roughness and runoff velocity. These models include the Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model (Lee et al., 2012; Lai et al., 2007), the Storm Water

* Corresponding author at: 321 Baker Labs, 1 Forestry Drive, SUNY ESF, Syracuse, NY 13210-2773, United States. Tel.: +1 315 530 5450.
E-mail address: yyang31@syr.edu (Y. Yang).

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Management Model (SWMM) (Rossman, 2010), and the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (Wong et al., 2002, 2006). Shamsi et al. (2014) used the SUSTAIN model to investigate the impact of green infrastructure on reducing runoff volume in Allegheny County, Pennsylvania. Sjöman and Gill (2014) used the Natural Resources Conservation Service Curve Number (NRCS-CN) method to study how spatial density of built cover and location on sandy soil or clay soil within the Höjeå river catchment in southern Sweden influenced infiltration and runoff generation. Qin et al. (2013) used SWMM to analyze water infiltration and retention of green roofs and permeable surfaces under different types of precipitation. In general, researchers expect green infrastructure to decrease flood water volume by increasing interception, infiltration, and evapotranspiration (Liu et al., 2014). By contrast, few studies have used a parsimonious model (i.e., few model parameters) to focus on simulating the effect of land parcel roughness in slowing down runoff velocity and delaying the flood peak time and lowering the flood peak magnitude.

In designing a parsimonious model, our goal is to create a model for inter-comparison of different land cover scenarios rather than creating a model that is calibrated and then run for different watersheds or storms. We start with representing a single flow path where green infrastructure is installed to intercept the stormwater runoff, and it has a surface roughness that reduces runoff speed, and provides infiltration or storage that reduces runoff volume and magnitude. Most stormwater runoff models are not configured to simulate a single surface runoff flow path and quantify the effect of green infrastructure on reducing runoff velocity and volume. In this study, we developed a model to simulate a single surface runoff flow path and isolate the impact on runoff velocity of land parcel conversion to green infrastructure, by adjusting the simulated roughness of the parcel. The model can represent individual and grouped land parcels of different roughness values, and our default settings make impervious parcels smoother than vegetated green infrastructure parcels. We used this model to conduct numerical experiments and illustrate the impact of land parcel roughness within flow paths networks as well as simulate entire urban watersheds with effective velocity and diffusivity to represent the bulk effect of fast and slow runoff processes.

Runoff theory

At the ground surface in permeable areas, rainfall is partitioned into surface runoff rather than infiltration based on the hydrological concept of infiltration excess, where rainfall rates exceed infiltration rates, or saturation excess, where saturation of the soil has been achieved (Dunne and Black, 1970). Urbanization can lead to soil compaction and imperviousness, increasing infiltration excess runoff, as well as reducing the roughness of the surface and allowing higher runoff velocities and shorter travel time of surface runoff from the land to the river channel (Pitt et al., 2003; Wurbs and James, 2002) and larger runoff peaks during rainfall events in urban areas (Leopold, 1968a,b). In rural and forest areas, soils have relatively high infiltration rates and surface runoff generally is small compared with subsurface flows (Mcdonnell, 2000). Gravity pulls surface runoff from higher potential energy land parcels to lower potential energy areas following flow paths determined by topography, and the runoff velocity and arrival time is determined by many factors, approximated by the Manning equation with terms for surface roughness, land slope, and hydraulic radius (Wurbs and James, 2002). In this section, we introduce two versions of our theoretical model to investigate how individual land parcels (Section "Runoff simulation for one-dimensional flow paths") and grouped land parcels (Section "Runoff simulation for two-dimensional catchments") influence runoff peak magnitude and timing.

