Case Study

Using the KINEROS2 Modeling Framework to Evaluate the Increase in Storm Runoff from Residential Development in a Semiarid Environment

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Abstract: The increase in runoff from urbanization is well known; one extreme example comes from a 13-ha residential neighborhood in southeast Arizona where runoff was 26 times greater than in an adjacent grassland watershed over a 40-month period from 2005 to 2008. Rainfall-runoff modeling using the newly described KINEROS2 urban element, which simulates a contiguous row of houses and the adjoining street as a series of pervious and impervious overland flow planes, combined with tension infiltrometer measurements of saturated hydraulic conductivity (K_s), indicate that $17 \pm 14\%$ of this increase in runoff is due to a 53% decrease in K_s in constructed pervious areas as compared to the undeveloped grassland. K_s in the urban watershed identified from calibrating the rainfall-runoff model to measured runoff is higher than measured K_s but much lower than indicated by a soil texture–based KINEROS2 parameter look-up table. Tests using different levels of discretization found that watershed geometry could be represented in a simplified manner, although more detailed discretization led to better model performance. **DOI: 10.1061/(ASCE)HE.1943-5584.0000655.** *© 2013 American Society of Civil Engineers.*

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Introduction

In recent years, the increase in storm-water runoff associated with urbanization has begun to be considered as a potentially renewable water source (Pinkham 1999; Furumai 2008; Lohse et al. 2010). This runoff can be reused directly, through rainwater harvesting efforts or groundwater recharge through focused infiltration in basins or dry wells, or indirectly, by routing runoff to natural stream drainages where it can contribute to groundwater recharge. In arid environments, where upland surface recharge is minimal, increased runoff from urbanization can lead to increased recharge, as rainfall that previously would have infiltrated at the land surface, and thus been subject to evaporation and transpiration, is instead routed to an area where deep infiltration and recharge can occur (Goodrich et al. 2004). Accurate urban rainfall-runoff models are needed to predict this potential urban-enhanced recharge, along with any changes in upland infiltration rates that might decrease already-small recharge.

Urban rainfall-runoff models typically consider the storm runoff volume due to the increase in impervious surfaces [Shuster et al. 2005; Boyd et al. 1993; U.S. Dept. of Agriculture (USDA) 1986] but less commonly consider the effect of changes in infiltration rates as a result of development activities or the effect of routing impermeable rooftops across permeable soils. In a Florida study, Gregory et al. (2006) found that infiltrability decreased up to 99% between undisturbed areas (natural forest, planted forest, and pastures) and residential lots. Pitt et al. (1999) found a strong correlation between compaction and infiltrability of sandy soils in Alabama, as did Woltemade (2010) at sites in Pennsylvania. That study also found a decrease in infiltrability in newer developments (post-2000), where the use of heavy machinery for site development was more common (Woltemade 2010). In general, site preparation and construction at each of these study areas was on a lot-by-lot basis and is thus not representative of the large-scale site preparation that utilizes heavy equipment, including scrapers and tracked bulldozers, typical of tract-housing developments in the American Southwest. Furthermore, the humid-region soils in the eastern United States considered in these studies are generally better developed and often have higher infiltrability than aridic soils in the Southwest (Birkeland 1999).

To investigate the increase in runoff with urbanization, and in particular the role of decreased pervious-area infiltrability, a discretization element has been developed to extend the applicability of the USDA Agricultural Research Service (ARS) watershed model KINEROS2 (Semmens et al. 2008; USDA 2013a) to urban areas. Many successful studies have demonstrated the applicability of KINEROS2 to simulate runoff in arid (Michaud and Sorooshian 1994) and humid (Smith et al. 1999) environments, postfire erosion (Canfield et al. 2005), channel infiltration (Woolhiser et al. 2006; Goodrich et al. 2004), and other processes. This new functionality, known as the KINEROS2 urban element, implements a physically based infiltration model, kinematic-wave routing on planar surfaces and in channels, and routing of surface runoff over pervious and impervious surfaces. The urban element is primarily intended for modeling street-scale residential areas with interconnected pervious and impervious areas. The KINEROS2 modeling framework

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also incorporates overland (hillslope), channel, pipe, and pond elements, spatially varied rainfall and infiltration, and erosion and sediment transport. In addition, the KINEROS2 model, including the urban element, can be utilized with the Automated Geospatial Watershed Assessment tool (AGWA) (Miller et al. 2007; USDA 2013b), a GIS package used to delineate and parameterize a watershed model using geospatial data (automatic discretization for urban elements is not yet implemented).

Various commercial and noncommercial urban runoff modeling alternatives exist, such as the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM; Huber et al. 2006), the U.S. Dept. of Agriculture's Urban Hydrology for Small Watersheds (TR-55) model (USDA 1986), and variations of the Rational Method or unit hydrograph approach. SWMM is widely used and provides a graphical user interface, various options for surface and subsurface infiltration and routing, pollutant routing, and a long history of case studies. The conceptual models TR-55 and the Rational Method, while easy to use and capable of producing accurate results, cannot incorporate physically based field measurements to investigate directly how soil properties affect runoff. KINEROS2 is differentiated from these by its use of the Smith-Parlange three-parameter infiltration model, integration with AGWA for automated parameterization of overland flow and channel elements, and flexible routing of runoff between pervious and impervious areas (Semmens et al. 2008). In addition, the urban element simplifies the use of existing KINEROS2 models to simulate urban runoff.

Here we present results from a KINEROS2 urban element case study in which runoff from a small residential tract-housing development is simulated using parameters identified from field measurements and model optimization. Parameter sensitivity and uncertainty, and the effect of discretization scale, are examined. Finally, the model is used to predict the increase in runoff attributable to changes in soil infiltration properties, independent of the increase in impervious area.

