Hydrologic Mitigation Using On-Site Residential Storm-Water Detention

By Christopher P. Konrad[1] and Stephen J. Burges,[2] Fellow, ASCE

Abstract: On-site storm-water detention systems can be used to mitigate the hydrologic effects of residential development and to provide a supplemental water supply at the scale of single residences. A three-year rainfall record from a site in the Puget lowland, Washington state, is used in a simple mass-balance model to simulate outflow from single- and multiple-purpose detention systems. Simulations are compared to time series of measured runoff from Evans Creek, a 37 km^2, rural basis, and a 0.37 km^2, zero-order forested subbasin. Discharge from a small on-site reservoir is sensitive to both the storage capacity and maximum controlled release rate of the system for extreme high flows (those exceeded 1% of the time) and low flows (those exceeded 80% of the time). An intermediate range of discharges (those exceeded 10–30% of the time) is primarily sensitive to release rate, rather than its storage capacity, suggesting that single-purpose systems with small reservoirs can be effective for hydrologic mitigation over a range of intermediate flows.

INTRODUCTION

The purpose of this paper is to demonstrate hydrologic benefits of local on-site storm-water detention systems, at the scale of single residences, to reduce some of the deleterious hydrologic effects of land-use change. Our application is for the Pacific Northwest where conversion of temperate, humid forests to residential and commercial developments changes the distribution of water among various hydrologic processes. Hydrologic consequences of residential development in temperate, humid regions begin with changes in the stochastic and spatial distribution of water in various hillslope processes including interception, depression storage, infiltration, evapotranspiration, subsurface flow, saturation overland flow, and ground-water recharge (Burges et al. 1989). Characteristic streamflow responses to these hillslope changes include increased magnitude and frequency of peak discharge during storms, increased sediment and associated pollutant transport, and reduced base flow (Schneider 1975; Hollis 1975; US EPA 1983).

Civil engineering projects attempt to counter these effects or otherwise limit deleterious effects of storm water on public and private property, typically, by implementing channel-based approaches emphasizing the collection of storm water in pipes, ditches, or streams, increasing the conveyance and stability of channels, and increasing storage within the channel network (e.g., ASCE and WPCF 1992; King County 1998). Channel-based storm-water management is fundamentally limited to controlling storm water after water is concentrated in the channel network. Since streams occupy a small fraction of the area of a basin (on the order of one percent), channel-based management activities are spatially constrained.

Storm water can be managed using dispersed, small-scale systems upslope of the channel network much in the way forested hillslopes stored and infiltrated storm water. We consider an elementary system applied at the scale of a single residence and refer to this as an "on-site" system even though "on-site" is applied to storm-water management systems that serve areas as large as 4 ha (Urbonas and Roesner 1993). We distinguish between single-purpose detention systems, which simply hold storm water and retard its release, and multiple-purpose systems, which divert storm water from surface drainage networks to subsurface drainage, domestic uses, or dry-season irrigation.

PHYSICAL CONDITIONS IN PUGET LOWLAND

Hydrologic processes and patterns in both a predevelopment and postdevelopment landscape depend on storm patterns, geologic formations, geomorphic and topographic features, and dominant forms of vegetation. As a result, storm-water management design guidelines generally have limited geographic application. The approach developed here for sizing storm-water management systems to emulate runoff and streamflow processes can be applied in other regions using local hydrologic data.

We assess on-site detention possibilities for the Puget lowland in Washington state. The Puget lowland encompasses areas below 200 m elevation draining to Puget Sound approximately between latitudes 47° and 48° north and longitudes 122° to 123° west (Fig. 1). The region has numerous broad, glacial-till-capped plateaus, glacial outwash deposits, and lacustrine sand and clay below glacial deposits. Freshwater marshes, swamps, and lakes are ubiquitous on till plateaus. Wetlands are typically drained by streams that form steep-walled ravines below plateaus and flow through broad, outwash-filled valleys.

The Puget lowland has a maritime climate with an annual rainfall pattern of dry summers and wet winters. Long-duration, low-to-moderate intensity storms occur frequently from November through April, though storms may occur during any month; the annual rainfall depth is about 1 m. At Seattle-Tacoma International Airport, the closest rain gauge with a multidecade record, the maximum daily rainfall has a 50% probability of exceeding 42 mm in any year. Interstorm periods typically range from 3 h to 2 weeks (Gan and Burges 1990). The regional hydrologic characteristics of forested hillslopes combined with frequent, low-intensity storms, result in annual surface runoff from forested zero-order basins that account for 10–30% of annual rainfall (Bauer and Mastin 1997; Wigmosta and Burges 1997).

Storm flow in temperate, humid forest streams is often produced by saturation overland flow and shallow subsurface flow (Hewlett 1961; Whipkey 1965; Dunne and Black 1970). The areas in the Puget lowland that produce saturation overland flow have thin soils and are in zones of topographic convergence, at the foot of concave hillslopes, adjacent to channels and swales, and expand upslope when storms are of longer duration, more intenses, or more frequent (Dunne et al. 1975). The dominant storm flow pathways, however, appear to be

[1]Res. Sci., Dept. of Civ. and Envir. Engrg., Univ. of Washington, Seattle, WA 98195.

[2]Prof., Dept. of Civ. Engrg., Univ. of Washington, Seattle, WA.

Note. Discussion open until September 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 28, 1999; revised February 15, 2000. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 127, No. 2, March/April, 2001. ©ASCE, ISSN 0733-9496/01/0002-0099–0107/$8.00 + $.50 per page. Paper No. 21968.