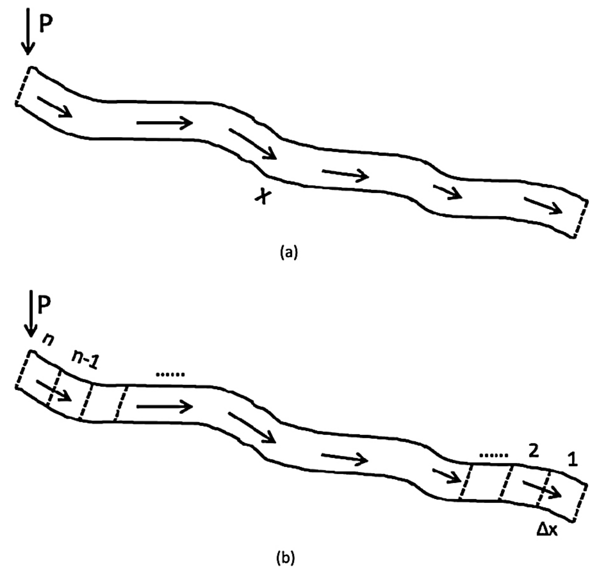

Fig. 1. (a) One dimension channel with uniform c and D; (b) one dimension channel with n segments, and each segment has uniform c and D. The arrows indicate the flow direction.

Runoff simulation for one-dimensional flow paths

Runoff magnitude and timing can be simulated with the advection–diffusion equation, which is considered a close approximation of the physics of overland flow and open channel flow (Cappelaere, 1997). To initiate overland and channel flow, a pulse of effective precipitation P_{eff} first arrives at an upslope location $x = 0$, where P_{eff} and x have length units [L]. The generalized advection–diffusion equation describes flow along a one-dimensional flow path (Fig. 1a) as (Yen and Tsai, 2001):

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = D\frac{\partial^2 Q}{\partial x^2} \quad (1)$$

In Eq. (1), Q [L/T] is the flow rate at a distance x [L] downstream from the point $x = 0$ where the effective precipitation arrived, c [L/T] is the flow celerity, and D [L^2/T] is the diffusivity which reflects the tendency of the water wave to disperse longitudinally as it travels downstream. P_{eff} is the available precipitation for runoff after the deduction of evapotranspiration, infiltration, canopy interception, depression storage and any other water loss from the total precipitation. Assuming c and D are constants for the whole flow path and P_{eff} is a unit pulse disturbance, an analytical solution for Eq. (1) can be obtained (Liu et al., 2003a,b):

$$Q(x,t) = \frac{1}{2\sqrt{\pi D}} x t^{-\frac{3}{2}} e^{-\frac{(x-ct)^2}{4Dt}} \quad (2)$$

This solution represents the response function of the flow path under a unit pulse disturbance at the inlet of the flow path; it indicates the main body of the flow moves to the outlet with a celerity c and with a dispersion of D. This solution can also be interpreted as the probability density function (PDF) of flow travel time spent in the flow path; the exponential term of Eq. (2) approximates the Gaussian distribution with ct as the mean and $2Dt$ as the variance. This solution assumes c and D are uniform along the flow path. In cases of spatial variation in land cover and where c and D are changing along the flow path, we can divide the flow path to n segments (Fig. 1b) and each segment has length Δx and approximate uniform c and D. For each segment, Eq. (2) can be applied.

In this case, with a unit pulse of effective precipitation at the inlet of the flow path, the discharge rate at the interface between the nth segment and the $(n-1)$th segment can be described by

$$Q_{n\to n-1}(t) = \frac{\Delta x}{2\sqrt{\pi D_n}} t^{-\frac{3}{2}} e^{-\frac{3(\Delta x - c_n t)^2}{4D_n t}} \quad (3)$$

$Q_{n\to n-1}(t)$ acts as input for the $(n-1)$th segment. The discharge rate at the interface between $(n-1)$th segment and the $(n-2)$th segment can be obtained through convolution of the input rate (Eq. (3)) and the response function of the $(n-1)$th segment (Eq. (2) of the $(n-1)$th segment):

$$Q_{n-1\to n-2}(t) = \int_0^\infty Q_{n\to n-1}(\tau) Q_{n-1}(t-\tau) d\tau \quad (4)$$

in which τ is a dummy variable (or free variable) which is used for the integration and will not appear in the final description of $Q_{n-1\to n-2}(t)$. The response function of the whole flow path can be obtained by performing convolutions along the entire flow path. For a flow path with n segments, $n-1$ convolutions are needed to get the final response function. Then given any time series of P_{eff} at time (t), the final shape of the transported flood wave can be simulated through convolutions of P_{eff} (t) and the response function of the entire flow path.

