EVALUATION OF HYDROLOGIC BENEFITS OF INFILTRATION BASED URBAN STORM WATER MANAGEMENT[1]

Jennifer K. Holman-Dodds, A. Allen Bradley, and Kenneth W. Potter[2]

ABSTRACT: As watersheds are urbanized, their surfaces are made less pervious and more channelized, which reduces infiltration and speeds up the removal of excess runoff. Traditional storm water management seeks to remove runoff as quickly as possible, gathering excess runoff in detention basins for peak reduction where necessary. In contrast, more recently developed "low impact" alternatives manage rainfall where it falls, through a combination of enhancing infiltration properties of pervious areas and rerouting impervious runoff across pervious areas to allow an opportunity for infiltration. In this paper, we investigate the potential for reducing the hydrologic impacts of urbanization by using infiltration based, low impact storm water management. We describe a group of preliminary experiments using relatively simple engineering tools to compare three basic scenarios of development: an undeveloped landscape; a fully developed landscape using traditional, high impact storm water management; and a fully developed landscape using infiltration based, low impact design. Based on these experiments, it appears that by manipulating the layout of urbanized landscapes, it is possible to reduce impacts on hydrology relative to traditional, fully connected storm water systems. However, the amount of reduction in impact is sensitive to both rainfall event size and soil texture, with greatest reductions being possible for small, relatively frequent rainfall events and more pervious soil textures. Thus, low impact techniques appear to provide a valuable tool for reducing runoff for the events that see the greatest relative increases from urbanization: those generated by the small, relatively frequent rainfall events that are small enough to produce little or no runoff from pervious surfaces, but produce runoff from impervious areas. However, it is clear that there still needs to be measures in place for flood management for larger, more intense, and relatively rarer storm events, which are capable of producing significant runoff even for undeveloped basins.
(KEY TERMS: infiltration and soil moisture; low impact development; modeling; infiltration based storm water management; surface water hydrology; storm hydrograph; water budget.)

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INTRODUCTION

There is little doubt that humans have caused significant impacts on the natural environment, including alterations to watersheds and the hydrologic cycle through urbanization. As areas undergo urbanization, surfaces are made less pervious, either through impervious covers or by disturbance of established soil structure. This has the effect of changing the local water balance by increasing storm flow rates and volumes and decreasing baseflow components. This problem has been exacerbated by traditional storm water management schemes, which seek to remove runoff from the site as quickly as possible.

In recent years, alternative approaches for dealing with urban storm water have been proposed. The idea is to carefully manage surface water from impervious surfaces (e.g., streets, parking lots, and buildings) to promote infiltration on adjacent pervious surfaces (e.g., vegetated areas). The exciting aspects of this alternative approach are that in addition to reducing the amount of surface runoff, it may also be possible to increase recharge of local ground water aquifers and streams, reduce erosion and stream widening, and improve stream water quality, all without the additional expense and maintenance associated with traditional engineered storm water infrastructure (Prince George's County, 1999; Patchett and Wilhelm, 1997; Tourbier, 1994).

In this paper, we present a group of preliminary experiments designed to investigate the hydrologic impacts of such alternative, "low impact" storm water management strategies. In particular, we evaluate

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changes in event runoff volume and hydrograph characteristics using traditional engineering methods developed by the Soil Conservation Service. In addition, we examine impacts to the water budget in more detail using a continuous simulation with a physically based, one-dimensional model. Although such experiments, using relatively simple hydrologic methods, are not able to provide a rigorous, quantitative analysis of the hydrologic impacts of low impact strategies, we are able to gain insight into the most important issues associated with alternative, infiltration based, urban storm water management.

BACKGROUND

For many years now, hydrologists have recognized the negative impacts of traditional storm water management strategies as water quality degrades, stream channels erode or aggrade, and flooding becomes more frequent and damage more costly (James, 1965; Hammer, 1972). In the past, storm water management strategies employed by municipalities have focused on the mitigation of localized peak flow impacts. This generally involves detention ponds, which temporarily store storm water to reduce peak flows. While this technique is able to change the timing of the flows, the increased storm water volume resulting from increased impervious areas is largely unaffected. It is becoming apparent that the increased total storm water volume, longer duration of higher flows, and the synergistic effects of many detention systems within a region are creating significant problems in some municipalities (Lakatos and Kropp, 1982).

Furthermore, as stream restoration has become increasingly popular, it has become apparent that in many cases, it is difficult, if not impossible, to restore bank characteristics and ecosystem function without addressing the changes in hydrology and sediment transport brought about by urbanization. For example, researchers have noted that although large peak flow may be capable of moving large quantities of sediment in a relatively short time period, overall stream geomorphology is influenced more by smaller, more frequent sediment transporting flows (Wolman and Miller, 1960; Wolman and Schick, 1967). Thus, even when storm water detention maintains the predevelopment peak flow for the two-year storm, the duration of this peak flow level is greatly increased due to increased total runoff volume. As a result, it may be necessary to address changes in not only the peak flows (e.g., two-year and ten-year), but also in the duration of flow capable of sediment transport.

In analyzing the impacts of urbanization, researchers have recognized the role of not only the quantity of impervious areas, but also the degree of connectivity of these impervious surfaces as an important influence on the significance of observed urbanization impacts (e.g., Alley and Veenhuis, 1983; Booth, 1990; Booth and Jackson, 1997). To incorporate this observed effect, connectivity may be used to classify impervious areas within a watershed. Such researchers have used the concept of effective impervious area to describe the relative impact of different urbanization practices. Effective impervious areas (EIAs) may be defined as impervious surfaces that are hydraulically connected to the channel drainage system. That is, areas that are effective in removing storm water from an area and moving it quickly downstream. A paved parking lot that drains directly to a street with a curb and gutter system connected to a local storm water conveyance system is an example of effective impervious area.