Study Area

The study area comprises an approximately 32-ha (79-acre) mesquite grassland and a 13-ha (31-acre) residential development (referred to as the grassland and urban watersheds, respectively) in the city of Sierra Vista, Cochise County, in southeastern Arizona (Fig. 1). The study area is located at approximately 1,300 m elevation, in the transition zone between the Sonoran Desert to the west and the Chihuahuan Desert to the south and east. Mean annual rainfall is 370 mm and occurs mainly in late summer and winter. Topographic relief is moderate, with a 25-m elevation difference between the highest point in the grassland watershed and the watershed outlet, and a 6-m difference between the outlet of the grassland watershed and the outlet of the urbanized watershed. Local slope varies from 1 to 10%.

The urbanized watershed was constructed from 2001 to 2005 and is typical of most tract-style housing in the Southwestern United States. This "conventional curvilinear" type development has been found to generate more runoff than clustered type developments (Brander et al. 2004). The site was completely graded and building pads compacted (underneath houses, not throughout the development) prior to construction. Houses 185 m^2 (2,000 ft^2) or larger, on relatively uniform lots 1,670 m^2 (18,000 ft^2) or larger, were built by independent general contractors and thus show a somewhat greater degree of heterogeneity than other developments of this type but have similar building materials and landscaping. Streets are asphalt, 7.3-m (24-ft) wide, with rounded curbs. A 1-m-wide pervious right of way exists between sidewalks and the street. Approximately 90% of roofs are sloped (25–35%) with corrugated cementitious tiles; the rest are low-slope (2–8%) with elastomeric coating. The tile roofs discharge runoff distributed along eaves, without gutters, while flat roofs discharge through focused downspouts. Storm drainage is via surface streets, with the exception of a 1.3 ha area in the northern part of the study area that drains to the watershed outlet via a 61-cm (24-in.) corrugated metal

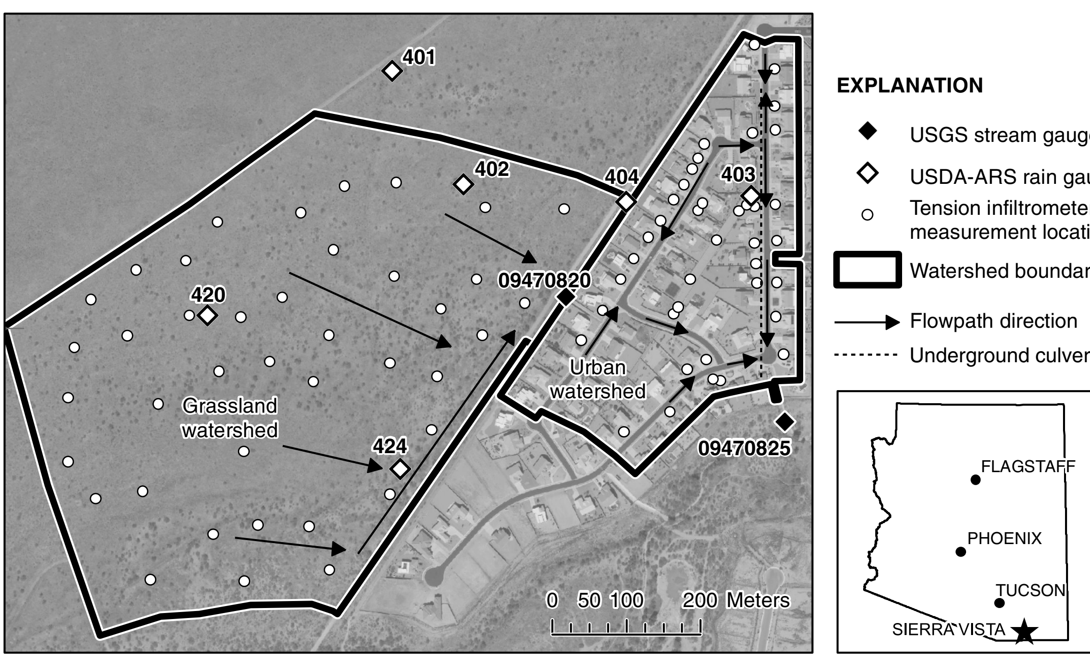

Fig. 1. Study area map showing gauge locations, infiltration measurement locations, and watershed boundaries; area in upper right of urban watershed drains directly to watershed outlet through an underground culvert; runoff from remaining area is routed along streets (background image courtesy USGS Earth Resources Observation and Science Center)

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pipe. Vegetation is immature, with only small areas of canopy cover. All pervious surfaces are covered with 2- to 4-cm-diameter gravel mulch, approximately 10-cm deep, with the exception of a few small irrigated turf areas. Approximately 10% of yards have pervious weed barrier fabric underlying the gravel mulch; no underlayment was present in the remaining yards.

Storm-water runoff from the grassland watershed is routed through the urbanized watershed. Runoff from both watersheds is of short duration and only in response to precipitation. Vegetation on the grassland watershed consists of 3- to 6-m-tall mesquite (*Prosopis velutina)*, at approximately 10-m spacing, with relatively abundant intercanopy grass up to 1-m tall. Vegetation transitions from mostly grass in the upper reaches to mostly mesquite in the lower reaches and is seasonally dormant.

