DOWNSTREAM HYDROGRAPHIC EFFECTS OF URBAN STORMWATER DETENTION AND INFILTRATION

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Abstract. Urban stormwater hydrographs with various degrees of detention and infiltration were routed through 30 hypothetical drainage networks. Only infiltration reduced flow volume. Infiltration shortened flow duration while detention lengthened it. Both detention and infiltration reduced peak rate of flow, but not to the degree for which they were designed; their effectiveness varied with drainage networks and urban hydrologic changes. These results encourage balanced consideration of infiltration and detention for solving specific problems of flooding and erosion in specific watersheds.

INTRODUCTION

Urban development alters the peak flow rate, total volume and duration of stormwater hydrographs. In freely flowing channels, increased peak rate leads to increased overbank flow onto streets and properties. At undersized culverts and other obstructions, increasing volume, alone or in combination with increased peak, aggravates flooding and drainage problems (Ferguson and Deak, 1994). As duration of moderate and high flows increases, channel erosion and sediment production increase (McCuen, 1979).

Detention, the temporary delay of surface flows in reservoirs, has been the most common response to these concerns in Georgia and other regions of the United States (Debo and Ruby, 1982). Another approach, infiltration, the diversion of surface volumes into the soil, is becoming more common in response to concerns of water quality and subsurface recharge (Ferguson, 1994). The physical design of detention and infiltration facilities is described in general stormwater management books such as that of Ferguson and Debo (1990).

The effects of individual detention and infiltration basins on storm hydrographs at the point of discharge, illustrated in Figure 1, are well known; they are directly determined by the design of individual facilities. However, their effects further downstream in complex watersheds where tributary flows combine over time are incompletely understood. Accumulating volumes and overlapping times of flow may add up to new and higher peak rates, durations and volumes, such that improperly applied stormwater management could aggravate downstream the problems it was intended to solve at the point of discharge.

This paper reports the results of a novel approach to bring more light to downstream hydrographic effects. A model was created that produces hypothetical watersheds by randomly (within realistic constraints) assigning hydrographic characteristics of subwatersheds and channel segments. By hypothesizing such watersheds quickly and recording their hydrographic outcomes systematically, the approach permits statistical analysis of downstream effects in a large number of watersheds, and thus a degree of generalization not possible from a small number of site-specific studies.

PREVIOUS STUDIES

McCuen (1974, 1979) first pointed out the complex downstream effects of detained hydrographs in urban watersheds. Applying runoff models to Maryland watersheds with 7 to 17 subwatersheds, he found that detention basins could cause increased flood peaks where their receding discharges overlap the peak flows of other tributaries.

Subsequent studies by others have confirmed McCuen's warnings. One such study was a recent combination of gaging and modeling to watersheds in Gwinnett County, Georgia containing two to six detention basins (Hess and Inman, 1994). The researchers found that individual basins mostly reduced downstream flood peaks, but that the degree of reduction varied with number and locations of basins, and that some basins slightly increased downstream peaks.

McCuen (1979) found by modeling that as duration of moderate and high flows increased with detention, bedload transport stayed high even where peak flow was reduced, thus channel erosion and sediment production were unmitigated. Subsequent studies again confirmed McCuen's warnings.

All these studies were based on modeling. Although hydrologic modeling is not necessarily always highly accurate, its control over input conditions allows the direct comparison of clearly defined alternatives. The modeling of specific watersheds uses input of watershed and management characteristics to produce a hydrograph for each subwatershed. Routing procedures then combine and attenuate hydrographs in the downstream drainage network.

These researchers all concluded that the effectiveness of detention downstream in a complex watershed is not the same as that at the point of discharge. Consequently they tended to criticize uniform on-site detention without watershed-wide analysis.

However, the results from geographically specific watersheds cannot be directly applied to other watersheds because every watershed's pattern of rainfall, land use, topography and drainage network is unique. Also, the number of stormwater management approaches that can reasonably be compared in such studies is limited, because each option requires laborious reentry of reservoir and outlet characteristics. Thus the results of previous studies have not made it possible to generalize in detail about the downstream hydrographic effects of stormwater management.