In addition, the possibility of modifying the infiltration potential of soils through changes in vegetative cover (Patchett and Wilhelm, 1997; Tourbier, 1994) or amending the soil with compost (Kolski *et al.,* 1995; Pitt *et al.,* 1999) has been recognized. For example, the use of bunch grasses (e.g., Big Bluestem and Little Bluestem) rather than sod grasses can be more effective in modifying soil structure to enhance infiltration (Janstrow, 1987; Hester *et al.,* 1997; McGinty *et al.,* 1991). Although this kind of "ecological restoration" of watersheds disturbed by human impacts shows great promise, developers are unwilling to invest in such approaches until the benefits can be clearly demonstrated. We need to be able to evaluate storm water management using more complete hydrologic information (beyond just peak reduction for selected design storms) and develop design criteria that allow engineers to take advantage of more ecologically sound strategies for storm water management and to determine the potential regional impacts that these kinds of solutions might have (Strecker, 2001).

EXPERIMENTAL DESIGN

To begin to explore some of these issues, we have designed several experiments based on basic engineering design tools and soil models. Prior to describing these experiments in detail, we first discuss the basic experimental scenarios and the watershed to which we tie these experiments.

Storm Water Scenarios

To examine the relative impacts of different forms of urbanization, we developed three development scenarios, which are illustrated in Figure 1. The first case, "Predevelopment," is characterized by being fully pervious, to represent conditions prior to urbanization.

The second case, "High Impact," represents development corresponding to traditional storm water design in which storm water is removed from individual lots and subdivisions as quickly as possible and dealt with using an "end of the pipe" strategy. In terms of EIA, all impervious areas are assumed to be fully connected, so EIA is equal to total impervious area. For these experiments, this scenario is 50 percent pervious and 50 percent impervious.

The third and final case, "Low Impact," represents urbanization using infiltration based storm water management. In this case, runoff from impervious areas is assumed to be completely rerouted across the pervious land segments, allowing an opportunity for infiltration. Although the impervious areas are disconnected from the receiving water body, the EIA may not be necessarily equal to zero, since the pervious receiving areas may be limited in their ability to absorb the additional runoff depending on relative ratio of pervious to impervious area, as well as the infiltration properties of the pervious areas. As for the high impact case, the basin is 50 percent impervious.

Ralston Creek Watershed

The experiments described in this paper are based on data and characteristics of the North Branch of the Ralston Creek watershed in Iowa City, Iowa. This basin, shown in Figure 2, provides an excellent case study, as much of southern and lower branches of the basin are already urbanized and experiencing flooding problems. It is likely that the North Branch will see development in the future as Iowa City continues to expand.

In addition, this small basin has a long history of watershed studies (e.g., Horton, 1933; Croley *et al.,* 1978; Kumar and Jain, 1982) and, for this size of a basin, an unusually high quality and high resolution data set available. For example, the precipitation data for these experiments come from a five-gage network on the 3.3 mi^2 (840 ha) North Branch Basin that was in operation from 1948 to 1974.

From this record, a 20-year period (January 1953 to December 1972) was used in these analyses. This was supplemented with the data from 1952 when needed for model initialization. The average monthly rainfall and runoff for this period is shown in Figure 3. On average, annual runoff is about 31 percent of the total precipitation, with an even lower runoff fraction during the warmer months of April to October. This suggests that evapotranspiration is an extremely important element in the basin water balance.

(a) (b) (c)

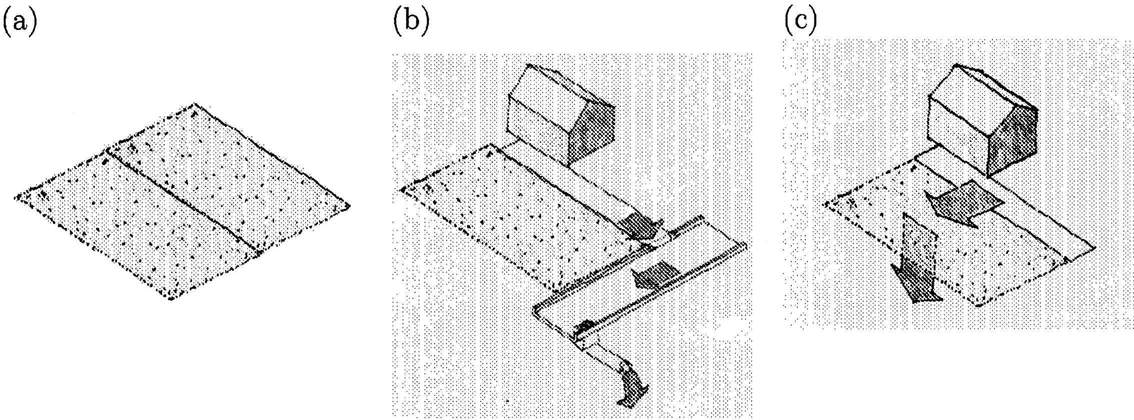

Figure 1. Schematic of Cases Examined in Experiments. (a) Predevelopment, in which the entire landscape remains vegetated; (b) high impact, developed using traditional storm water management, in which runoff from impervious surfaces are routed directly to a receiving water body through storm sewers or other channelized conveyances; and (c) low impact, developed using infiltration based storm water management, in which runoff from impervious surfaces is rerouted across adjacent pervious areas to maximize infiltration opportunities.