Field Measurements

Stream stage was measured at 1-min intervals by an automated bubble gauge upstream of a 90° v-notch weir at the channel connecting the two watersheds (USGS Station 09470820) and at the outlet of the combined watersheds (USGS Station 09470825) from May 2005 until September 2008 (Fig. 1). For most of the study period 1-min stage data are available, but during some periods only 10-min data are available. Stage data were converted to discharge using a standard v-notch weir rating (Rantz 1983). No field discharge measurements were possible due to the short-lived nature of storm runoff from the site. Sediment behind the weirs was removed periodically and did not unduly influence the measured stage. Daily data are available from the USGS National Water Information System (USGS 2013). Rainfall data were collected by the USDA Southwest Watershed Research Center (SWRC) at 1-min intervals at four weighing recording rain gauges in 2005 and 2006 (SWRC Gauges 401, 402, 403, 404), and two additional rain gauges in 2007 and 2008 (SWRC Gauges 420 and 424). From August 2006 onward, each rain gauge was equipped with a Hydra-Probe soil moisture sensor (Stevens Water; mention of this or other trade names does not imply endorsement by the U.S. government.) at 5-cm depth to provide initial saturation data for the rainfall-runoff model. Rainfall and soil moisture data are available online from the SWRC (USDA 2013c).

An extensive real-time kinematic GPS survey was conducted in both watersheds to characterize land surface slope and watershed boundaries. Survey data were used to construct a digital elevation model for comparison with the preconstruction elevation provided in the grading plans for the subdivision. Approximately 1.7×10^5 m^3 of cut material and 2.5×10^5 m^3 of fill material were moved during the grading process. Therefore, some additional amount of material beyond that created from the cut process was likely imported to the site.

Tension infiltrometer measurements were made at 69 sites throughout both watersheds. A stratified random sampling scheme was used to locate sites evenly on areas of both cut and fill in the urbanized watershed and on both the upper, grass-dominated areas and the lower, mesquite-dominated areas in the grassland watershed. Measurements were made using a 22-cm disk at −10, −30, and −70 mm pressure heads for durations of 30, 15, and 15 min, respectively. Water levels were recorded electronically using a differential pressure transducer connected to the top and bottom of the water reservoir (Ankeny et al. 1988). Soil samples were collected before and after the infiltration measurements for gravimetric water content analysis and hydrometer analysis for soil texture. Bulk density was determined using a sand displacement method to allow determination of volumetric water content. A steady-state method (Wooding 1968) assuming an exponential soil was used to determine saturated hydraulic conductivity, K_s, from the infiltrometer data (Reynolds and Elrick 1991), as described by Kennedy (2007). This method assumes that the soil is homogeneous and isotropic, the soil moisture content is uniform throughout the soil profile, and the initial soil pressure head is sufficiently small so that the initial hydraulic conductivity is insignificant relative to the final hydraulic conductivity. Four soil compaction measurements were made at each site using a pocket penetrometer.

Rainfall-Runoff Modeling

A rainfall-runoff model of the urbanized watershed was constructed using the KINEROS2 modeling framework. The KINEROS2 framework is well documented, and many case studies have been published (Smith et al. 1995; Woolhiser and Goodrich 1988; Smith and Goodrich 2000; Semmens et al. 2008). A brief overview of the model follows; complete documentation and source code (version 3.3) is available online (USDA 2013a).

Rainfall Infiltration and Runoff Routing

KINEROS2 is based on the Smith-Parlange three-parameter infiltration model (SP3) (Parlange et al. 1982). The SP3 model, a modification of the well-known Green and Ampt (GA) infiltration model (Green and Ampt 1911), incorporates a third term, α, to represent the relation between diffusivity (D) and hydraulic conductivity (K) at the wetting front. If K is nearly constant while D increases rapidly with volumetric water content, θ, then α approaches 0, and the equation approaches the GA model and is most accurate for sand textures. On the other hand, if D is proportional to $dK/d\theta$, and both D and K rise rapidly with increasing θ, then α approaches one, and infiltration rates are closer to those of a well-mixed loam. Therefore, α is a parameter that accounts for soil texture. In this study, α is fixed at 0.85, shown to be a reasonable value for a range of soil types (Smith 2002). The KINEROS2 infiltration model also simulates two-layer soil profiles, redistribution of water during short periods of no rainfall, and lognormal spatial variation of saturated hydraulic conductivity (K_s) characterized by a coefficient of variation (CV). For a more complete discussion of the model see Smith (2002).

Parameters K_s, net capillary drive (G), pore size distribution (λ), and porosity were initially identified using the soil texture lookup table developed for AGWA (Table 1). The average soil texture of 20 samples was $74.7 \pm 6.9\%$ sand, $13.4 \pm 5.5\%$ silt, and $12.0 \pm 1.4\%$ clay. Local soil is identified as the sandy loam Gardencan-Lanque complex on Soil Survey Geographic (SSURGO) soil maps (USDA 2008). Rock fraction was estimated at 10% based on excavations made for tension infiltrometer measurements, and CV was set to 1 (Smith and Goodrich 2000). Table 1 summarizes the parameter estimation methods for all parameters.