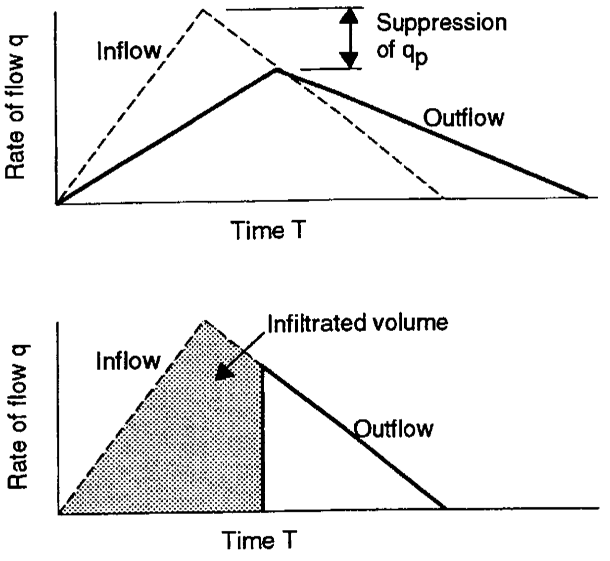

Figure 1. Effects of detention (top) and infiltration (bottom) at the point of discharge.

METHOD

The model for this study differed from previous models in that it bypassed entry of specific watershed geography to generate hypothetical hydrographs and drainage networks directly. Random creation of drainage networks, when subject to realistic constraints, has been show to produce networks that reflect mean parameters found in nature (Leopold, Wolman and Miller, 1964, p. 416, 431). For each watershed 240 attributes were randomly assigned: 5 for each of 20 subwatersheds, and 7 for each of 20 channel segments.

The model was constructed in three spreadsheet files: the random generation of each hypothetical watershed, the routing of the watershed's hydrographs through the drainage network, and the recording of results.

Because of the exclusive focus of this model on hydrographs, numerous watersheds were produced and their outcomes seen rapidly. The number of hypothetical watersheds reported in this paper exceeds by several times the total number of geographically specific studies reported in the literature, and the range of alternatives modeled for each of them has never before been attempted.

The model assigned to each subwatershed and channel segment the characteristics listed in Table 1. The ranges of values are comparable to those that other researchers have observed in or predicted for urbanizing watersheds. Recurrence interval of any given Q or q_p was not considered. The purpose of this study was to compare the relative changes in flow following development and management, no matter what the recurrence interval would be in any specific locale. Each subwatershed's time to peak T_p was calculated as 0.375 of the total time of flow (the base of the triangular hydrograph).

The model's routing segment allowed the specification of undeveloped or developed conditions, and the degree of detention or infiltration to be applied to developed subwatersheds. Detention was specified as the reduction in discharging q_p as a proportion of q_p before development. Infiltration was specified as the reduction in discharging Q as a proportion of total flow volume. Infiltration reduced discharging q_p if the reduction in Q was greater than 0.375.

In routing, each channel segment combined upstream hydrographs and delayed their throughflow by the randomly specified time interval.

For the last channel in the network (the bottom of the watershed), the model reported q_p, Q and duration of flow over 0.5 m^3/s and over 1.0 m^3/s. In this study 16 conditions of development, detention and infiltration were modeled for each of 30 hypothetical watersheds, giving 480 routing runs.

RESULTS

Only infiltration controlled volume at all, as shown in Figure 2. The reduction followed linearly from degree of infiltration in individual subwatersheds. This is a direct result of physical management processes: infiltration reduces total

Table 1. Characteristics Assigned to Hypothetical Watersheds

Characteristic	Range
Subwatersheds	
Flow volume Q before development	From 500 to 2,500 m^3
Peak flow q_p before development	From 0.0 to 0.5 m^3/s
Subwatershed to be developed	50% chance
Change in Q (ΔQ) if developed	From 1 to 4 times undeveloped Q
Change in q_p (Δq_p) if developed	From 1 to 2 ΔQ = from 1 to 8 times
Channel segments	
Channel entering from upstream	Assigned in numerical order
Second channel to enter from upstream	50% chance, assigned in numerical order
Subwatershed entering from upstream	Assigned in numerical order
Second subwatershed to enter	50% chance, assigned in numerical order
Travel time T_t before development	From 0 to 10 modeling time increments
Channel segment to be developed	50% chance
Change in T_t if developed	From 0.0 to 0.5 of undeveloped T_t

flow volume, no matter how tributaries combine in time; detention only delays it, even when detention reduces q_p to predevelopment levels and below.