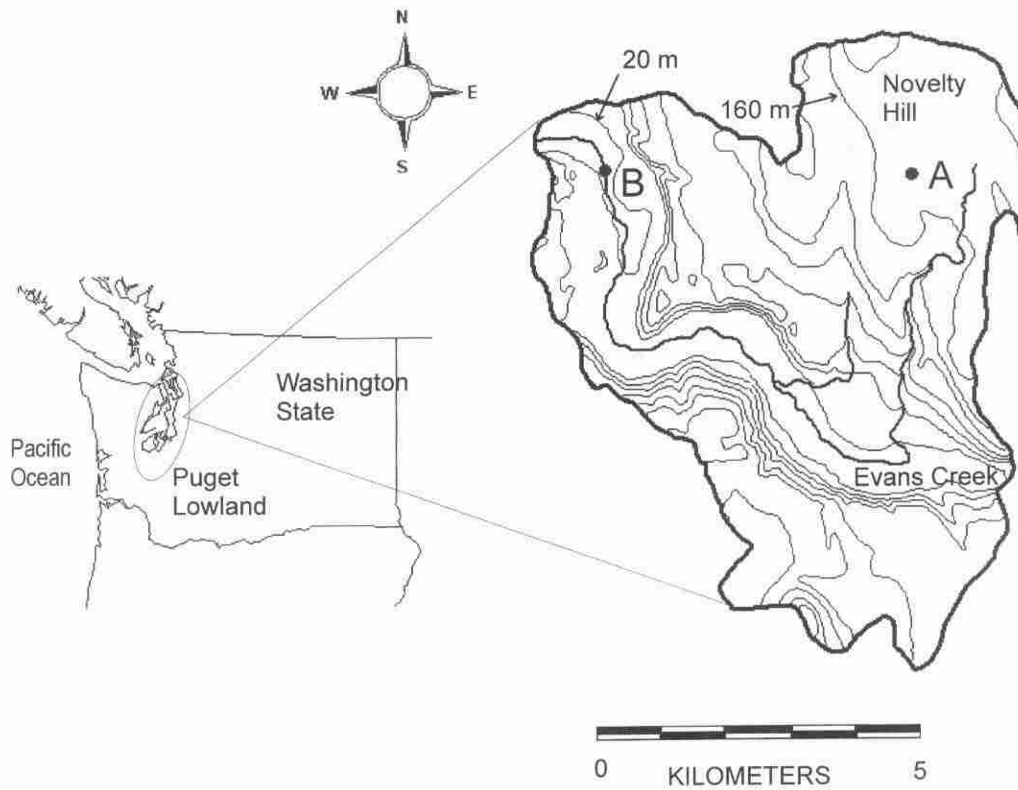

FIG. 1. Evans Creek Basin with Novelty Hill Stream Gauge (A) and Evans Creek Stream Gauge (B) King County, Washington

subsurface for catchments in the Puget lowland (Bauer and Mastin 1997; Wigmosta and Burges 1997). In the Puget Sound region, direct precipitation on wetlands generates substantial quantities of storm flow even as wetlands store water (Burges et al. 1989).

Hydrologic patterns have been modified in many Puget lowland streams due to spatially extensive conversion of forested hillslopes to homes, lawns, and roads. Forests with their deep, permeable soils and undulating topography have been replaced by graded hillslopes with residential and commercial structures, roads, and thin-soil lawns. Constructed drainage networks (i.e., ditches, storm sewers, and other connected impervious surfaces) have been added. When hillslopes are converted from forest to residential or urban uses, the loss of canopy, topographic depressions, and deep soils increase the frequency and volume of storm flow production. The increase in storm flow is most pronounced in areas underlain by glacial till and fine-grained lacustrine subsoils. The low hydraulic conductivity and high field capacity of these subsoils promote rapid saturation of overlying soil column during storms. Rain on saturated soils, in turn, generates runoff in the form of shallow lateral subsurface flow and saturation overland flow. Increased storm-water production has been implicated as a major cause of channel erosion and degradation of aquatic ecosystems in the Puget lowland (Booth 1990; Reinelt and Horner 1991).

DESCRIPTION OF HYDROLOGIC TIME SERIES

Given the storm patterns in the region, storm-water management systems are best evaluated using a time series of rainfall that includes long-duration storms and storms corresponding to a variety of antecedent catchment conditions rather than a single design event. A 1004-day record of rainfall is used as input to the detention simulation model. Records of discharge from Evans Creek, a largely forested, second-order (Strahler) stream basin and runoff from Novelty Hill, a forested zero-order subbasin within the Evans Creek basin are used as standards for evaluating the discharge from an on-site system. Wigmosta et al. (1994) recorded rainfall and runoff from Novelty Hill located 25 km northeast of Seattle, at latitude 47° 42′ N and longitude 122° 01′ W located in Fig. 1. Data were recorded at 15-min intervals and the records span the period from 1 October 1990 to 30 June 1993.

Novelty Hill is a glacial-till-mantled plateau covered by approximately 1 m of sandy loam soil and second-growth forest comprising Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), western red cedar (*Thuja plicata*), big leaf maple (*Acer macrophyllum*), and vine maple (*Acer cirinatum*). The Novelty Hill zero-order basin has an area of 0.37 km^2 and an oblong shape with a length of 1000 m. The upper areas of the basin have slopes of 3–5% while the lower hillslopes are between 1% and 2%. A swale runs through the center of the basin for approximately 800 m upstream from its outlet. Ephemeral discharge through the swale was measured at point A in Fig. 1 using a weir.

The Evans Creek basin comprises till-mantled plateaus, including Novelty Hill, with marshes and swamps and a lower outwash valley. The basin is covered by second-growth forest of the type described for Novelty Hill along with residential developments and pastures. Stage for Evans Creek is recorded by King County Department of Land and Water Resources. Evans Creek has a drainage area of 37 km^2 above the stream gauge at point B in Fig. 1. The Novelty Hill catchment constitutes 1% of the area of the Evans Creek basin.

Precipitation during the period of analysis was highly variable year to year and exhibited a variety of stochastic storm patterns (Fig. 2). Annual rainfall during the period of analysis ranged from 913 mm to 1331 mm. Large storms in November 1990, April 1991, and January 1992 delivered over 100 mm of rain during multiple-day periods. The greatest daily rainfall total was 59.7 mm on 24 November 1990. The greatest multiple-day rainfall total was 3–5 April 1991 when 100 mm of rain fell.

Outflow recorded at the Novelty Hill gauge is also shown

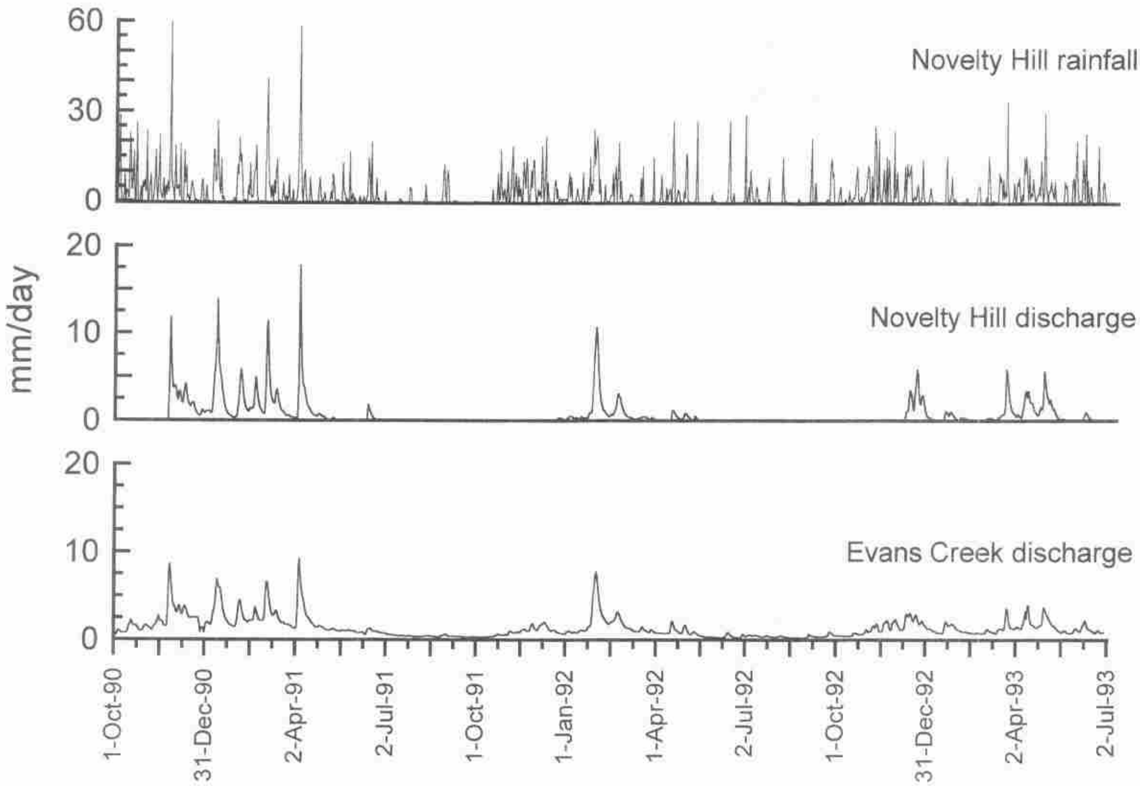

FIG. 2. Daily Hyetograph and Hydrographs for Novelty Hill and Evans Creek from 1 October 1990 to 30 June 1993