Runoff simulation for two-dimensional catchments

To simulate the total runoff of two-dimensional catchments, we could apply the theory presented in section "Runoff simulation for one-dimensional flow paths" by: (1) identifying the flow path of each location within the catchment; (2) performing convolution calculations for each flow path; and (3) summing the convolution results of all flow paths to get the total runoff of the whole catchment. While the procedure is straight forward, the convolution calculations require significant computational power for large catchments, which may limit the application of the model. Thus, we introduce the Yang and Endreny (2013) two-parameter advection–diffusion routing model to study how grouped urban and green areas influence the total runoff of a two-dimensional catchment. The two-parameter advection–diffusion routing model is a simplified lumped version of the spatially distributed model presented in section "Runoff simulation for one-dimensional flow paths", and provides computational efficiency. This 2-parameter model simulates the runoff flood wave generated by a land area, and can represent fast surface flow and slow subsurface flow. The lumped advection–diffusion routing model predicts runoff at any time, t:

$$Q(t) = \frac{P_{eff} * A}{\sqrt{\pi}} \sqrt{\beta} * t^{-\frac{3}{2}} e^{-\frac{\beta}{t}} e^{-\frac{t}{\alpha}} e^{2\sqrt{\frac{\beta}{\alpha}}} \quad (5)$$

where P_{eff} [L] is the effective precipitation on area A [L^2]. The two parameters are α [T] and β [T], defined as $\alpha = 4D/c^2$ and $\beta = x^2/4D$, in which x [L] is a length scale representing the distance between the land parcel to the outlet. The term c [L/T] is the kinematic wave celerity, and D [L^2/T] is the diffusivity. The runoff wave peak time and runoff peak amplitude were determined by the two time parameters α and β:

$$t_{max} = -\frac{3}{4}\alpha + \frac{3}{4}\alpha\sqrt{1 + \frac{16}{9}\frac{\beta}{\alpha}} \quad (6)$$

$$Q_{max} = \frac{P_{eff} * A}{\sqrt{\pi}} \sqrt{\beta} * t_{max}^{-\frac{3}{2}} e^{-\frac{\beta}{t_{max}}} e^{-\frac{t_{max}}{\alpha}} e^{2\sqrt{\frac{\beta}{\alpha}}} \quad (7)$$

Double-peak hydrographs are often generated in urbanized watersheds, especially for watersheds with large urban parcels clustered near the downstream area. Simulating the observed double-peak hydrograph is a challenge for many hydrological models, but for our model we simulate double-peak hydrograph phenomena by applying Eq. (5) in two parts, respectively with two sets of model parameters (Yang et al., 2015):

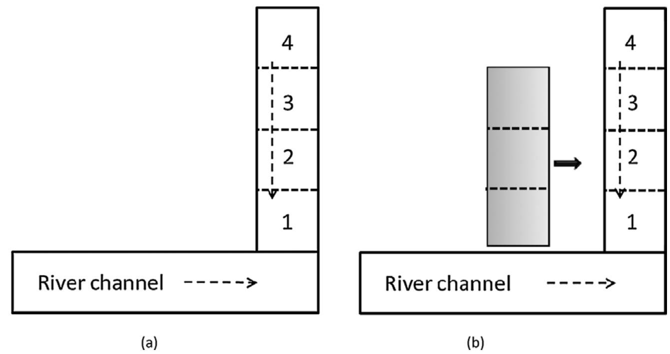

Fig. 2. Schematic plots for (a) pre-urbanization condition with four location options for urbanization; (b) post-urbanization condition with all four locations urbanized but green infrastructure can be installed at locations 1, 2 and 3. Dashed arrows show the water flow directions.