On duration, infiltration and detention had opposite effects, as shown in Figure 3. Detention tended to lengthen duration of flow at both of the recorded flow rates; duration increased with increasing suppression of q_p. This is a logical outcome of detention, which releases detained peak flows at moderate rates later in the storm event. Infiltration, in contrast, reduced duration at the recorded rates. This is a logical outcome of infiltration, which chops off a part of the hydrograph in time as shown in Figure 1.

Infiltration and detention reduced downstream peak rate of flow, on the average, to astonishingly similar degrees, as shown in Figure 4. The reduction increased with increasing degrees of control. However, neither approach reduced the downstream peak to the degree it controlled discharge from individual subwatersheds. The conflicts among detained flows occurred, as McCuen (1974, 1979) had warned, but were partly averaged out among many tributaries combining at different times. The infiltration process (Figure 1) left spikes of discharge in the downstream hydrograph which were sometimes high in peak rate although short in duration.

Detention's and infiltration's reductions of q_p varied with the ways drainage networks and development patterns caused tributary flows to combine in time. Where both were successful, one or two tributaries, with peaks arriving at similar times, dominated the total developed flow, so that either infiltration or detention in those subwatersheds had a direct effect on total flow rate downstream. Where only detention was successful, the downstream hydrograph was long and slow, from many tributaries dispersed in time; thus detained flows did not overlap into new peaks, while infiltration's discharging spikes remained in the hydrograph. Where only infiltration was successful, the downstream hydrograph was short, with tributary flows arriving almost simultaneously; detained flows in the tributaries piled up into later peaks, while infiltration reduced the peak at the core of the hydrograph.

CONCLUSIONS AND RECOMMENDATIONS

Infiltration reduces downstream flow volume to the degree for which it is designed in individual subwatersheds. It shortens flow duration very effectively. On the average it reduces peak rate, but not in proportion to its reduction in flow volume.

Detention has no effect on flow volume, and it lengthens downstream flow duration. On the average it reduces downstream peak rate, but not to the degree to which it is designed in individual subwatersheds.

These results are important for matching management approaches to specific watershed geographies and management objectives. Where reducing channel erosion is the principal objective, infiltration can be highly favored.

For reducing drainage problems at undersized culverts and other obstructions, infiltration has an advantage in that it reduces total flow volume (Ferguson and Deak, 1994).

Where reducing flooding in freely flowing channels is the objective, neither infiltration nor detention is consistently favored over the other. To a degree, the types of effects to be expected in specific watersheds can be foreseen in geographic patterns of drainage networks and land development. Site-specific modeling remains the ultimate check on q_p effect that should be expected from specific management proposals.

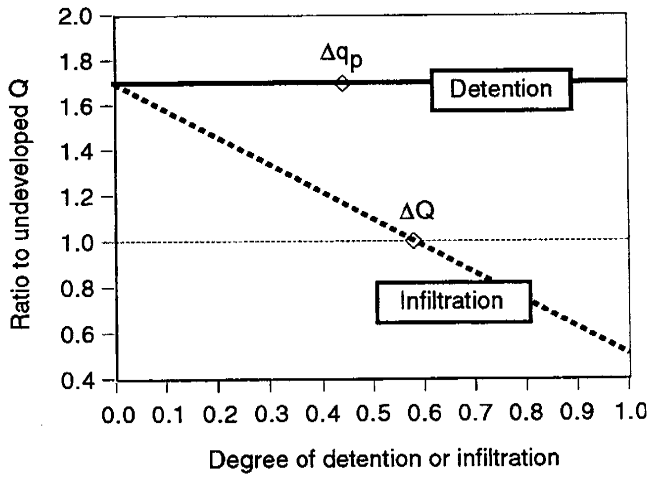

Figure 2. Average effects of infiltration and detention on downstream flow volume Q. ΔQ is infiltration of the difference in subwatershed flow volume attributable to development. Δq_p is detention suppressing subwatershed peak flow rate to that before development.