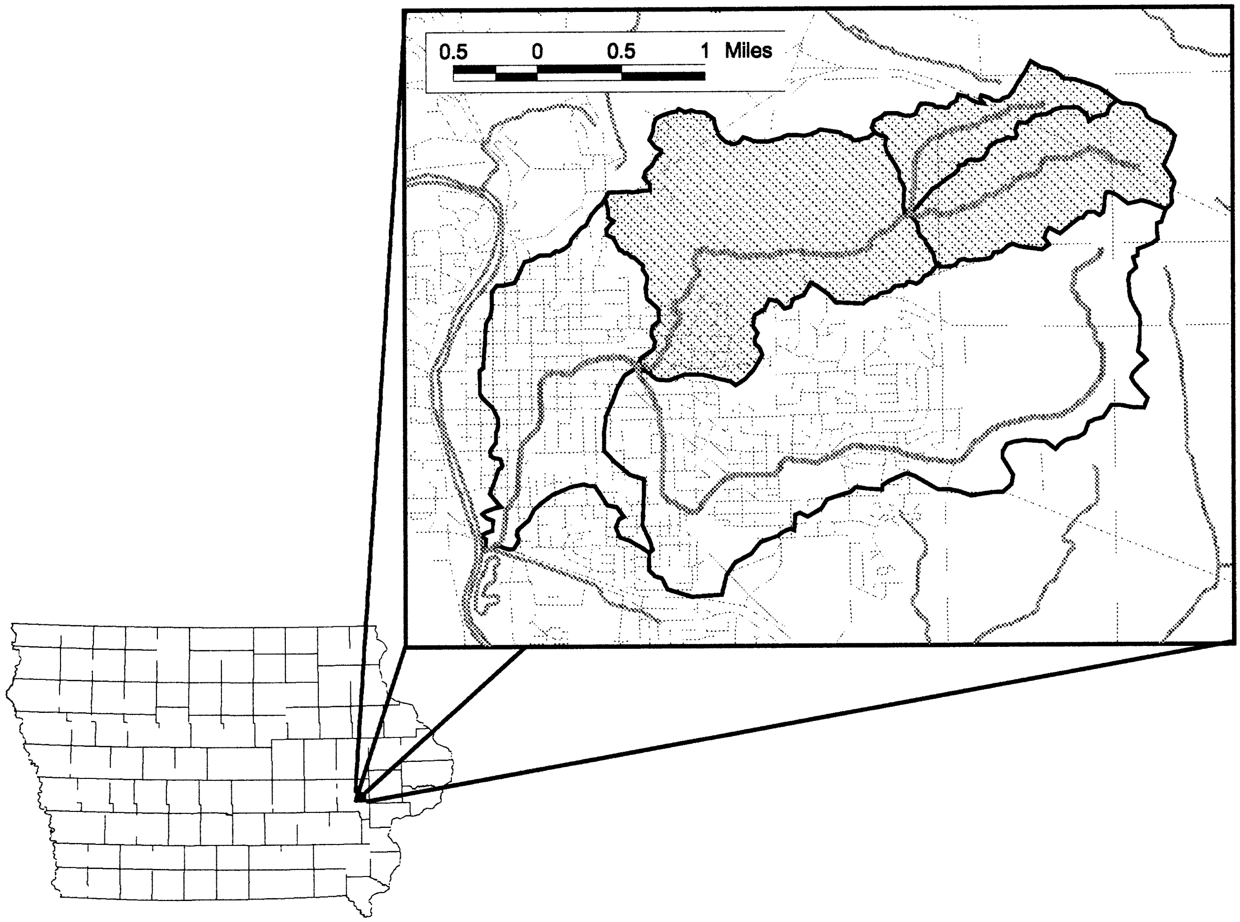

Figure 2. The Ralston Creek Watershed Feeds Into the Iowa River in East-Central Iowa. These experiments are based on the 3.3 mi^2 North Branch subbasin, which is shaded in the figure. This subbasin is largely agricultural, but is likely to be developed as Iowa City expands in the future.

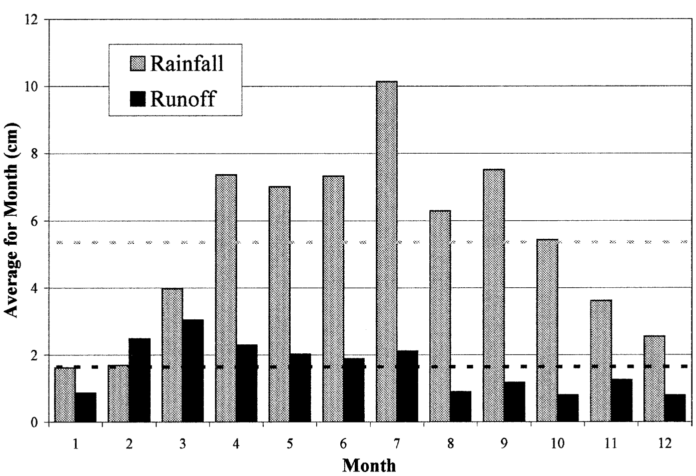

Figure 3. Average Monthly Rainfall and Runoff for North Branch Ralston Creek for January 1953 to December 1972. On an annual basis (shown by dashed lines), average monthly runoff is 1.64 cm and average monthly rainfall is 5.36 cm, which gives a basin runoff coefficient of 31 percent.

ANALYSIS AND RESULTS

Event Runoff Volume

To examine the effect of urbanization strategies on individual storm events, the Soil Conservation Service (SCS) Curve Number model was used (McCuen, 1982). This standard engineering model relates runoff volume to precipitation depth and soil properties. The soil properties are summarized using a curve number based on soil infiltration capacity, soil texture, type and condition of ground cover, and antecedent moisture condition (Rawls *et al.,* 1993).