$$Q(t) = Q_{urban}(t) + Q_{rural}(t)$$
$$= \frac{P_{eff1} * A_1}{\sqrt{\pi}} \sqrt{\beta_1} * t^{-\frac{3}{2}} e^{-\frac{\beta_1}{t}} e^{-\frac{t}{\alpha_1}} e^{2\sqrt{\frac{\beta_1}{\alpha_1}}} + \frac{P_{eff2} * A_2}{\sqrt{\pi}} \sqrt{\beta_2} * t^{-\frac{3}{2}} e^{-\frac{\beta_2}{t}} e^{-\frac{t}{\alpha_2}} e^{2\sqrt{\frac{\beta_2}{\alpha_2}}} \quad (8)$$

In Eq. (8) we use subscript 1 for urban runoff parameters and subscript 2 for rural runoff parameters. $P_{eff1} * A_1$ represents the total runoff volume from urban area and $P_{eff2} * A_2$ represents the total runoff volume from rural area. The four terms, the effective precipitation (P_{eff1}, P_{eff2}) on the associated sub-watershed areas (A_1, A_2), may be unknown, so we simplified $P_{eff1}{}^*A_1$ and $P_{eff2}{}^*A_2$ to $C_1{}^*P$ [L^3] and $C_2{}^*P$ [L^3], in which C_1 and C_2 are two unknowns and P is the measured precipitation. Therefore, given the measured precipitation P, the model of Eq. (8) has 6 parameters in total: α_1, β_1 and C_1 for urban runoff, α_2, β_2 and C_2 for rural runoff. These parameters can be obtained by fitting the simulated discharge to the measured discharge, and the calibrated parameters reflect the properties of two land types on flood generation and transportation.

Modeling a flow path: 1 dimensional simulations

The model explained above was run in a 1 dimension framework, which allows it to represent a single flow path, with or without curvature. Two experiments were conducted with this 1D model to investigate the influence of parcel urbanization on runoff magnitude and timing. For the first set of experiments, we assumed a pre-urbanization condition and then allowed for urbanization in one of four alternative parcels, each on the same overland flow path connecting to a river channel (Fig. 2a). The pre-urban and urban parcels were 100 m × 100 m, and the distance from the edge of the parcel to the river channel ranged from 0 m to 300 m for the four parcels that will undergo urbanization. The pre-urbanization land cover was a uniform rural, but experiments can consider variation such as grass, fields, or forest.

Model estimates of surface flow velocity over the rural and urban land cover were obtained using Manning's equation (Wurbs and James, 2002):

$$v = \frac{R^{2/3}S^{1/2}}{m} \tag{9}$$

in which R [L] is the hydraulic radius, S is local land slope, and m is land surface roughness. For surface flow, R can be approximated by the depth of the effective precipitation. The flow celerity c and diffusivity D used in Eqs. (1) and (2) were estimated by (Liu et al., 2003a,b; Henderson, 1966):

$$c = \frac{5}{3}v \tag{10}$$

$$D = \frac{vR}{2S} \tag{11}$$

For rural land cover, the R value ranged from 1 mm to 10 mm, the S value ranged from 0.1 to 0.0001, and m value ranged from 0.1 (short grass) to 0.8 (dense underbrush) (Wurbs and James, 2002). With these inputs, based on Eq. (9), the surface runoff velocities ranged from 0.0001 m/s to 0.15 m/s, and according to Eqs. (10) and (11), the c ranged from 0.00017 m/s to 0.25 m/s, and D ranged from 0.00002 m^2/s to 0.25 m^2/s. From within this range, our modeling experiments used c = 0.02 m/s and D = 0.1 m^2/s for the rural parcels (representing medium slope and rain conditions), and representing a 10-fold decrease in roughness of impervious surfaces, urban parcels were set to c = 0.2 m/s and D = 1.0 m^2/s.