in Fig. 2 and illustrates the predevelopment runoff response of a forested zero-order catchment in the Puget lowland to storms over a broad range of antecedent conditions. Principal hydrologic features of the Novelty Hill catchment are reported in Wigmosta and Burges (1997) and Burges et al. (1998). Total runoff was 710 mm (22% of rainfall) for the period of analysis. Burges et al. (1998) found that subsurface storm flow is the dominant runoff mechanism for Novelty Hill. There is no surface flow from Novelty Hill for half of the year during the summer and autumn. Streamflow lags the onset of winter rains as the soil pores fill with water as indicated by the hydrograph for Novelty Hill during the period from 1 October 1990 to 20 November 1990 (Fig. 2). Even after the onset of flow, runoff from Novelty Hill during early season storms is strongly attenuated. Precipitation not accounted for in streamflow was transpired, evaporated, or recharged groundwater beneath the till (Burges et al. 1998).

The runoff response of Novelty Hill reflects the large storage capacities and infiltration rates of forested hillslopes relative to volumes and rates of rainfall in the region. During the November 1990 storm, maximum mean daily runoff was only 51 L/s (11.8 mm/day or 20% of the maximum rainfall during the storm). The maximum mean daily runoff for the period of analysis was 76 L/s (17.8 mm) on 4 April 1991. Typically, the area-normalized discharge rate for Novelty Hill is much less than 10 mm/day; higher rates were recorded for only five multiple-day storms during the period of analysis.

There are two gaps in the measured Novelty Hill streamflow record for a total of 64 days of the 1004-day period of record: 17 January 1993 to 5 February 1993 and 31 March 1993 to 14 May 1993. During these periods, 250 mm of rainfall were recorded at Novelty Hill with a maximum daily total of 29.7 mm. This represents 7.6% of the total rainfall for the period of analysis. Discharge for these periods was simulated using a rainfall-runoff model developed by Wigmosta and Burges (1997). The simulated discharge, normalized for area, is 84 mm and accounts for 12% of the total runoff volume analyzed.

A comparison of area-normalized hydrographs for Novelty Hill and Evans Creek in Fig. 2 illustrates two primary effects of increased catchment area on streamflow: reduced peak flow and increased base flow. Storm flow in Evans Creek is less than that for Novelty Hill on a unit area basis probably due to a combination of network routing, in-channel storage in a large wetland, or less precipitation at lower elevations in the basin. For these reasons, discharge from Evans Creek is not used as standard for evaluating the performance of on-site detention systems for attenuating high flows. Evans Creek flows perennially, so we use its streamflow record to provide reference low-flow conditions for evaluating on-site detention systems. Our approach assumes that an on-site detention system would drain directly to a stream without any losses. The median daily discharge in Evans Creek was 1 mm and the lowest recorded daily discharge was 0.3 mm (0.09 m^3/s).

Hillslope hydrologic processes control the catchment's runoff response during storms. Fig. 3 shows daily rainfall and normalized 15-min outflow from Novelty Hill and streamflow from Evans Creek during April 1991. During the period 3–5 April, more than 80 mm of rain was recorded at the Novelty Hill rain gauge. Evans Creek has a longer lag time to peak, is more attenuated, and has a more gradual recession than runoff from Novelty Hill.

SIMULATION OF ON-SITE STORM-WATER MANAGEMENT SYSTEM

On-site detention systems are simulated with a discrete time-step, mass-balance model. The model calculates runoff from a completely impermeable surface (typically roofs, sidewalks, and driveways in a residential area) during a time step as the product of the surface area and rain depth falling during a time step. The surfaces are assumed to have no depression storage or evaporative losses. No time delay between rainfall and runoff is provided. This simple representation is consistent with measurements of roof runoff by Hollis and Ovenden (1988) who found that sloped roofs provide 0.5 mm depression storage but runoff volume accounts for 90% of rainfall volume

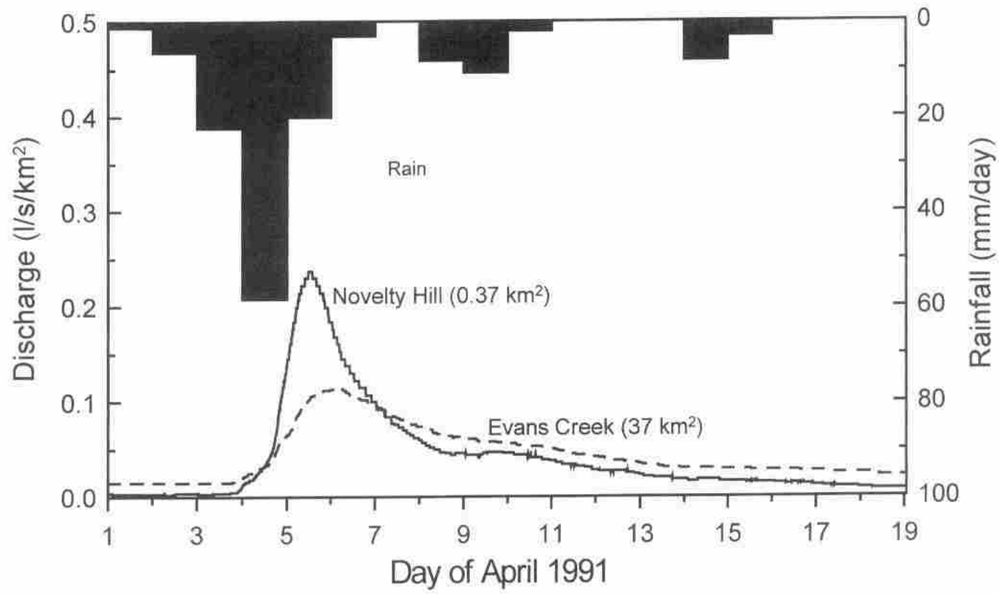

FIG. 3. Comparison of Area-Normalized Storm Response of Novelty Hill and Evans Creek for April 1991

for storms over 5 mm and peak rates were not attenuated by response of distant parts of a roof.