The three landuse scenarios were modeled as follows. The predevelopment case uses standard curve number methods with soil properties based on the North Branch Ralston Creek basin and a "meadow" covering (CN = 58). The high impact case was modeled assuming that all precipitation that falls on the impervious half becomes runoff. The pervious portion is modeled in the same way as the predevelopment case. The total runoff is the area weighted average of the two segments. The low impact case is modeled by assuming that the precipitation volume on the pervious segment is equal to the pervious segment rainfall plus the impervious area runoff.

For each landuse scenario, event runoff was computed for a number of design storm depths ranging from 0.5 inches up to the 100-year, 24-hour design storm depth of 7.13 in (Huff and Angel, 1992) for various SCS soil classifications. Results for two of these soil classifications are summarized in Figure 4, which compares the highest infiltration capacity soil (Type A, on the left) with the lowest infiltration capacity soil (Type D, on the right).

For high infiltration capacity soils, almost no runoff is generated for the predevelopment case. The runoff fraction is less than 0.1, even for precipitation totals approaching the 100-year, 24-hour depth. However, for the high impact development case, the runoff fraction is around 0.5. This reflects the situation where all of the precipitation on the impervious areas (here, 50 percent of the catchment) produces runoff. Hence, the change in storm event runoff going from predevelopment to high impact development is dramatic. Still, by rerouting the runoff from the impervious areas over the pervious areas in the low impact case, most of this extra runoff is infiltrated. For precipitation depths less than about 3 inches (the two-year, 24-hour depth), the runoff fraction remains near zero. As the precipitation approaches the 100-year, 24-hour depth, the runoff fraction grows slowly to 0.18, which is still much less than in the high impact development case.

The situation is significantly different for low infiltration capacity soils. For the predevelopment case, a large fraction of the precipitation becomes runoff. The runoff fraction increases with increasing precipitation, going from 0.36 for a two-year, 24-hour depth (3 inches) to 0.64 for a 100-year, 24-hour depth (7 inches). For the high impact development case, the runoff fraction is even higher, as all the precipitation

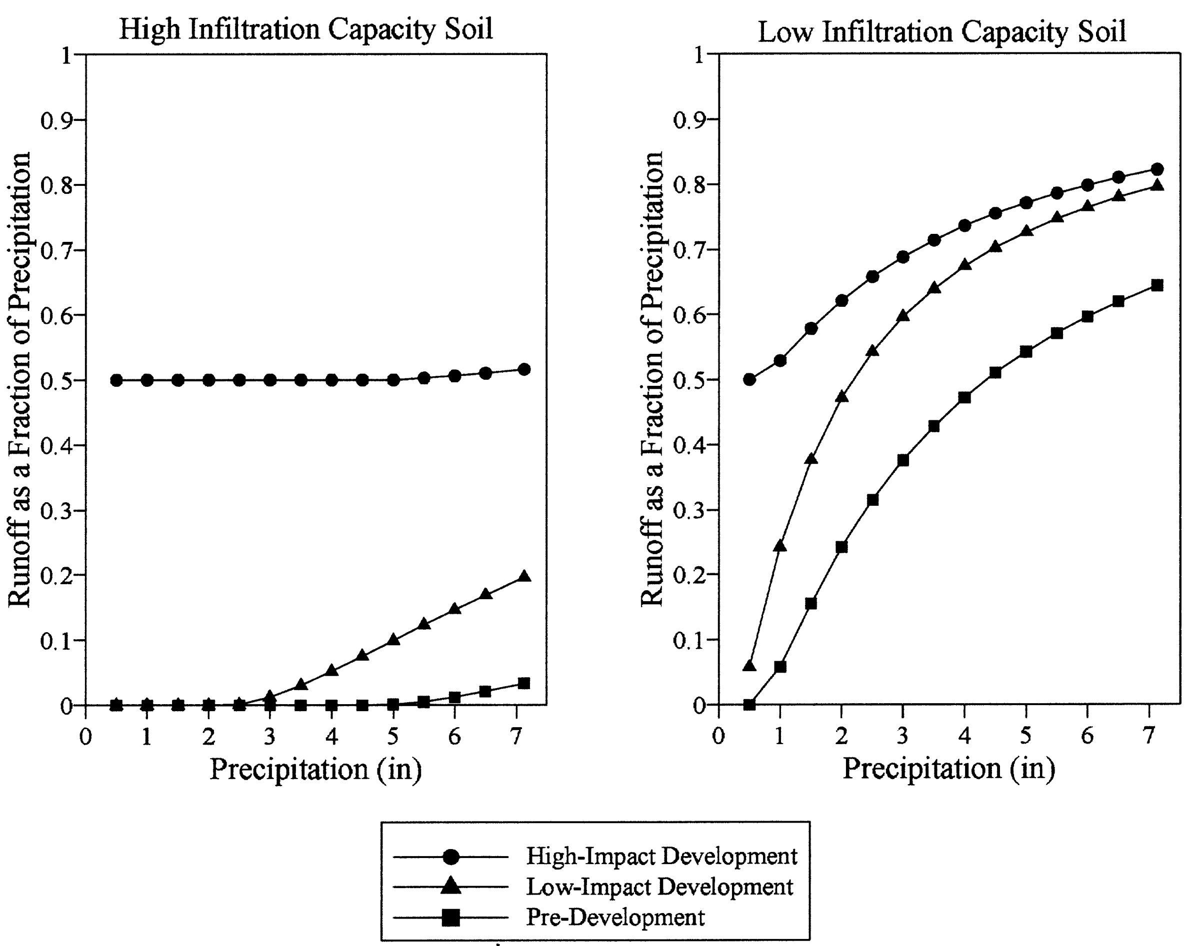

Figure 4. Runoff Fraction Under Different Development Scenarios. High infiltration capacity soil is modeled using SCS soil classification 'A' and low infiltration capacity soil is modeled using SCS soil classification 'D.'

from the impervious half of the catchment produces runoff. For the low impact development case, the runoff fraction is low for very small precipitation depths (1 inch or less). However, as the precipitation depth increases, the runoff fraction approaches the runoff fraction for the high impact development case. Although water from the impervious areas is given a chance to infiltrate, the low infiltration capacity of the soil prevents most of the excess water from infiltrating, and most becomes runoff anyway.