Our modeling experiments simulated urbanization of the four parcel locations sequentially (Fig. 2a), starting with location 1 closest to the river. When a parcel was converted from rural to urban, we only changed the land cover of one parcel, and for each land parcel conversion the runoff increased in magnitude and velocity. When parcel 1 was urbanized, which was located along the river, the runoff was 10 times greater in magnitude and 10 times faster than the pre-urbanization condition (Fig. 3a). When parcel 2 was urbanized, located 100 m from the river, the runoff wave was 1.5 times greater in magnitude and 2 times faster than the pre-urbanization condition (Fig. 3b). When parcel 3 was urbanized, the runoff wave was 1.2 times greater in magnitude and 0.5 times faster than the pre-urbanization condition (Fig. 3c). When parcel 4 was urbanized, the runoff wave was 0.18 times greater in magnitude and 0.3 times faster than the pre-urbanization condition (Fig. 3d).

In each simulation, we assumed the effective precipitation of rural parcels and urban parcels were identical; however, the effective precipitation for urban parcels may be several times larger

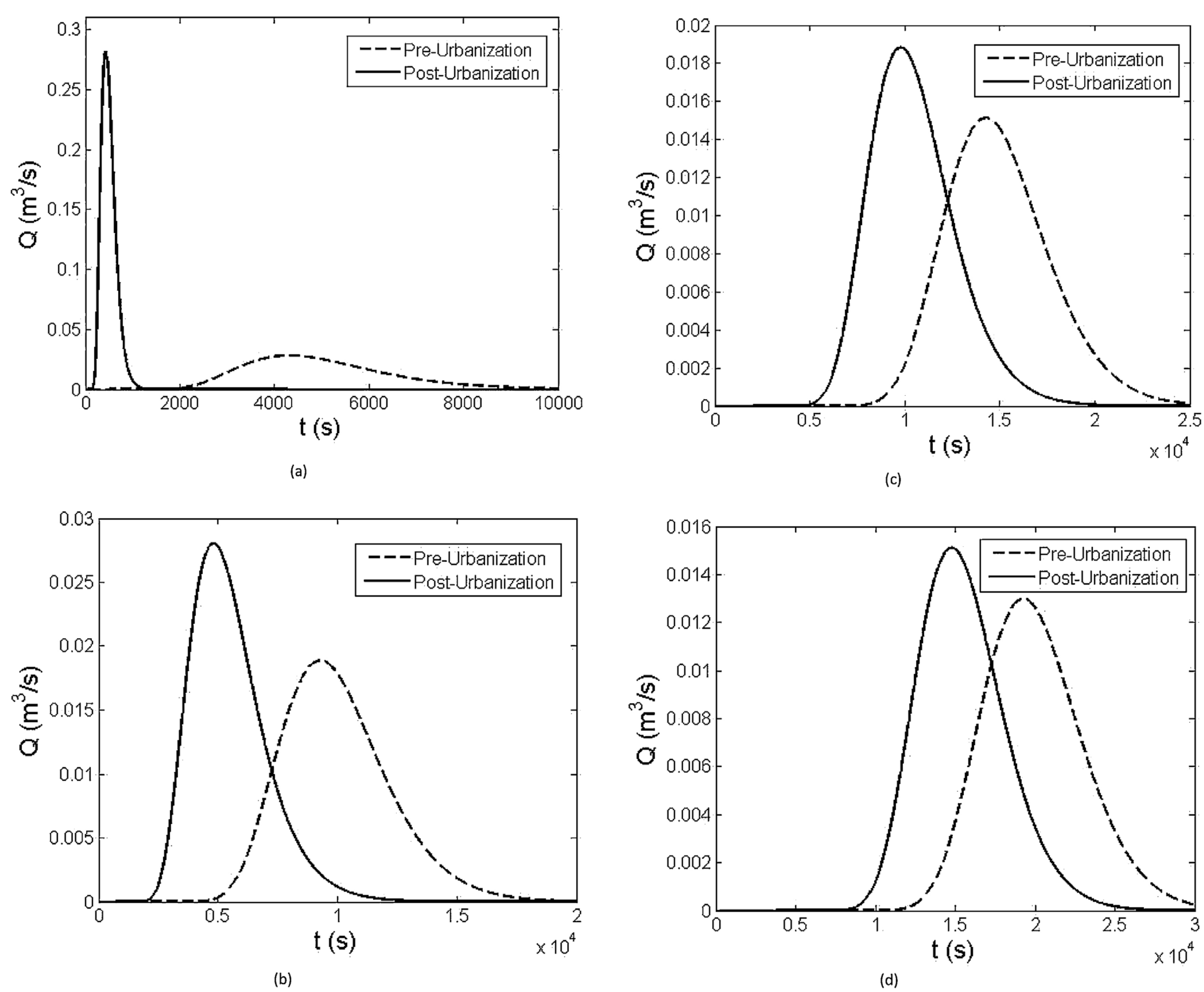

Fig. 3. Simulated flood waves of pre- and post-urbanization for (a) location 1, (b) location 2, (c) location 3, and (d) location 4.

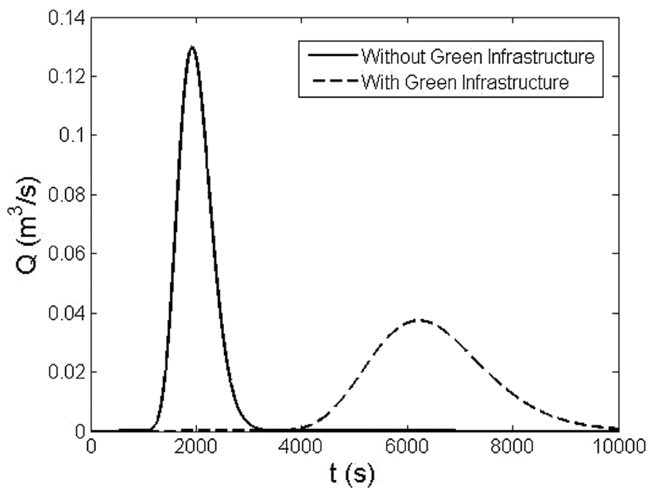

Fig. 4. Compared flood waves of with and without green infrastructure installed at location 1, 2 and 3.

due to lower green canopy interception, pervious soil infiltration, and evapo-transpiration, resulting in even larger peak runoff. Our model also held hydraulic radius constant along the parcel flow path, but hydraulic radius increases with increasing runoff depth, then runoff velocities would increase and result in flashier hydrographs.

In a second set of experiments with the 1D model, we assumed that all the four parcels in Fig. 2a were urbanized but green infrastructure was installed at parcels 1, 2 and 3 to control storm water by reducing flow celerity and diffusivity (Fig. 2b), changing from urban values of 0.2 m/s and 1 m^2/s to green infrastructure values of 0.05 m/s and 0.25 m^2/s. The change in runoff generated in these experiments captured a reduction in the runoff peak, to less than one third of the original value (Fig. 4), while the time to peak was delayed by 3 times the original value. The modeling experiments provide an illustration of how this analytical model can simulate: (1) the decrease in runoff magnitude and velocity with placing urban parcels further from receiving channel; and (2) the additional decrease in runoff magnitude and velocity with installing green infrastructure parcels along the flow pathbetween urban parcels and receiving channel.