The model allocates total rain volume falling on a surface in each time step to storage, release (controlled outflow), or spill (uncontrolled outflow)

$$S(t) = S(t - \Delta t) + I(t) - R(t) - Sp(t) \tag{1}$$

where $S(t)$ = volume of water in storage at time t; $I(t)$ = inflow volume from rain falling during the time interval from $t - \Delta t$ to t; $R(t)$ = release (controlled) volume for the time interval; and $Sp(t)$ = spill (uncontrolled) volume for the time interval. The outflow is assumed to arrive instantaneously at a receiving stream. The necessary inputs are a time series of rainfall, a surface area of the impervious catchment, a specified storage volume (S_{max}), and the release function. The model is implemented here using a 15-min time-step.

Two types of detention systems are simulated: single-purpose systems that would only provide storm flow control, and multiple-purpose systems from which releases are extracted for residential use. Releases from actual systems depend on the design of storage tanks and control devices that are not considered here.

Single-purpose storm-water management systems are simulated with a linear reservoir release function

$$R(t) = S(t)K_S \tag{2}$$

where $K_S = R_{max}/S_{max}$. While discharge from a detention system is generally a direct function of storage (e.g., discharge increases with the water level in a pond or tank), the relationship is usually nonlinear. The discharge recession coefficient (K_r) for a linear reservoir model is

$$Q(t) = Q(t_0)(-K_r^t) \tag{3}$$

The storage coefficient (K_S) is related to the recession coefficient as

$$K_S = -\ln K_r \tag{4}$$

The simulated discharge from the single-purpose systems is the sum of controlled releases and spill volumes.

Releases from multiple-purpose systems are simulated using a constant extraction rate provided there is stored water available for release. If storage volume is less than the extraction volume for a 15-min increment, all of the stored water is extracted. Discharge from a multiple-purpose system to a drainage network occurs only as overflow during a time step when extraction plus any available storage is less than the rainfall. We assume that all stored water is used without returning to the local flow paths. This assumption will underestimate low-flow augmentation provided by multiple-purpose systems where stored water is infiltrated or disposed of through on-site septic systems.

SIZING ON-SITE DETENTION SYSTEMS

We consider three features of the Novelty Hill rainfall and runoff time series for preliminary design of linear reservoir systems that approximate runoff patterns from a forest catchment: (1) maximum cumulative rainfall depth as a function of time interval; (2) peak storm flow rate; and (3) storm flow recession. These features were used to configure the various detention-system reservoir capacities and release rates. For multiple-purpose systems, extraction rates approximate typical residential water-use rates.

The problem of sizing detention reservoirs can be approached by comparing the cumulative inflow volume produced by a time series of rainfall and the cumulative outflow volume produced by a specified release rate. The largest difference between these quantities represents the storage capacity necessary to prevent uncontrolled spills from the system. Fig. 4 shows the maximum cumulative 1-day, 2-day, and up to 100-day rainfall volume and the cumulative outflow for a release rate of 5 mm/day. The use of the maximum n-day rainfall as the ordinate rather than a chronological series of cumulative inflow offers the convenience of a shorter axis for the figure. The maximum rainfall for a short time interval is not necessarily "nested" in the maximum rainfall for a longer time interval. For example, the 1-day maximum rainfall occurred on 24 November 1990 while the 3-day maximum occurred 3–5 April 1991.

The storage required to prevent a constant-release-rate system from spilling can be estimated graphically as the maximum difference between the cumulative n-day rainfall curve and cumulative outflow line. For example, a system releasing water at a constant rate of 5 mm/day would require 144 mm of storage to prevent all spills given the Novelty Hill rainfall record. In contrast a system with a constant release rate of 20 mm day, slightly more than the maximum mean daily runoff from Novelty Hill, requires 40 mm of storage to prevent spills. These two systems provide outer bounds for sizing on-site detention systems with the former example representing a

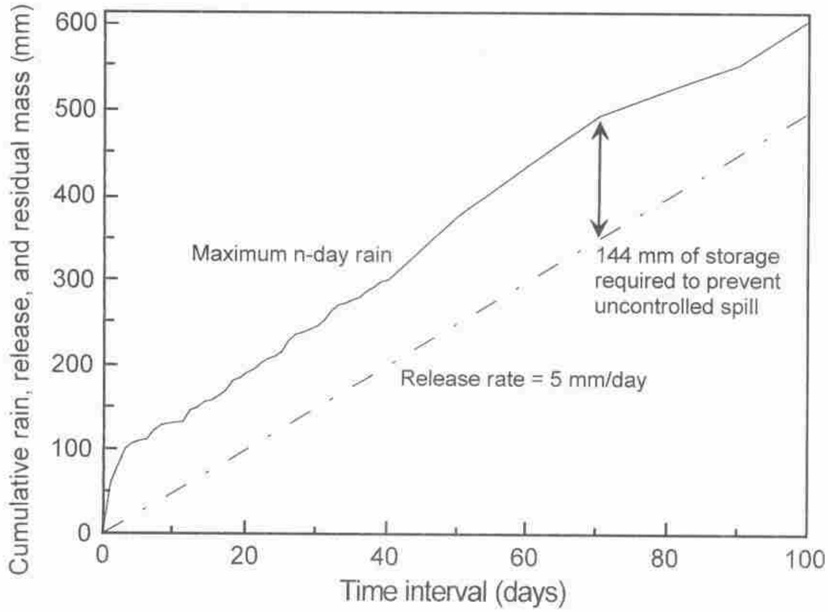

FIG. 4. Cumulative Mass Plot of Maximum *n*-Day Rain and a Constant 5 mm/day Release Rate

large reservoir system and the latter representing a high-release-rate system.

Storm-flow recession from Novelty Hill can be analyzed as a linear reservoir process with the objective of designing on-site detention systems to match patterns of storage depletion. During the winter of 1991 (Fig. 2), the recession coefficient K_R for Novelty Hill varied from 0.6 to 0.7, which is equivalent to a storage coefficient K_S of approximately 0.4. A single linear reservoir cannot, however, match peak discharge and recession rates from a forested hillslope. A linear reservoir with a maximum release rate of 20 mm/day and K_S of 0.4 would have a storage capacity 50 mm. Such a system would fill repeatedly during the winter, however, releasing and spilling storm water at high rates much more frequently and for longer durations than observed at Novelty Hill. Alternatively, for example, a system with 100 mm of storage and K_S of 0.4 would have a maximum release rate of 40 mm/day, which is much greater than the maximum observed runoff from Novelty Hill.

In consideration of the natural hydrologic behavior of Novelty Hill and practical concerns regarding the size of reservoirs, we chose to simulate single-purpose detention systems with maximum release rates of 5 mm/day and 10 mm/day and storage volumes of 20 mm and 100 mm, which give K_S values of 0.05 to 0.5 (K_R of 0.6–0.95). For a 100 m^2 roof, which represents a roof area for single residences in the region (Wigmosta et al. 1994), the simulated detention systems would require reservoirs of 2,000 and 10,000 L, respectively. The reservoirs could be located beneath the residence as part of the structure or as stand-alone tanks or pools.