This analysis suggests that the relative impacts of urbanization, as measured by the difference in runoff between predevelopment and high impact development, are generally greater for more pervious soils. However, the potential for mitigation of these impacts, as measured by the difference in runoff between high impact development and low impact development, is also much greater. In addition, both the urbanization effect and the mitigation potential are also strongly dependent on total rainfall depth, with greater relative effects for smaller storm depths. Although the mitigation is most effective for high infiltration capacity soils, there may be some potential for significant reductions in runoff during small, more frequent events, even for low infiltration capacity soils.

Results specific to the Ralston Creek basin (predominantly SCS soil type B) are shown in Figure 5 for the 24-hour design storm depths for a variety of return periods. In contrast to the previous figure, this figure shows runoff as an average depth over the basin (rather than as a runoff fraction). For the moderately high infiltration capacities in the Ralston Creek basin, storm event runoff for low return periods (≤ 1 year) is near zero for the predevelopment case. Runoff increases significantly for high impact development, but is nearer to predevelopment levels for low impact development. For longer return periods (≥ 10 years), storm event runoff for low impact development is nearer to the runoff for the high impact development, although the reduction in runoff amounts is still significant. Hence, we may conclude that, for this relatively pervious basin, there may be significant reductions in runoff by using low impact development strategies, especially for the smaller, more frequent events.

Storm Hydrograph Analysis

To analyze urbanization impacts on storm runoff hydrographs, the North Branch of Ralston Creek was modeled using the design storm hydrograph procedure described in Technical Release 55: Urban Hydrology for Small Watersheds (TR-55) (Soil Conservation Service, 1986). To model the predevelopment

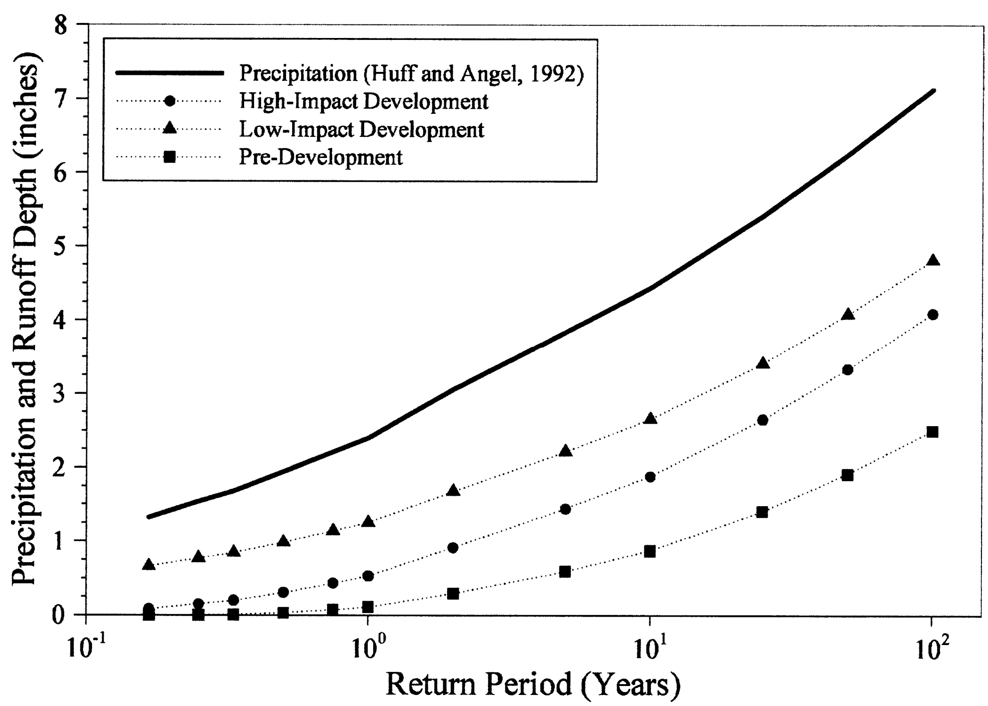

Figure 5. Event Based Runoff for 24-Hour Design Storms for the Three Development Scenarios for Ralston Creek Basin. For comparison, the 24-hour design storm depths are shown.

case, a standard TR-55 analysis was done using data derived from DEM data and existing field measurements (T. L. Steurer, 1996, unpublished M.S. Thesis) and soil properties consistent with the event runoff volume experiments (CN = 58).

To model the high impact case, half of the watershed is covered with a directly connected impervious area. To model this, the watershed was divided into two segments, each with half of the total watershed areas that were routed in parallel, with total runoff being combined at the basin outlet. One of the segments was modeled using predevelopment cover (CN = 58), the other with concrete cover (CN = 98). For both segments, predevelopment routing lengths and slopes were maintained.

For the low impact case, a composite curve number (CN = 73.5) was selected to duplicate runoff volumes obtained in the event runoff volume experiments. Overland flow routing lengths were divided into two segments with properties corresponding to concrete impervious surfaces and to predevelopment conditions, respectively.