Rainfall is interpolated at the centroid of each model element (described below) from the three nearest rain gauges and applied uniformly across the element. Rainfall interception parameters, Inter 1 and Inter 2, apply to the pervious areas and impervious areas, respectively. For the impervious area this parameter represents depression storage, formed by small irregularities in the asphalt or concrete surface. Depression storage can be estimated as the largest rainfall depth that does not produce runoff. Because of scatter in the data, the average depth of the 10 largest rainfall events that did not produce runoff was used (0.46 mm). For the pervious area the interception parameter represents abstraction due to vegetation canopy cover and ground cover, such as gravel mulch. The pervious area interception parameter may be multiplied

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Table 1. Summary of Methods for Determining KINEROS2 Parameter Values in Case Study

Parameter	Method
Canopy area	Assumed 1, to represent abstraction to vegetation and gravel mulch
Pervious area interception (*Inter 1*)	AGWA lookup table/NALC classification
Impervious area interception (*Inter 2*)	Estimated from rainfall-runoff data
Impervious area	Estimated from satellite imagery
Percent rock	Estimated from tension infiltrometer samples
Saturated hydraulic conductivity (K_s)	AGWA lookup table, tension infiltrometer measurement, optimization
K_s coefficient of variation (CV)	Literature value
Net capillary drive (G)	AGWA lookup table based on soil texture/optimization
Manning's roughness—impervious	Literature value
Manning's roughness—pervious	Literature value
Slope (S)	Estimated from field measurement
Initial soil saturation	Soil moisture probe measurement
Pore size distribution (λ)	Estimated from AGWA lookup table/SSURGO texture
Porosity	Estimated from AGWA lookup table/SSURGO texture

by a second parameter between 0 and 1, Canopy, if only part of the previous area is subject to interception. Pervious area interception was identified as 4 mm using the urban classification of the AGWA lookup table. Canopy was identified as 1 to account for the thick gravel mulch found throughout the urban watershed.

KINEROS2 implements kinematic wave flow routing to route runoff within the urban element and in channels. Infiltration is computed at each computational node based on surface flow, soil water status, and rainfall conditions. For this study the friction slope in the kinematic wave solution is determined using the Manning hydraulic resistance law. KINEROS2 also allows use of the Chezy roughness coefficient. Roughness coefficients may be specified individually for streets, indirectly and directly connected impervious areas (driveways and rooftops), and pervious areas. These values were 0.015, 0.012, and 0.25, respectively (Chow 1959; U.S. Dept. of Agriculture 1986).

Discretization and the KINEROS2 Urban Element

KINEROS2 simulates a watershed as a series of cascading overland flow planes or curvilinear surfaces, channels, pipes, and ponds (Semmens et al. 2008). The newly presented urban element is a series of planes, defined within a single input block, intended to represent a contiguous row of residential lots along one side of a street (referred to as the main element area) and one-half of the street. The street half is modeled as an impervious channel that also receives rainfall. One boundary of this channel is vertical, representing the curb. The other boundary is planar with slope specified by the crown slope parameter, CS. The channel is assumed to have infinite depth; that is, flow does not overtop the channel (curb) and spread laterally. The geometry of each part of the urban element is identified individually (Fig. 2 and Table 2). Slope is identified

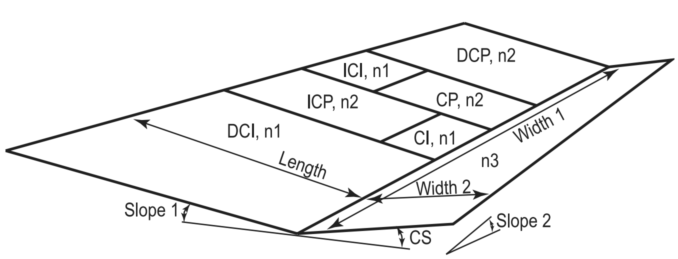

Fig. 2. Schematic of KINEROS2 urban element; see Table 2 for parameter descriptions

individually for the main element area, the street crown slope, and the channel slope in the direction of flow (Fig. 2). At each time step, total runoff from the main element area and the street is distributed evenly along the length of the channel. Runoff from an upstream urban, plane, channel, pipe, or pond element, or as specified by hydrograph time-discharge pairs, may be routed into the street channel at the upstream boundary.

The main element area is subdivided by surface type and connectivity. An impervious area is either directly connected (DCI, also known as effective impervious area), where there is no intervening pervious area between the impervious area and the street, such as driveways; indirectly connected (ICI), where impervious area runoff flows over a pervious area before reaching the street, such as where runoff from rooftops is drained onto yards; or connecting impervious area (CI), which connects indirectly connected pervious areas to the street (Fig. 2). A pervious area (unpaved portion of a building lot, including front, side, and backyards) is treated similarly, with directly connected pervious area (DCP), indirectly connected pervious area (ICP), and connecting pervious area (CP). Not all classifications need to be identified in the model, although the total of all areas present must sum to 100%, and if ICI or ICP is present, then the corresponding CP or CI must be present. K_s and G are uniform for the entire pervious overland flow area within an urban element.

The fractional area of each land-surface type in the study area was digitized from 60-cm resolution QuickBird imagery (Digital Globe, Inc.). The total impervious area was 37%. Driveways (7% of the watershed) were considered DCI; streets (10% of the watershed area) were not included because they were not part of the main urban element area. Rooftops and sidewalks (20% of the watershed area) were considered ICI, and the corresponding CP comprised some fraction of the pervious area of the element. The division of pervious area between DCP and CP (fraction of connecting pervious) is treated as a model parameter and is discussed further under parameter identification results.

Any physically based rainfall-runoff model requires simplifying the watershed geometry through discretization into elements to which the numerical models can be applied. This effect is investigated at three levels (Fig. 3). The finely discretized model comprises 23 urban elements, 2 channel elements, and 1 pipe element [Fig. 3(a)]. A simpler model, discretized at a medium level and comprising five urban elements and one pipe element, represents the detail considered in the hydrologic design report prepared for the development [Fig. 3(b)]. Finally, a coarsely discretized model uses a single urban element for the entire development [Fig. 3(c)].