For multiple-purpose systems, we use storage volumes 20 mm and 100 mm to facilitate comparison with single-purpose on-site detention systems. A release rate for the simulated multiple-purpose system is estimated from residential water use in the region, which is approximately 400 L/day per capita (Economic 1995). This extraction rate for a two-person household, normalized for a 100-m^2 catchment is 8 mm/day. We used a constant extraction rate of 5 mm/day.

RESULTS

Results of seven simulations are reported. Multiple-purpose systems (M) are represented by three simulations: M1 (20 mm of storage, 5 mm/day extraction rate), M2 (100 mm of storage, 5 mm/day extraction rate), and M3 (100 mm of storage, 5 mm/day extraction rate during summer months). Single-purpose systems (S) are represented by four simulations: S1 (100 mm of storage, 5 mm/day maximum release rate); S2 (100 mm of storage, 10 mm/day maximum release rate), S3 (20 mm of storage, 5 mm/day release rate), and S4 (20 mm of storage, 10 mm/day release rate). The simulation results are shown in Table 1 in terms of the total unit-area discharge, median discharge rate, and volume and duration of discharge exceeding 10, 5, and 0.2 mm/day. Statistics from rainfall and streamflow records for Novelty Hill and Evans Creek are also shown in Table 1 and provide standards for assessing on-site system performance.

Hydrologic Records

The main depth for the period of analysis (1 October 1990 to 30 June 1993) was 3243 mm with 52% of the days having measurable rain. Median daily rainfall was 0.3 mm. Daily rainfall exceeded 5 mm/day for 22% of the period and totaled 2700 mm. Daily rainfall exceeded 10 mm/day for 11% of the period and totaled 1889 mm. The rain duration curve is provided in Fig. 5.

Fig. 5 also shows the daily flow duration curves for Novelty Hill and Evans Creek. Runoff recorded at the Novelty Hill Outlet weir totaled 712 mm (including 84 mm of simulated runoff for periods when the gauge was not recording). Water flowed out through the Novelty Hill weir for 52% of the period of analysis. Runoff exceeded 5 mm/day for 3% of the period and totaled 228 mm. Runoff exceeded 10 mm/day for 0.8% of the period and totaled 98 mm. These statistics are used, below, to evaluate simulated on-site systems.

The total discharge from Evans Creek during the period of analysis was 1361 mm. Total discharge comprised a greater fraction of rainfall (42%) than runoff from Novelty Hill due to additional ground-water inflow and less rainfall at lower elevations in the basin than was recorded on Novelty Hill. The median discharge was 1 mm/day; discharge exceeded 0.2 mm/day on all days. The discharge exceeded 5 mm/day for 2.4% of the period and totaled 160 mm. Discharge from Evans Creek did not exceed 10 mm/day during the period of analysis.

Multiple-Purpose Systems

Fig. 6 shows the daily-flow-duration curves for spills (uncontrolled outflow) from the three simulated multiple-purpose systems. The multiple-purpose system M1, which has the larg-

TABLE 1. Summary of Hydrologic Records and On-Site Detention Simulations

(1)	Storage capacity (mm) (2)	Release rate (mm/day) (3)	Total outflow (mm) (4)	Median rate (mm/day) (5)	Volume Discharged at Rates Exceeding: 10 mm/day (mm) (6)	Volume Discharged at Rates Exceeding: 5 mm/day (mm) (7)	Percent of Time that Discharge Rate Exceeds: 10 mm/day (%) (8)	Percent of Time that Discharge Rate Exceeds: 5 mm/day (%) (9)	Percent of Time that Discharge Rate Exceeds: 0.2 mm/day (%) (10)
(a) Novelty Hill Hydrologic Records									
Rainfall	—[a]	—[a]	3,243	0.3	1,889	2,700	10.7	21.6	51.8
Runoff	—[a]	—[a]	712	0.0	98	228	0.8	2.8	39.6
(b) Evans Creek Hydrologic Record									
Discharge	—[a]	—[a]	1,361	1.0	0	160	0.0	2.4	100.0
(c) Multiple-Purpose Systems									
M1	100	5	52[c]	0.0	25	42	0.1	0.3	0.6
M2	20	5	617[c]	0.0	327	515	1.7	4.0	7.8
M3	100	5[b]	3,176[c]	1.4	1,402	1,998	7.9	15.9	73.8
(d) Single-Purpose, Linear Reservoirs									
S1	100	5	3,176[d]	2.8	382	547	2.0	4.2	100.0
S2	100	10	3,212[d]	2.8	47	1,352	0.2	20.9	98.4
S3	20	5	3,232[d]	2.2	1,098	1,485	6.1	11.4	90.2
S4	20	10	3,238[d]	2.0	884	1,938	5.2	21.0	82.6

[a]Not applicable.
[b]Water released from June through August.
[c]Uncontrolled spill.
[d]Controlled release plus uncontrolled spill.

est storage capacity (100 mm), spilled a total of 52 mm, which is equal to 7% of runoff from Novelty Hill. Spills at rates greater than 10 mm/day amounted to 25 mm or 26% that of Novelty Hill. M1 spilled water only 8% of time as compared to measurable discharge from Novelty Hill for 52% of the time.

Cumulative spills from M2 were slightly less (617 mm) than Novelty Hill for the period of record. Spills from M2 at rates greater than 10 mm/day totaled 327 mm, or 3 times the amount of runoff exceeding a rate of 10 mm/day from Novelty Hill. Spills from M2 at rates greater than 10 mm/day occurred 1.7% of the time. While a small storage capacity reduces the performance of on-site systems during high flows, M2 still extracts 90% of the rain for the period of analysis compared to 98% for M1.

The multiple-purpose detention system M3, which only extracts storm water at a rate of 5 mm/day only during summer months, provides little attenuation of storm flow except during the first storms in autumn. The total amount of storm water discharged at rates greater than 5 mm/day was 1998 mm and occurred 16% of the time (Fig. 6). Given that the majority of rain falls in autumn, winter, and spring, a reservoir would need a storage capacity equal to the annual volume of runoff from a catchment, in this region about 1 m, to maximize the water available for summer watering.

Single-Purpose Systems

Flow duration curves for the outflow (controlled release plus uncontrolled spill) from single-purpose systems are shown in Fig. 7 in addition to the summary provided in Table 1. Note that total discharge does not equal rainfall because of residual water remaining in storage at the end of simulations. S1, which has a 100-mm reservoir and 20 mm/day maximum controlled release rate, limited the amount of storm-water discharged above 10 mm/day to 382 mm, which is four times the total runoff from Novelty Hill exceeding 10 mm/day but only slightly greater than volume of discharge at rates exceeding 10 mm/day from the smallest multiple-purpose system. S1 was the only system we considered here that had a sustained outflow of at least 0.2 mm/day throughout the period of analysis. This rate is approximately equal to the lowest recorded discharge for Evans Creek normalized for drainage area.