The generated storm hydrographs for 24-hour design storms with two-year and 100 year return periods are shown in Figure 6. In these hydrographs, the expected impacts of urbanization are apparent, including increased total runoff volume, increased peak discharges, increased duration of high flows, and reduced time to peak runoff. For the two-year storm, peak discharges after urban development are significantly greater than for the predevelopment case, due to the significant increases in storm event runoff (see Figure 5). However, the peak discharge for the low development case is only 60 percent of that for the high impact case. Still, the efficacy of low impact techniques decreases with storm size. For the 100-year design storm, mitigation ability is almost negligible. This suggests, for Ralston Creek, that small, frequent events may be well controlled by infiltration based storm water management, while larger, less frequent events may still require additional flood management strategies to reduce flooding impacts for the relatively rare, large volume rainfall events.

One-Dimensional Water Budget

The final set of experiments uses the UNSAT-H model, which models the one-dimensional flow of water, vapor, and heat in soils (Fayer, 2000). The primary goal of these experiments was to model a more comprehensive water budget, including precipitation, evaporation, plant transpiration, soil water storage, and deep soil drainage. The predevelopment case was modeled using UNSAT-H alone to represent a homogeneous area covered by vegetation.

For the high impact case, the pervious areas were modeled with UNSAT-H, while the impervious areas were modeled using a simple bucket model developed to model interception and surface storage, allowing for evaporation from impervious surfaces. These models were run in parallel, combining outputs as an area weighted average.

To model the low impact case, the bucket model was run first to simulate the impervious response. Then, after combining the impervious runoff with the pervious area precipitation, UNSAT-H was used to model the pervious runoff response. Other outputs were combined as area weighted averages. For all cases, "average" soil properties from Ralston Creek

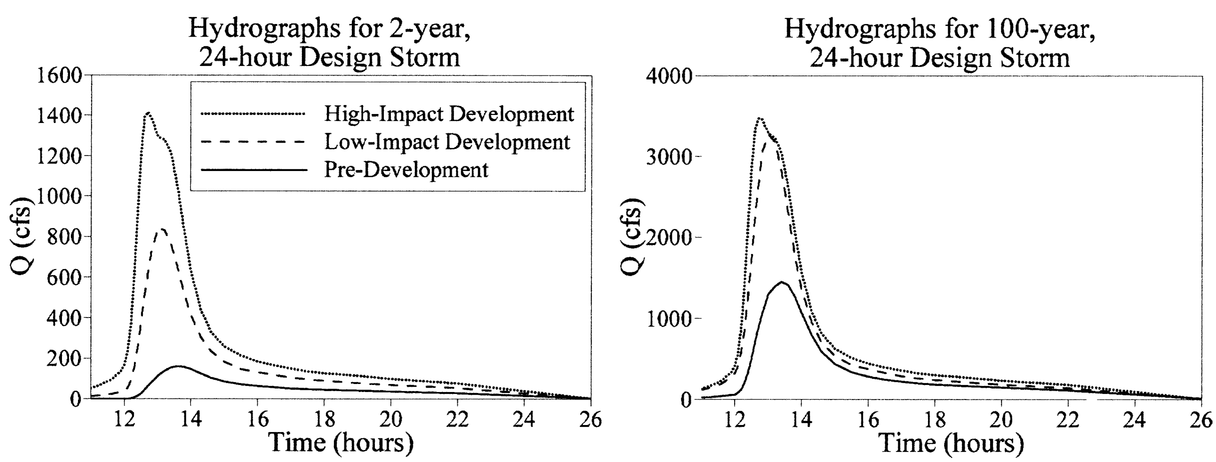

Figure 6. Simulated Storm Hydrographs for North Branch Ralston Creek for the Two-Year (24-hour rainfall depth of 3.06 inches) and the 100-Year (24-hour rainfall depth of 7.13 inches) Design Storms.

were used, along with a 20-year continuous record of meteorological inputs.

The division of the precipitation inputs into direct runoff, evapotranspiration, and recharge (deep soil drainage) for the 20-year simulation period for these three scenarios is summarized in Figure 7. From this figure, we can see that total runoff is almost tripled, while evapotranspiration and deep soil drainage are reduced for traditional storm water management schemes. As in the previous experiments, the low impact strategies are able to reduce direct runoff compared with the high impact case, but direct runoff remains nearly double that of the undeveloped case.

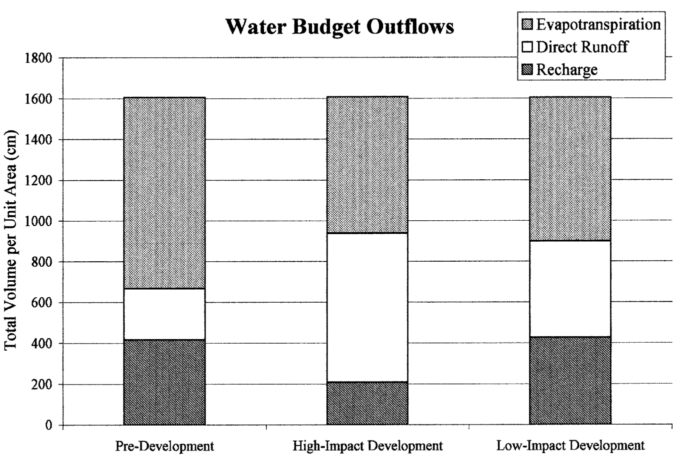

Figure 7. One-Dimensional Water Budget Outflows. Outflows are equal to total precipitation less\ any net gain in soil moisture storage.