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Table 2. KINEROS2 Urban Element Parameter Definitions

Symbol	Description	Unit
DCI	Directly connected impervious area	Proportion of total element area, excluding street
CI	Connecting impervious area	Proportion of total element area, excluding street
ICI	Indirectly connected impervious area	Proportion of total element area, excluding street
DCP	Directly connected pervious area	Proportion of total element area, excluding street
CP	Connecting pervious area	Proportion of total element area, excluding street
ICP	Indirectly connected pervious area	Proportion of total element area, excluding street
Slope 1	Slope of main element area in direction of flow	Length/length
Slope 2	Slope of street element area in direction of flow	Length/length
CS	Crown slope of street, perpendicular to flow	Length/length
Length	Length of main element area in directions of flow	Length (feet or meters)
Width 1	Length of street element in direction of flow	Length (feet or meters)
Width 2	Width of street perpendicular to flow	Length (feet or meters)
n1	Roughness parameter for impervious areas	Manning's *n* or Chezy roughness coefficient
n2	Roughness parameter for pervious area	Manning's *n* or Chezy roughness coefficient
n3	Roughness parameter for street element	Manning's *n* or Chezy roughness coefficient
Inter 1	Rainfall interception/abstraction on pervious area	Length (inches or millimeters)
Inter 2	Rainfall interception/abstraction on impervious area	Length (inches or millimeters)
Canopy	Inter 1 multiplier, 0 to 1	None

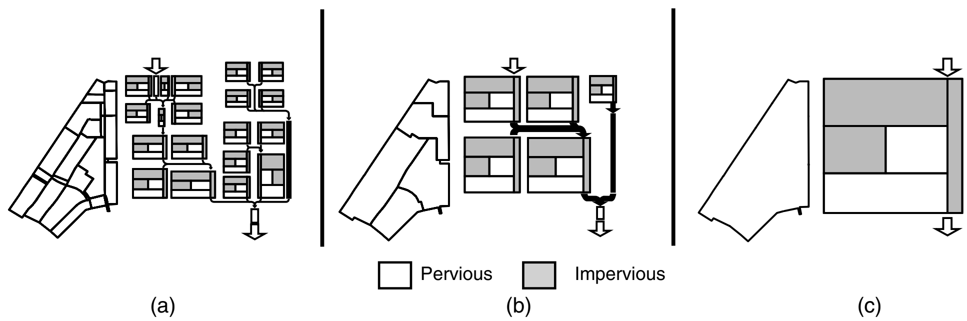

Fig. 3. Discretization schemes for watershed-scale simplification: (a) finely discretized; (b) moderately discretized; (c) coarsely discretized; left part of each panel shows spatial distribution of urban elements within watershed; right part shows conceptual arrangement of urban elements; hollow arrows: inflow from grassland watershed and outflow from combined watersheds; solid arrows: routing of runoff between urban elements

Monte Carlo sampling was used to investigate the parameter space and estimate model uncertainty. The four parameters varied, and the ranges over which they were uniformly sampled using a Latin hypercube method are as follows: K_s (0–25 mm/h), G (0–50 mm), CV (0–4), and the fraction of CP relative to DCP (FCP; 0–1). For FCP, a uniform value was applied within each urban element across the watershed. For each of the 20 largest runoff events (using a consistent parameter set) for each of the three discretization levels 2,000 simulations were run. Model results were evaluated on an event basis using a metric similar to the Nash-Sutcliffe efficiency, the normalized mean square error (NMSE):

$$\mathrm{NMSE} = \frac{\sum_{t=1}^{N}(q_s^t - q_o^t)^2}{2\sum_{t=1}^{N}(q_o^t - \bar{q})^2} \quad (1)$$

where N = number of observations; q_s^t and q_o^t = simulated and observed discharge at each time step (1 and 10 min in this study); and $\bar{q}$ = mean observed discharge. NMSE is a useful metric for an event-based model because it is bounded by [0, σ^2] when the model volume error is small (Gupta and Kling 2011); by taking the mean NMSE across all events, an overall metric that equally weights large and small events is obtained. A NMSE equal to 0 implies perfect linear correspondence between predicted and observed runoff.

Results

Increase in Storm Runoff and Decrease in Infiltrability

A summary of the rainfall and runoff observations is presented in Table 3 and Fig. 4. Assuming the grassland watershed represents predevelopment conditions, urbanization causes a 26-fold increase in runoff during the 40-month study period. Of this increase, 56% derives from streets and driveways, calculated by summing the event rainfall depths (minus initial abstraction) times DCI, which comprises 17% of the urban watershed. The remaining increase is generated from pervious areas, either directly from rainfall or from run-on from indirectly connected impervious (ICI) areas (rooftops and sidewalks).

The increase in pervious-area runoff is influenced by the difference in infiltrability between the two watersheds, reflected in the difference in K_s measurements (Table 3). The range and standard deviation of K_s values in the urban watershed is smaller than in the grassland watershed, likely due to the homogenizing effect of grading, cut/fill modifications, and soil mixing during site development. A two-tailed Student's t-test assuming unequal variance indicates that the difference in mean K_s of the grassland and urban watersheds is statistically significant. (H_0: Sample means are identical, $p = 6.4E-7$). This decrease in K_s in the urban watershed is accompanied by an increase in compaction measured by

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Table 3. Summary of Rainfall, Runoff, and Infiltration Observations during Observation Period from July 2005 to September 2008

Watershed	Total rainfall (mm) and number of rainfall events	Mean and standard deviation of event rainfall totals (mm)	Total runoff (mm) and number of runoff events[a]	Mean and standard deviation of event runoff totals (mm)	Cumulative runoff-to-rainfall ratio	Mean, standard deviation, and range of K_s (mm/h)
Urban	1,230 (146)	8.2 ± 8.8 mm	323 (125)	2.2 ± 4.1	0.26	2.9 ± 1.6 0.3–7.7 $n = 29$
Grassland	1,230 (146)	8.2 ± 8.8 mm	12 (57)	0.2 ± 0.4	0.01	6.2 ± 3.5 1.4–13.0 $n = 40$

[a]Periods of continuous measured discharge from urban watershed.