Increasing the maximum controlled release rate of a 100-mm linear reservoir to 10 mm/day (S2) reduced the amount of storm-water discharged at rates greater than 10 mm/day to 47 mm which is less than Novelty Hill. S2 discharged a larger volume of storm water (1352 mm) at rates greater than 5 mm/day compared with 228 mm for Novelty Hill and 547 mm for S1. The median discharge from both S1 and S2 was approximately 2.8 mm/day.

A single-purpose linear reservoir with 20 mm of storage and a maximum release rate of 5 mm (S3) discharged 1485 mm at rates greater than 5 mm/day. This volume is comparable to the amount released by S1, which has a larger reservoir and the same maximum controlled release rate, at rates greater than 5 mm/day. Because of its smaller storage capacity, S3 is not as effective at controlling higher discharges as S1: total discharge from S3 at rates exceeding 10 mm/day was 1098 mm and lasted for 6% of the period (Fig. 7). S3 had a median discharge of 2.2 mm/day and exceeded 0.2 mm/day for 90% of the time, which is comparable to the median and low-flow discharge from S1.

DISCUSSION

Hillslope processes account for much of the attenuation between rainfall and streamflow, as illustrated by comparing the duration of rainfall and discharge greater than 4 mm/day in Fig. 5. For any duration, the difference between the rainfall rate and the Novelty Hill discharge is greater than the difference between the Novelty Hill discharge and the Evans Creek discharge. The influence of hillslope processes on streamflow and the modification of hillslope hydrologic processes during residential development motivated this investigation of storm-water management strategies at the scale of individual residences.

Differences in the hydrologic responses of a roof, a zero-order basin, and a stream basin can be attributed in part to differences in spatial scales [e.g., fig. 10-3 in Dunne and Leopold (1978)]. Fig. 3 shows that the larger catchment of Evans Creek (37 km^2) produces lower area-normalized peak discharge and recession rates than the smaller catchment of Nov-

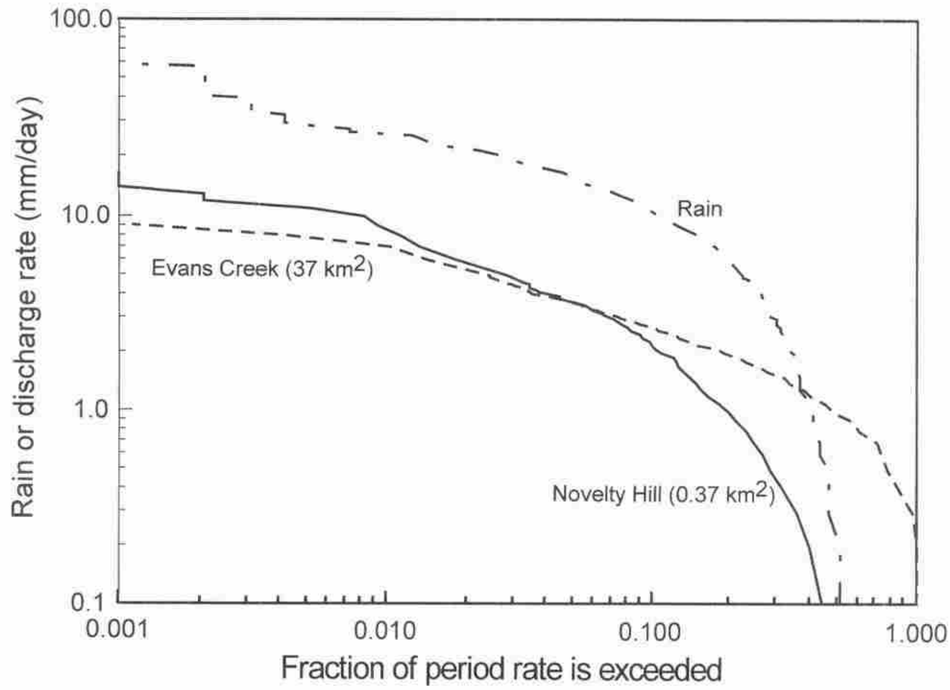

FIG. 5. Daily Duration Curves for Rain Rate and Flow Rates at Novelty Hill, and Evans Creek

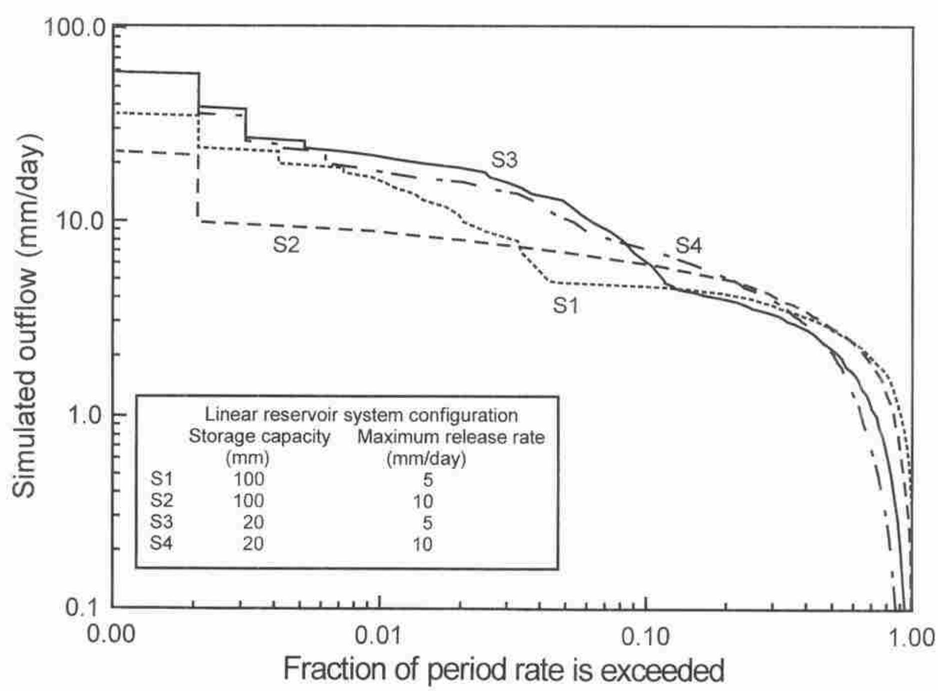

FIG. 6. Flow Duration Curves for Simulated Uncontrolled Spill, not Including Extracted Water from Three Multiple-Purpose Systems

elty Hill (0.37 km^2). Runoff from Novelty Hill reflects the effects of hillslope processes over a length scale of 300 m and open-channel flow over a length scale of, at most, 800 m. Evans Creek discharge is influenced by hillslope processes over a similar length scale as well as network routing from multiple tributaries and main-channel flow.

We used the integrated response of a forested, zero-order basin as a standard for evaluating the effectiveness of on-site detention for diminishing high flow response from residential areas. While runoff production from an "elementary" forested area the same size as a residential roof might be an appealing alternative standard for evaluating the performance of on-site storm-water management systems, such a standard has a number of drawbacks. Measurement of runoff at this scale in a forest is technically difficult and runoff production is likely to vary among small hillslope elements, making it difficult to choose a performance standard. For example, storm-flow production varies between upland areas and saturated hollows (areas of topographic convergence).