While the division of the total water budget provides some insight, we also need to examine the frequency and timing of runoff as well. Figure 8 shows the exceedance probability for daily direct runoff conditioned on the occurrence of measurable precipitation for the day in the North Branch Ralston Creek basin. This shows that exceedance probabilities increase significantly for all sizes of runoff events as development occurs. Although the high impact scenario increases the exceedance probability for all sizes of runoff events, the largest increases are seen for the smaller runoff depths. Similarly, these are the storms for which the low impact scenario gives the greatest benefits in reducing runoff occurrence.

Changing the distribution of storm and base flows also has implications for the sediment transporting capabilities of a stream. We can combine flow duration information from the one-dimensional model with a theoretical sediment rating curve by assuming a simple power relationship between stream sediment load (mass per day), L, and discharge, Q, of the form

$$L = aQ^b \tag{1}$$

where a and b are regression coefficients (Shen and Julien, 1993). In this regression, the coefficient b is dimensionless, ranges from 1.0 for the finest sediment size classes to 2.5 to 3.0 for sand sized sediment, and is typically about 1.5 to 1.7 if all sediment size fractions are considered (Andrews, 1986). Since the coefficient a is dependent on units selected and can vary over several orders of magnitude, we report our results as L/a as shown in Figure 9 for the three scenarios using flow duration probability estimated from the 20-year daily simulated flows. This allows us to compare relative sediment transporting ability of the scenarios without specifying the units for the sediment load.

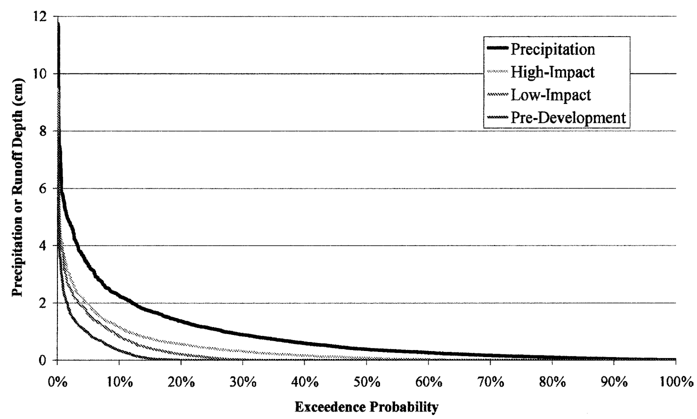

Figure 8. Exceedance Probability for Direct Storm Runoff From One-Dimensional Modeling, Conditioned on Measurable Daily Precipitation.

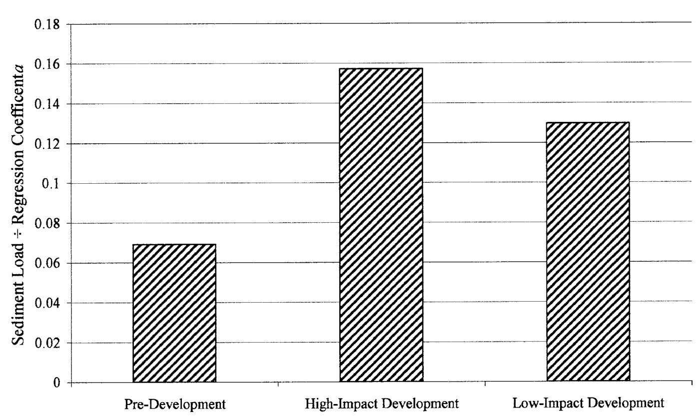

Figure 9. Relative Average Annual Stream Sediment Load for Each Scenario. Sediment load has been computed for discharge in daily volume per unit area (cm).

In this figure we see a significant increase in sediment carrying capacity for the traditional development scenario. While this increased capacity may be initially satisfied by an increased supply of sediment due to erosion in conjunction with urban construction, eventually this will lead to bed and bank erosion, and possibly an unstable channel cross section. In contrast, the increases seen in the low impact case are smaller since direct storm runoff has been reduced. Note, however, that this analysis does not consider the effects of storm water detention, which is utilized in urban settings to reduce peak discharges. This results in lower peak discharges, but a longer period with high flows, which would tend to reduce the estimated sediment load for both low and high impact development cases.

DISCUSSION

Overall Results

When looking at these three groups of experiments as a group, a number of conclusions may be drawn. First, it appears that the degree of urbanization impact, as well as the potential for mitigation by means of infiltration, is dependent on soil texture. This suggests that it may be valuable to incorporate storm water management into the planning process by careful placement of zoning areas within a watershed. For example, areas of a basin with less pervious soils would be more appropriate for commercial or industrial development, where there is a greater fraction of impervious cover and where it may be more difficult to reroute runoff onto pervious areas.

At a smaller scale, it may be possible to plan the layout of residential areas to best capitalize on existing drainage paths and infiltration patterns. For example, in many basins, the more pervious soils tend to be in the upland areas, while riparian areas are less pervious. This suggests that directly implementing infiltration zones into riparian buffer zones would not be a workable solution. Instead, storm water needs to be managed where it falls, distributed throughout the catchment as numerous, small systems. This idea has also been noted with regard to storm water detention systems (Konrad and Burges, 2001). However, this is not to suggest that riparian buffer zones do not provide other valuable watershed functions including floodplain storage and limited filtering effects in wetlands.

Furthermore, both the urbanization impacts and mitigation ability are strongly dependent on storm size. For smaller rainfall events, urbanization causes relatively greater impacts, while mitigation ability offers relatively larger benefits. However, these are the events that are seen most frequently and account for the largest fraction of total rainfall volume as shown in Figure 10. This figure shows that a one-inch daily rainfall is exceeded only approximately 9 percent of the time and accounts, on average, for about 62 percent of total rainfall. As shown in Figure 4, for events less than one inch, low impact design is able to fully compensate for development for high infiltration capacity soils and to significantly reduce runoff for the lowest infiltration capacity soils, compared with traditional storm water management.