Modeling a watershed: 2 dimensional simulations

To represent multiple flow paths within a watershed, we applied the 2D model described in section "Runoff simulation for two-dimensional catchments" on the 285 km^2 Onondaga Creek watershed, draining into Syracuse, New York, a city with 145,170 inhabitants and a land area of 66.4 km^2, with 85% of Syracuse within the Onondaga Creek watershed (Fig. 5). Storm water in Syracuse creates three problems, the first has been combined sewer overflows polluting Onondaga Creek, the second has been overloading the wastewater treatment plant with combined sewer flows that do not spill into Onondaga Creek, and the third has been flashy, polluted hydrographs damaging the Onondaga Creek ecosystem. To address these problems, the community has invested in sewer separation as well as an award winning Save the Rain program to convert urban parcels to green infrastructure and reduce runoff velocities, increase retention, and naturalize the watershed hydrology.

To demonstrate the use of our model for watershed simulation, we compared our 2D watershed model predicted runoff to observed runoff in Onondaga Creek for 3 days of storms during October 2008, which included a maximum rainfall rate of 11 mm/h (Fig. 6). The

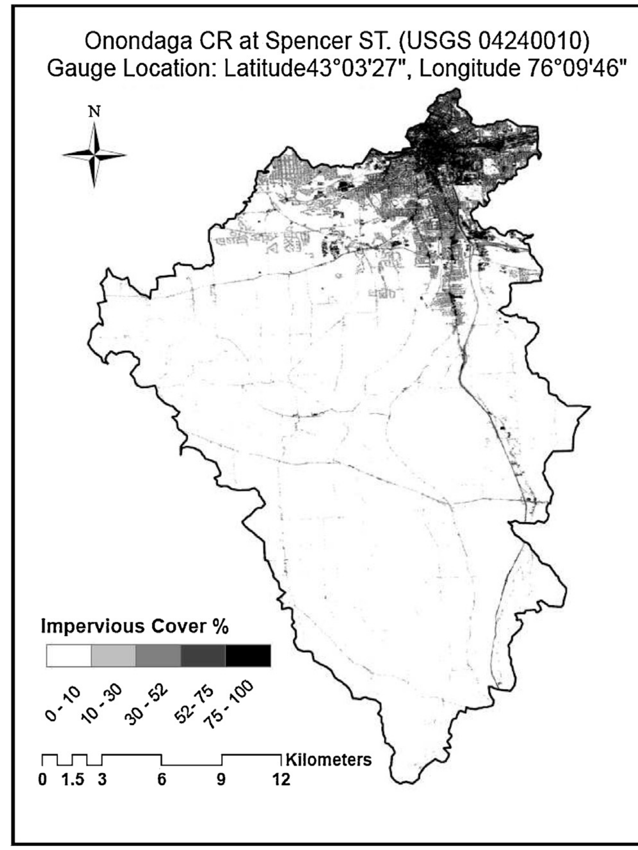

Fig. 5. Boundary and NLCD 2001 impervious cover percentages for Watershed of Onondaga Creek at Spencer Street, Syracuse, NY.

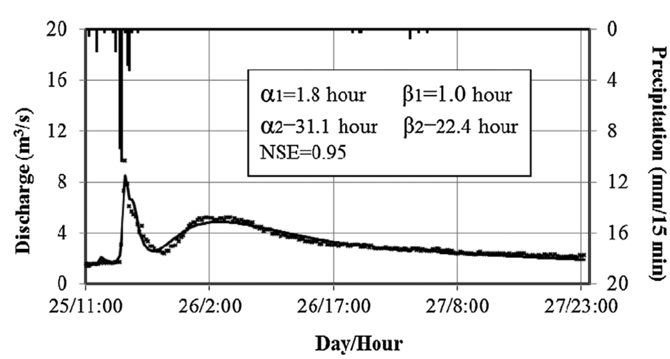

Fig. 6. Observed (star markers) and simulated (solid lines) hydrographs for Onondaga Creek at Spencer Street, Syracuse, NY.