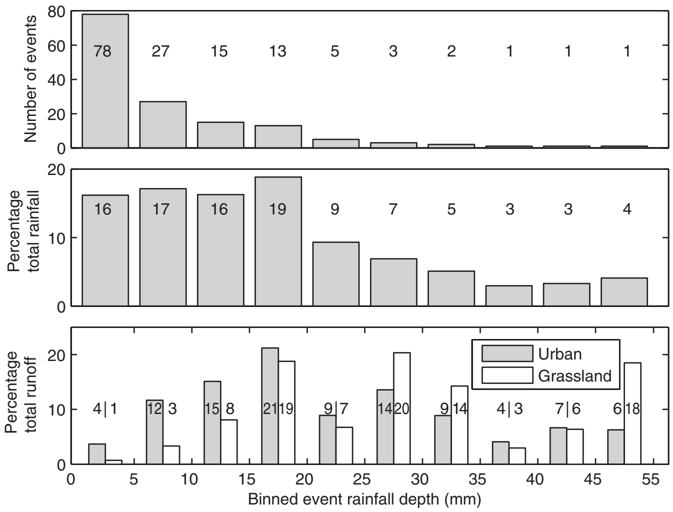

Fig. 4. Classification of rainfall-runoff events by precipitation depth; top: histogram of rainfall events by event depth; middle: cumulative rainfall depth for all events within each bin as percentage of total rainfall; bottom: contribution to total runoff from each watershed for all events within each bin as percentage of total runoff; values are the magnitude of each bar

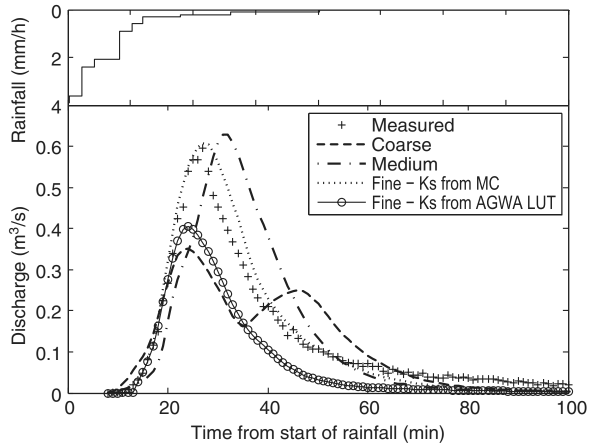

Fig. 5. KINEROS2 output hydrographs for three discretization levels of urban watershed shown in Fig. 4 and recorded discharge at watershed outlet (USGS Station 04970825); MC: K_s determined as optimal value from Monte Carlo simulation; AGWA LUT: K_s determined from lookup table used with Automated Geospatial Watershed Assessment tool based on soil texture

pocket penetrometer tests at each tension infiltrometer site (data not shown).

Level of Discretization and Parameter Identification

The influence of discretization can be demonstrated with a simple hydrograph that represents model behavior for events having a single discrete rainfall pulse (Fig. 5). Model output from the fine and medium discretizations using identical parameter sets is similar, but time to peak is longer in the latter case. The coarse discretization differs significantly, with a lower peak runoff rate, a more attenuated hydrograph, and an output hydrograph with two peaks: the first results from rapid runoff from DCI, and the second from rapid runoff from ICI routed across the connecting pervious area (CP). Using a priori infiltration parameters determined from an AGWA lookup table (LUT) based on soil texture ($K_s = 26$ mm/h), runoff volume is 440, 450, and 385 m^3 for the fine, medium, and coarse discretization, respectively, much smaller than the 820 m^3 of measured runoff. Modeled runoff volume using the optimized K_s value (the single best value from the Monte Carlo simulation for each discretization level, identified by minimizing the mean NMSE) is similar for both the fine and medium discretizations—790 and 810 m^3, respectively. Modeled runoff volume for the coarse discretization using the optimized K_s value is 670 m^3.

Many small rainfall events generate runoff only from DCI, and the model is insensitive to infiltration parameters in these cases. Only larger events, where runoff is generated from CP and ICI, are useful for model calibration. The following discussion focuses on 20 rainfall events greater than 10 mm in depth. Qualitative examination of hydrographs for these events indicates that the fine and medium discretizations, used with a single parameter set (identified by minimizing the mean NMSE across all events), are capable of reasonably simulating most runoff events. The mean Nash-Sutcliffe efficiency across all events for the best single parameter set identified with Monte Carlo simulation is 0.81, 0.81, and 0.78 for the fine, medium, and coarse discretizations, respectively. Volume bias (predicted minus observed runoff, normalized by observed runoff) of the 10 best parameter sets becomes progressively worse with coarser discretization, increasing from a mean of 1% (fine) to 6% (medium) to 10% (coarse).