However, we do still need to consider mitigation of larger, less frequent events. Because the larger flood events result from intense precipitation events that can often overwhelm infiltration capacity even in undeveloped areas, changes in land cover will have a relatively smaller impact on the severity of these events. Thus, it will still be necessary to develop strategies for reducing flooding impacts, possibly including local or regional detention or more restrictive floodplain management and zoning.

Experimental Limitations

In considering the interpretation of these experimental results, one also needs to be aware of the limitations of the experimental design. For these experiments, we use typical, well established engineering tools, but we use them in ways that they were not intended to be used when they were being developed. Because of such limitations, these experimental results may not be fully valid in a strictly quantitative sense. However, such experiments are still valuable as they provide a better basic qualitative understanding of key processes. Furthermore, in the process of improving our qualitative understanding of this research problem, other important issues and future research directions are suggested.

One significant limitation of the experiment is that, in the low impact case, we assume that the runoff from the impervious areas is perfectly redistributed over the pervious landscape segments, to allow maximum opportunity for infiltration. In reality, it is more likely that some fraction of the impervious runoff will occur as concentrated flow with reduced potential for infiltration. Still, while we may be skeptical of the absolute quantitative results, we are still able to draw inferences qualitatively.

Furthermore, all of these experiments neglect important components that will need to be explored further with more sophisticated tools. For example, for these experiments, homogeneous soil properties

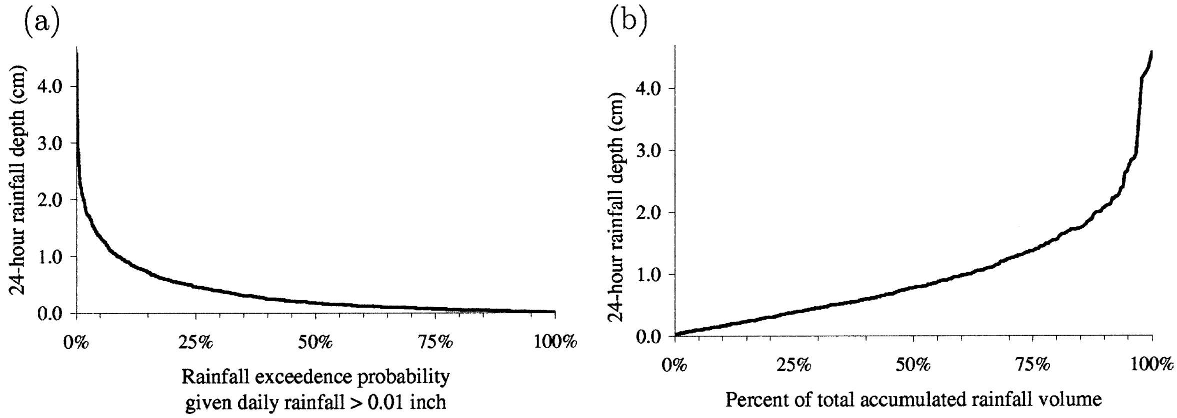

Figure 10. Summary of Daily Rainfall Totals for January 1953 to December 1972. (a) Exceedance probability conditioned on measurable daily precipitation (of the 20-year record, an average of 23 percent of days have measurable precipitation; of days with measurable rainfall, half have less than 0.18 inches and only 9 percent are greater than 1 inch). (b) Cumulative rainfall volume fraction versus daily rainfall depth (days with one-inch of rainfall or less account for 62 percent of the total rainfall volume on average).

are used. This does not consider either natural spatial variability or changes in soil properties as vegetation is established and as root structure grows and dies. This may include the development of macropores, which can radically alter infiltration properties. This is likely to be even more important when one considers modifying soil and infiltration properties in the upper area of the soil column using either deep rooted native vegetation or soil amendments. Likewise, none of these experiments addresses spatial layout, except in the most cursory of ways. It is clear that the layout and orientation of pervious and impervious areas in relation to one another will have a significant impact on infiltration patterns and runoff response.

CONCLUSIONS

In this paper, we have examined the potential for using innovative, infiltration based approaches to storm water management in urbanizing areas by comparing three basic scenarios of development: an undeveloped landscape; a fully developed landscape using traditional, high impact storm water management; and a fully developed landscape using infiltration based, low impact design. We have approached this problem using relatively simple engineering tools. While these tools may not provide a complete, quantitative understanding of the hydrologic impacts for various landuse scenarios, we have gained considerable qualitative insight into the way in which watershed processes are affected by development strategies, as well as a better understanding of the relative importance of various water budget components.

Based on these experiments, it appears that by manipulating the layout of urbanized landscapes to disconnect impervious surfaces from streams and, instead, reroute runoff from impervious surfaces across adjacent pervious surfaces, we are able to reduce impacts on hydrology relative to traditional, fully connected storm water systems. However, the amount of reduction in impact has been shown to be sensitive to both rainfall event size and soil texture, with greatest reductions being possible for small, relatively frequent rainfall events and more pervious soil textures, respectively. Furthermore, it is clear that there needs to be measures in place for flood management for larger, more intense, and relatively rarer storm events, which are capable of producing significant runoff even for undeveloped basins as soils become quickly saturated.

Although we have gained valuable insight with these relatively simple preliminary experiments, many issues remain unresolved. Questions that remain to be answered include: (1) can we provide a quantitative confirmation of results with more sophisticated modeling tools; (2) can we quantify how vegetation and soil infiltration properties interact; (3) can we provide engineering design guidance with respect to location and surface treatment of infiltration zones for urban landscape planning; and (4) can we quantify hydrologic impact based on design parameters that will satisfy municipal concerns with runoff and flooding due to urbanization?

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