Our comparisons of simulated on-site detention systems illustrate the magnitude of storage capacities, release rates, and extraction of storm water needed for residential areas to match aspects of runoff production from forest hillslopes and streamflow from forested catchments. The water balance of forest hillslopes is a starting point for evaluating whether storm-water management systems can replicate hydrologic processes in residential areas. In particular, storm-water management systems must divert storm water from surface-water drainage to the atmosphere and subsurface flow paths to match the water balance of forested catchments.

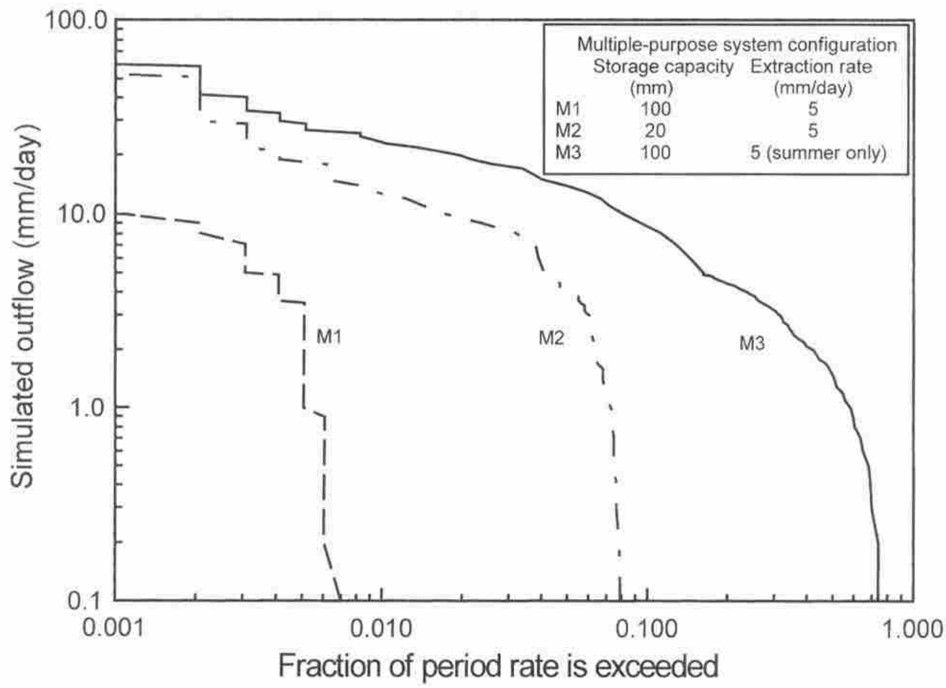

FIG. 7. Flow Duration Curves for Simulated Controlled Release and Uncontrolled Spill from Four Single-Purpose, Linear Reservoirs

Discharge from a linear reservoir for extreme high and low flow periods is sensitive to both the storage capacity and maximum controlled release rate of the system. An intermediate range of discharges, those exceeded 10–30% of the period, is primarily sensitive to release rate, rather than storage capacity indicating that single-purpose systems with small reservoirs are effective for hydrologic mitigation over a range of intermediate flows. The storage capacity, however, controls the range of higher discharges that are exceeded 1–10% of the time.

While small single-purpose, on-site detention systems cannot replicate the runoff-response of a forest hillslope, they can attenuate the peak responses generated from impermeable surfaces. The smallest system considered here, S3, discharged a total of only 1098 mm at rates greater than 10 mm/day compared to 1889 mm of rainfall that exceeded 10 mm/day. The capacity of a reservoir providing 20 mm of storage for a 100 m^2 roof is 2000 L and could be integrated into many residential sites without limiting other uses of the land. Single-purpose systems with larger storage capacities, represented by simulations S1 and S2, reduce the volume and duration of discharge during large storms, but they have little effect on the pattern of discharge at rates less than 5 mm/day.

Storm-water control during the largest storms can be improved if maximum release rates are increased, thus providing greater active storage capacity at the start of the next storm. A single-purpose system with 10 mm/day maximum release rate (S2 and S4) discharged less storm flow at rates greater than 10 mm/day than the system with the same storage capacity but lower release rates (S1 and S3, respectively). There is a tradeoff, however, for increasing maximum release rates of a linear reservoir: a system with lower maximum release rate (S1 and S3) discharged less water at rates greater than 5 mm/day than a system providing the same storage but higher maximum release rates (S2 and S4, respectively). Since 5 mm/day represents the 3% flow duration for Novelty Hill and 2% for Evans Creek, it cannot be dismissed as an ecologically benign flow rate.

While storm-water management systems are generally designed to limit peak rates, they may be able to restore low-flow patterns as well. Single-purpose systems sustain discharge at area-normalized rates comparable to minimum-flow conditions in Evans Creek over long periods (ranging from 83% to 100% of the period of analysis) particularly when they have low release rates. In contrast, all of the multiple-purpose systems (M1, M2, and M3) discharge water for less than 10% of the period of analysis as compared to approximately 50% for Novelty Hill and 100% for Evans Creek. This illustrates another tradeoff: single-purpose systems are better suited for increasing low-flow discharge while multiple-purpose systems are better for attenuating high flows.

On-site systems can mitigate hydrologic effects of residential development at nearly the same spatial scale that the effects occur. Dispersed, on-site systems provide a better representation of the predevelopment spatial distribution of water storage in a forested catchment and may more closely approximate the predevelopment temporal distribution of release of stored water (McCuen 1979). One cautionary note, however, is that storm-water management systems can aggravate flooding when runoff from areas lower in a stream basin is delayed and released coincident with a flood-wave generated from upstream areas (Hardt and Burges 1976; McCuen 1979).

On-site approaches use larger areas to manage storm water before runoff is concentrated into a channel network. On-site systems can restore fluxes of water through the land surface if they allow storm water to infiltrate into the ground and to evaporate or to be transpired into the atmosphere, for example, by irrigating vegetation. Since on the order of 30% or more of the land surface in residential areas is occupied by structures and roads, restoration of hydrologic fluxes in residential areas requires enhanced infiltration, subsurface flow, and evapotranspiration to compensate for the fraction of the land area that no longer supports these processes.

Opportunities exist for designing systems comprising single-purpose and multiple-purpose reservoirs. Unlike larger regional facilities, on-site detention reservoirs can be integrated into structures or landscapes at a site such that a relatively small area is dedicated solely to storm-water management. The added benefit of "storage for use" is reduction of imported water for residential use. This latter design feature has been incorporated into commercial buildings. Examples include the Fujita Corporate headquarters in Tokyo and the King Street

Center in Seattle. Many civilizations have used small, multiple-purpose detention systems in urban and residential areas to gain the dual benefits of water supply and improved drainage (Hofkes and Huisman 1983; Crouch 1993).

CONCLUSIONS

We have demonstrated the potential to ameliorate some hydrologic effects of residential development using on-site storm-water management. Many practical details were not addressed including the paths for discharge and spills from storage reservoirs; the network routing of runoff; and the design of collection systems, storage reservoirs, and control devices. Such details are necessary concerns for any demonstration and implementation of on-site storm-water management.