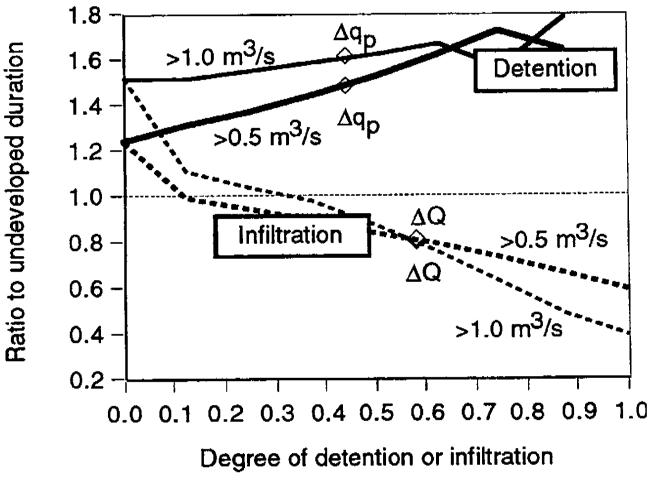

Figure 3. Average effects of infiltration and detention on downstream flow duration at two flow rates.

In Georgia, uniform on-site detention is almost the only approach to urban stormwater management. These results warn that this exclusive approach is probably having unintended effects on flow rate, duration and volume. These results invite consideration of infiltration on an equal basis with detention. They encourage infiltration even in small amounts for the purpose of reducing downstream channel erosion.

These results concerning storm hydrographs can be added to existing knowledge of infiltration's and detention's addi-

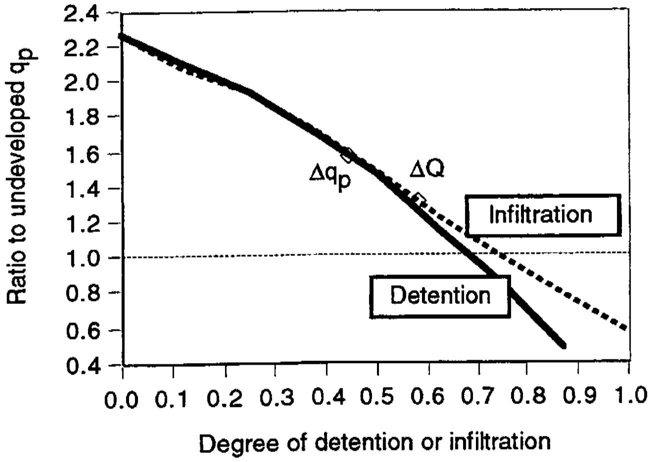

Figure 4. Average effects of infiltration and detention on downstream peak rate of flow.

tional effects on water resources such as ground water recharge, base flow maintenance and water quality, to select and guide management which is broadly effective.

LITERATURE CITED

Debo, Thomas N., and Holly Ruby, 1982. Detention Basins, An Urban Experience, *Public Works* January 1982, pages 42-43, 93.

Ferguson, Bruce K., 1994. *Stormwater Infiltration*, Boca Raton: Lewis Publishers.

Ferguson, Bruce K., and Tamas Deak, 1994. Role of Urban Storm-Flow Volume in Local Drainage Problems, *Journal of Water Resources Planning and Management* vol. 120, no. 4, pages 523-530.

Ferguson, Bruce K., and Thomas N. Debo, 1990. *On-Site Stormwater Management, Applications for Landscape and Engineering*, New York: Van Nostrand Reinhold.

Hess, Glen W., and Ernest J. Inman, 1994. *Effects of Urban Flood-Detention Reservoirs on Peak Discharges in Gwinnett County, Georgia*, Water-Resources Investigations Report 94-4004, Atlanta: U.S. Geological Survey.

Leopold, Luna B., M. Gordon Wolman, and John P. Miller, 1964. *Fluvial Processes in Geomorphology*, San Francisco: Freeman.

McCuen, Richard H., 1974. A Regional Approach to Urban Storm Water Detention, *Geophysical Research Letters* vol. 1, no. 7, pages 321-322.

McCuen, Richard H., 1979. Downstream Effects of Stormwater Management Basins, *Journal of the Hydraulics Division, American Society of Civil Engineers*, vol. 105, no. HY11, pages 1343-1356.