The three levels of discretization produce similar patterns of parameter estimates, but the mean NMSE progressively improves with finer discretization (Fig. 6). An optimum value for K_s is identifiable, whereas the other parameters exhibit similar model performance across the range of values considered. The discretization scale has little effect on the optimal K_s values. Considering the top 5% of the Monte Carlo simulations as behavioral, the model-optimized K_s is 9.5 ± 2.8 mm/h, 9.4 ± 3.2 mm/h, and 9.2 ± 3.6 mm/h for the fine, medium, and coarse discretizations,

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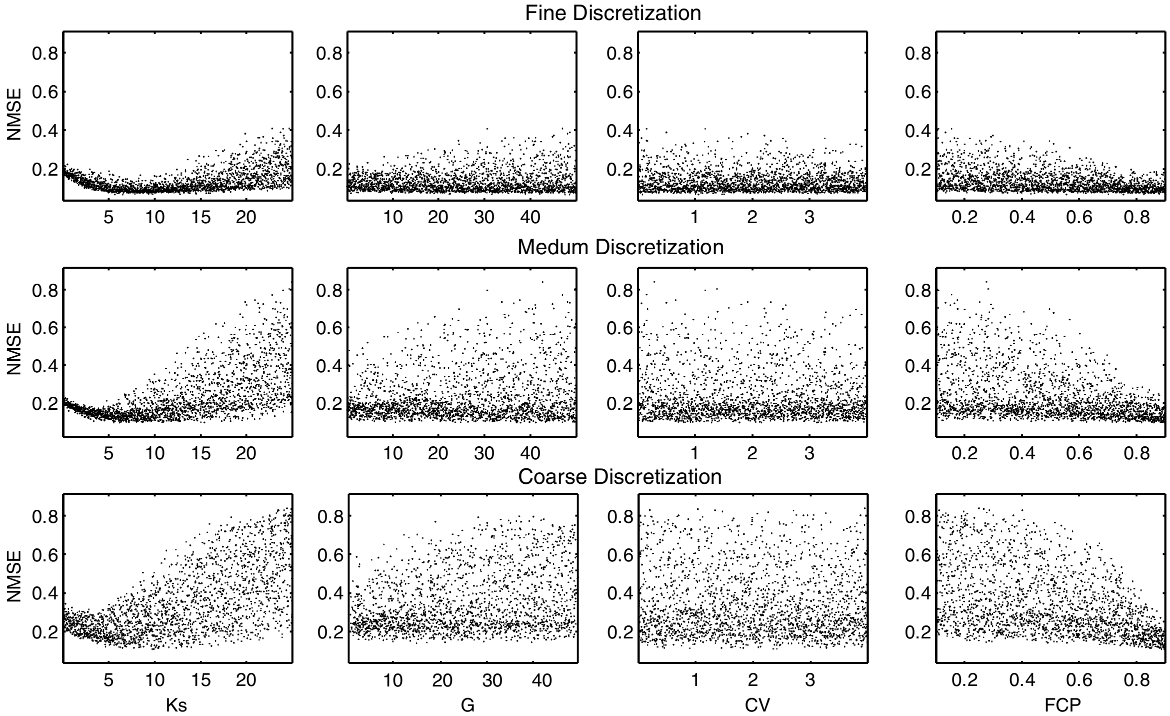

Fig. 6. Dotty plots showing mean normalized mean square error (NMSE) for 2,000 simulations of each of the 20 largest events for each of three levels of discretization; NMSE calculated as mean over all events of mean square error divided by two times the variance; for each simulation, an identical parameter set was used for all runoff events

respectively. The dotty plots (Fig. 6) are also useful for evaluating where model performance is poor; K_s and FCP can potentially produce poor model performance at the high end (K_s) and low end (FCP) of their ranges. Alternatively, if these parameters are on the opposite ends of their range, then model performance is much improved regardless of the other parameter values.

The significant influence of K_s on model behavior results in a clear relationship ($R^2 = 0.85$) between it and simulated runoff volume (Fig. 7). Because fine discretization produces the best model performance, as measured by mean NMSE (Fig. 6), it is used in a linear regression model to make predictions about the impact of the decrease in infiltrability from urbanization on runoff volume. The best fit linear model for the Monte Carlo simulations shown in Fig. 7 is

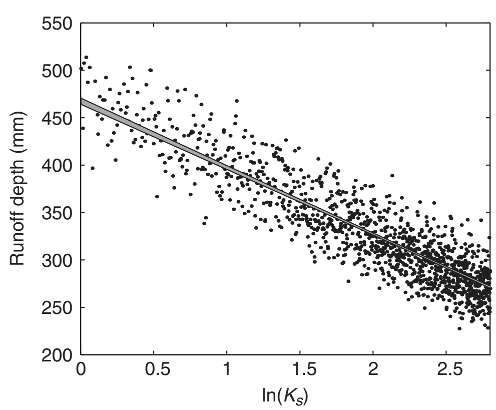

Fig. 7. Scatter plot of model-simulated runoff volume versus natural log of saturated hydraulic conductivity (K_s); shaded region: uncertainty (95% confidence intervals) of linear regression model [Eq. (2)]

$$V = -(70 \pm 1.3)\ \ln K_s + (468 \pm 3) \tag{2}$$

where V = depth of total runoff volume for the study period (in millimeters), and uncertainty is expressed as the 95% confidence intervals on the regression parameters. Statistical tests on the regression residuals show them to be independent and normally distributed, and standard ordinary least-squares methods are used to estimate uncertainty.