Runoff production from a zero-order hillslope catchment and a second-order stream basin provide standards for evaluating the high-flow attenuation performance of on-site detention systems. The differences between surface runoff produced at the hillslope scale (0.37 km^2) and streamflow from a larger catchment (37 km^2) shown in terms of the storm hydrograph in Fig. 3 and flow duration curves in Fig. 5 emphasize the importance of monitoring hydrologic processes over a range of spatial and temporal scales when assessing land-use effects and developing mitigation schemes.

Relatively small on-site detention systems can be used to manage much of the storm water generated from impermeable surfaces during frequent, low-intensity storms in the Puget lowland. Small, single-purpose systems can be effective for hydrologic mitigation particularly for the range of intermediate-magnitude discharges exceeded 10–30% of the time and for providing sustained base flow. Storage capacity for a single-purpose on-site detention system must be more than 100 mm and is likely to approach 150 mm to match the peak discharges and intervening recessional flows of a forested catchment. Smaller storage capacities can be employed when stormwater is extracted for use, though these multiple-purpose systems can diminish base flow if some of the extracted water is not returned to local surface or subsurface flow paths. In any application, the deleterious ecological effects of storm flow with high magnitude, low frequency, storms should be assessed relative to lower-magnitude, higher-frequency storms given the additional cost of larger reservoirs.

On-site detention augments channel-based storm-water management by taking advantage of spatially diffuse storage and release without dedicating an area solely to storm-water management. On-site systems can manage storm water before it is concentrated in drainage systems providing opportunities for emulating natural hillslope processes after land has been developed. Since different system configurations (i.e., storage capacities and release rates) provide various high-flow and low-flow benefits, the tradeoffs among systems must be evaluated in terms of the value of restoring different aspects of the hydrologic cycle in specific residential areas.

ACKNOWLEDGMENTS

Bruce Jensen, Kyle Kolsti, Ronald Nece, and Lorin Reinelt contributed to the authors interest and understanding of the problems discussed in this paper. We appreciate the helpful and constructive suggestions provided by two anonymous reviewers. Mark Wigmosta and Jack Meena provided rainfall and stream flow data for Novelty Hill. King County Department of Natural Resources provided stream flow data for Evans Creek. The work was supported by the Centennial Clean Water Fund Program, Grant Number G4900029 administered by the Washington State Department of Ecology with additional contributions from King County.

APPENDIX. REFERENCES

ASCE and WPCF (1992). *Stormwater management manual of practice*, Water Pollution Control Federation, Alexandria, Va.

Bauer, H. H., and Mastin, M. C. (1997). "Recharge from precipitation in three small glacial-till-mantled catchments in the Puget Sound lowland, Washington." *Water Resour. Investigation Rep. 96-4219*, USGS, Tacoma, Wash.

Booth, D. B. (1990)."Stream-channel incision following drainage-basin urbanization." *Water Resour. Bull.*, 26(3), 407–417.

Burges, S. J., Wigmosta, M. S., and Meena, J. M. (1998). "Hydrologic effects of land-use change in a zero-order catchment." *J. Hydrologic Engrg.*, ASCE, 3(2), 86–97.

Burges, S. J., Stoker, B. A., Wigmosta, M. A., and Moeller, R. A. (1989). "Hydrologic information and analyses required for mitigating hydrologic effects of urbanization." *Water Resour. Ser. Tech. Rep. No. 117*, Dept. of Civ. Engrg., Univ. of Washington, Seattle.

Crouch, D. P. (1993). *Water management in ancient Greek cities*, Oxford University Press, New York.

Dunne, T., and Black, R. D. (1970). "An experimental investigation of runoff production in permeable soils." *Water Resour. Res.*, 6(2), 478–490.

Dunne, T., and Leopold, L. B. (1978). *Water in environmental planning*, W. H. Freeman, San Francisco.

Dunne, T., Moore, T. R., and Taylor, C. H. (1975). "Recognition and prediction of runoff-producing zones in humid regions." *Hydro. Sci. Bull.*, 20(3), 305–327.

Economic and Engineering Sciences, and CHZM Hill. (1995). "Water demand forecast." *Rep. Prepared for Tacoma Public Utility*, Olympia, Wash.

Gan, T. Y., and Burges, S. J. (1990). "Assessment of a conceptual rainfall-runoff model's ability to represent the dynamics of small hypothetical catchments 2. Hydrologic responses for normal and extreme rainfall." *Water Resour. Res.*, 26(7), 1605–1619.

Hardt, R. A., and Burges, S. J. (1976). "Some consequences of area wide runoff control strategies in urban watersheds." *Tech. Rep. No. 48*, Dept. of Civ. Engrg., Univ. of Washington, Seattle.

Hewlett, J. D. (1961). "Soil moisture as a source of base flow from steep mountain watersheds." *Southeast Experimental Station Paper 132*, U.S.D.A. Forest Service, Washington, D.C.

Hofkes, E., and Huisman, L. (1983). *Small community water supplies*, Wiley, London.

Hollis, G. E. (1975). "The effects of urbanization on floods of different recurrence intervals." *Water Resour. Res.*, 11(3), 431–435.

Hollis, G. E., and Ovenden, J. C. (1988). "The quantity of stormwater runoff from ten stretches of road, a car park and eight roofs in Hertfordshire, England during 1983." *Hydrologic Processes*, England, 227–243.

King County Department of Public Works. (1998). *Surface water design manual*, Surface Water Management Division, Seattle.

McCuen, R. H. (1979). "Downstream effects of stormwater management basins." *J. Hydr. Div.*, ASCE, 105(11), 1343–1356.

Reinelt, L. E., and Horner, R. R. (1991). "Urban storm water impacts on the hydrology and water quality of palustrine wetlands in the Puget Sound region." *Puget Sound Res. '91 Proc.*, Puget Sound Water Quality Authority, Olympia, Wash.

Schneider, W. J. (1975). "Aspects of hydrological effects of urbanization." *J. Hydr. Div.*, ASCE, 101(5), 449–468.

Urbonas, B. R., and Roesner, L. A. (1993). "Hydrologic design for urban drainage and flood control." *Handbook of hydrology*, D. R. Maidment, ed., McGraw-Hill, New York, 28.1–28.52

U.S. Environmental Protection Agency (1983). "Results of the nationwide urban runoff program." *NTIS PB84-18552*, Washington, D.C.

Whipkey, R. Z. (1965). "Subsurface storm flow from forested slopes." *Int. Assn. of Sci. Hydr. Bull.*, 10(2), 25–33.

Wigmosta, M. S., and Burges, S. J. (1997). "An adaptive modeling and monitoring approach to describe the hydrologic behavior of small catchments." *J. Hydro.*, Amsterdam, 202, 48–77.

Wigmosta, M. S., Burges, S. J., and Meena, J. M. (1994). "Modeling and monitoring to predict spatial and temporal hydrologic characteristics in small catchments." *Water Resour. Ser. Tech. Rep. No. 137*, Dept. of Civ. Engrg., University of Washington, Seattle.