precipitation data were from north of the city at Syracuse Hancock airport (WBAN: 725190 14771) and the observed discharge data were from the Kirkpatrick Street USGS gauge (station 04240010). The model was auto-calibrated with PEST software (Doherty, 2001) by adjusting the time parameters α_1 and β_1 for urban runoff, α_2 and β_2 for rural runoff, C_1 for urban runoff, and C_2 for rural runoff to minimize the R^2 of observed and predicted runoff. The calibrated model was fit to the observed hydrograph (Fig. 6) with a 0.95 Nash-Sutcliff efficiency (NSE) (Nash and Sutcliffe, 1970). The simulated urban runoff time constant α_1 was 1.8 h and β_1 was 1.0 h, which are much lower than the time constants for rural runoff with α_2 at 31.1 h and β_2 at 22.4 h. To achieve this simulation, the C_1 was fit to 435.35 m^2 and the C_2 was fit to 2719 m^2, which is approximately the same ratio of urban sub-watershed to rural sub-watershed area.

After calibrating the model, it can be used to evaluate how different land cover types would likely affect runoff for the calibrated storm. In cases where watershed planners want to naturalize hydrology, the model can simulate the effect of green infrastructure installations in the urban area. To illustrate this concept, if we reduced the urban celerity c_1 and diffusivity D_1, this would cause an increase in the urban time constants α_1 and β_1. For example, if we assume green infrastructure reduced c_1 and D_1 to half of their original values, this would double the time constants of α_1 to 3.6 h and β_1 to 2.0 h. As a result, time to peak was doubled and the peak magnitude was reduced to half of the original value.

Discussion and conclusion

The parsimonious runoff model presented in this paper facilitates analysis of green infrastructure effects on urban runoff timing and magnitude. Although other models have investigated how green infrastructure can reduce flood volume, our model is unique in using celerity and diffusion parameters to represent urban land parcel roughness and its effect on runoff velocity, which impacts the runoff flood peak. The model we developed is not intended for accurate prediction of runoff for uncalibrated events, and instead is for historical analysis of calibrated storms to examine how parcel roughness affects runoff timing and magnitude, or for model intercomparison simulations. In this study, we presented a 1D and 2D version of the runoff model. The 1D model allowed us to study how the parameters of each individual land parcel influenced the runoff velocity along a single flow path, and how different distributions of urban area and green infrastructure contribute to the final discharge at the outlet. The 1D model analysis can be used to assess the hydrological impact of current and future land cover and to evaluate the effectiveness of green infrastructure practices; model results can remain conceptual if the user does not have accurate estimates of model parameters for each land parcel. While the 1D model can be extended to 2D and applied to watershed scale, parameterizing parcels for the entire watershed is a tremendous challenge. Because poor estimation of these distributed parameters may introduce larger simulation errors than the conceptual errors from using a lumped model with fewer parameters (Smith et al., 2013), we recommend using the lumped model for 2D studies of entire watersheds.

Our study focused on presenting a new model to quantify the impact to runoff peak magnitude and timing of replacing urban impervious parcels with green infrastructure parcel. We presented a theoretical analysis of the advection–diffusion equation, and developed a spatially distributed model to simulate runoff along a flow path with varying surface roughness for the land parcels. Using this spatially distributed flow path model, we quantified the impact to runoff peaks of changing individual land parcels between rural and urban development. Our model complies with physics and intuition, and simulation results predict that urbanization will increase runoff flashiness, but this can be mitigated by placing urban parcels further from the river channel or installing of green infrastructure in the flow path. Our model was generalized to represent sub-watershed areas as a lumped routing model. We applied this routing model to the Onondaga Creek watershed and illustrated that fast and slow runoff responses can be simulated to match observed double peaked hydrographs. Each of these models can be used to assess the hydrological impact of current and future land cover practices and to evaluate the effectiveness of green infrastructure restoration. The models are tools to assist urban planners and hydrologists on land use planning and management to naturalize watershed hydrology while reducing flood impacts.

Acknowledgements

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