Predicting Increases in Runoff from Changes in Infiltrability Due to Urbanization

The difference in K_s between the grassland and urban watersheds was used to investigate the influence of decreased infiltrability on the increase in runoff with urbanization. Ideally the predevelopment K_s could be determined from areal-averaged model optimization of a grassland model. Unfortunately, parameter and model runoff predictions from the grassland watershed were poor, in large part because the runoff coefficient was very small and few storms produced runoff. Instead, field measurements in the two watersheds were used. Three sources of uncertainty were considered. First was the uncertainty in tension infiltrometer measurements of K_s. Based on repeat measurements, Bailey (1995) estimated the repeatability of K_s to be approximately 2 mm/h, and more than an order of magnitude smaller than spatial variability. The second source of uncertainty was in scaling these point measurements to watershed-scale effective values. Previous studies showed KINEROS simulations to be insensitive to spatial variation in K_s for large events (Smith and Goodrich 2000), and CV is uncorrelated with runoff volume in the Monte Carlo simulations in the present study ($R^2 = 0.04$). Lacking a more precise method, we used the assumption that the combined measurement and scaling uncertainty was equal to the spatial variability of measured K_s in the urban watershed (±1.6 mm/h). Finally, there was uncertainty in the parameters of the linear

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regression model relating $\ln(K_s)$ to runoff volume [Eq. (2)]. Note that because the regression is used to evaluate the effect of a relative change in K_s, rather than to predict runoff volume for a particular value, the standard error of prediction was not used.

The field-measured K_s values, 6.2 in the grassland watershed and 2.9 mm/h in the urban watershed, indicate a 3.3 ± 2.3 mm/h decrease as a result of development. Using the linear regression model [Eq. (2)], this decrease in K_s causes an increase in total runoff over the study period of 53 ± 43 mm, or $17 \pm 14\%$ of the 311 mm total increase in runoff. As described earlier, DCI accounts for 175 mm (56%) of the increase in runoff. The uncertainty associated with this value is less than that for the increase in runoff caused by the decrease in K_s because it is calculated directly from the data rather than from the model. The remaining 83mm (27%) of the increase in runoff not accounted for by DCI or a decrease in K_s is estimated to originate from ICI.

Conclusions

Based on the data and analysis presented, the primary conclusions regarding the impact of suburban development on storm runoff are as follows:

1. A 26-fold increase in runoff associated with urbanization was observed in this study.
2. Accurate model simulations were largely dependent on determining an appropriate value of K_s.
3. It is possible to represent multiple homes and lots with the KINEROS2 urban model element with little decrease in model performance.
4. Increases in runoff were not due solely to the construction of impervious areas. Roughly 17% of the additional runoff is attributed to compaction of pervious soils due to site preparation and construction.

Regarding the first conclusion, the increase is influenced in part by the difference in watershed size; in general, as catchment area increases, the runoff coefficient decreases in this semiarid environment (Goodrich et al. 1997). The grassland watershed is not necessarily representative of current conditions in the region, as grazing has been excluded for 50 years or more, grass cover is abundant, and a higher proportion of canopy interception exists than would be observed in more heavily impacted areas with less grass and more shrubs. Nonetheless, the grassland watershed does likely represent presettlement (i.e., pre-1880s) conditions throughout the region. One limitation of the study is the lack of significant wintertime rainfall; these storms are typically of lower intensity, produce less runoff, and are presumably less sensitive to changes in infiltrability.

With respect to the second conclusion it should be noted that this small urban watershed study—with good rain gauge coverage, good channel control at streamflow gaging stations, soil moisture data, surveyed topography, and detailed aerial imagery—represents a best-case scenario in comparison with typical engineering studies. Furthermore, the watershed's small size relative to the size of runoff-generating storms, and the ability to perform detailed discretization with short flowpath lengths, makes for a more accurate model than those in studies using KINEROS2 in larger watersheds (Michaud and Sorooshian 1994; Al-Qurashi et al. 2008). Nonetheless, accurate results depended largely on determining an appropriate value of K_s. Tension infiltrometer measurements of K_s, which averaged 2.9 mm/h, were closer to the optimal effective K_s determined by parameter identification, 9.5 mm/h, and produced better results than using the value determined from AGWA lookup tables for the appropriate soil texture (26 mm/h).

Regarding the third conclusion, the level of discretization in a rainfall-runoff model is often a tradeoff between simulating processes at a detailed level and the time required to construct the model. The urban element extension of KINEROS2 allows the user to easily specify the relative proportion of directly and indirectly connected impervious and pervious areas and the corresponding impervious and pervious connecting areas. This study found that a fairly simple model with five elements (medium discretization) could simulate runoff nearly as well as a more complex model. In comparison with correctly identifying infiltration parameters, primarily K_s, the level of discretization has a relatively small influence on model behavior. For the coarsest discretization, however, model performance was worse and parameter sets that produced poor results were more common.

Concerning the fourth conclusion, directly connected impervious areas account for the majority of the increase in runoff measured in the study area, 56%, and little can be done at the lot scale to minimize this value (apart from reducing the amount of DCI). The remaining 44% increase, from pervious areas and rooftops, was estimated using the rainfall-runoff model to comprise a $17 \pm 14\%$ increase from decreased infiltration and 27% from ICI. This increase could be reduced by capturing some of the runoff from ICI on site, minimizing soil compaction, or constructing infiltration-enhancing features. Although uncertainty in the increase in runoff caused by decreased infiltration is relatively large, field measurements indicate a statistically significant difference in K_s between the watersheds, and the model simulations show that runoff volume is inversely proportional to K_s.

Few studies exist concerning the small-scale hydrologic impact of compaction in the desert Southwest of the United States. The study area's tract-housing building style is mostly representative of the vast majority of new-home construction in recent decades, and the KINEROS2 urban element presented should be effective in this setting for simulating the impact of urbanization on rainfall infiltration and storm-water routing. The precise impact of development on infiltrability for soils other than the sandy loam in the study area may be different, but in most cases it would be expected that infiltrability would remain the same or decrease as a result of development. If design considerations require minimizing the increase in runoff from a development, minimizing activities that reduce infiltrability, such as compaction, may be helpful.

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