DIRECTLY CONNECTED IMPERVIOUS AREAS AS MAJOR SOURCES OF URBAN STORMWATER QUALITY PROBLEMS-EVIDENCE FROM SOUTH FLORIDA

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ABSTRACT

This paper reports on early results from a US EPA sponsored project on optimization of urban wet-weather controls for managing water quality. The emphasis of this research is on micro-scale systems in order to evaluate the efficacy of decentralized controls such as on-site storage and infiltration. Micro-scale is defined as objects that are the basic components of urban parcels including roofs, streets, parking, driveways, and pervious areas. Private parcels and rights-of-way are evaluated separately. An international search for high quality wet-weather quantity and quality data led to the U.S. Geological Survey's database on South Florida. This data was collected in the 1970's for four sites: residential houses, apartments, commercial, and highway (Miller 1979). Our evaluation of this data indicates that runoff can be partitioned into two components:

- Runoff from the directly connected impervious area (DCIA) that occurs rapidly and comprises the bulk of the runoff from urbanized areas.
- Runoff from all other areas that occurs only after the soil moisture zone has reached saturation and surface ponding causes runoff. This type of runoff occurs much less frequently and is only associated with the larger storms.

The separation of these two phenomena is clearly supported by the intra-storm and storm event data. These results indicate that strong emphasis should be given to minimizing runoff from DCIA's by reducing the use of curb and gutter drainage.

INTRODUCTION

The purpose of this paper is to quantify the sources of urban runoff from the smaller storms that have the largest impact on urban stormwater quality. Data from four sites in South Florida are used to develop separate rainfall-runoff relationships for directly connected impervious area (DCIA) and the other area (OA). These calibrated relationships are used to run a 50-year simulation using hourly data for Miami, Florida to estimate the percentage of total runoff that comes from DCIA and OA. Based on these findings, recommendations are made regarding drainage design and evaluation practices for Florida and other areas.

Study Sites

The four study sites in South Florida, shown in Table 1, are used to evaluate rainfall-runoff relationships and how they are affected by DCIA. An international search for high quality wet-weather quantity and quality data led to the U.S. Geological Survey's database on South Florida. This data was collected in the 1970's for four sites: residential houses, apartments, commercial, and highway (Miller 1979). It remains one of the best databases in the world for evaluating rainfall-runoff relationships. DCIA ranges from a low of 5.9 % for the low-density residential area to 98.0 % for the commercial area. The number of storm events sampled varied from 16 to 27.

Table 1. General characteristics of four study sites in South Florida (Miller 1979).

Land Use	Location	Area (ha)	Total IA	DCIA	Storms
HD Residential	Miami	5.95	70.7%	44.1%	16
LD Residential	Pompano Beach	16.51	43.9%	5.9%	25
Commercial	Ft. Lauderdale	8.26	98.0%	98.0%	27
Highway	Pompano Beach	23.59	36.2%	18.0%	25

Precipitation Patterns

The rainfall database at the Miami WSCMO Airport, Miami, Florida covers the period from August 1948 to December 2000 with a 1-hour frequency. A rainfall event is assumed to end if it hasn't rained for six consecutive hours. During this period, the total number of rainfall events was 7,204 and the depth of total rainfall was 77,809 mm. The cumulative density function for the rainfall events is shown in Figure 1. Event based rainfall depths are plotted against the percent of the rainfall events that are less than or equal to the indicated value. For example, about 91% of the rainfall events are less than or equal to 30 mm in total depth. Typical drainage designs use the 2 to 10 year recurrence interval for their evaluation. However, as is shown in Figure 1, events with a recurrence interval of less than or equal to one month comprise over 90% of the total rainfall that occurs in Miami. Thus, control of these frequent events is the most critical component of urban stormwater quality management.

Rainfall-runoff models and long-term analysis

For developing a runoff depth estimation model, runoff was analyzed as a function of rainfall using the U.S. Geological Survey's rainfall-runoff database for each study site. To calculate excess rainfall, 2.54 mm of initial abstraction (or depression storage) is assumed for both impervious and pervious area. Total runoff can be estimated by combining runoff from DCIA and other areas. The conceptual model is shown below and models developed for the four sites are presented in next section.

$$Total\ runoff = DCIA\ runoff + Other\ runoff \qquad (1)$$

$$DCIA\ runoff = \frac{DCIA}{Total\ area}(Excess\ rainfall) \qquad (2)$$

$$Other\ runoff = \mathrm{a}\,(Excess\ rainfall) + \mathrm{b} \qquad (3)$$

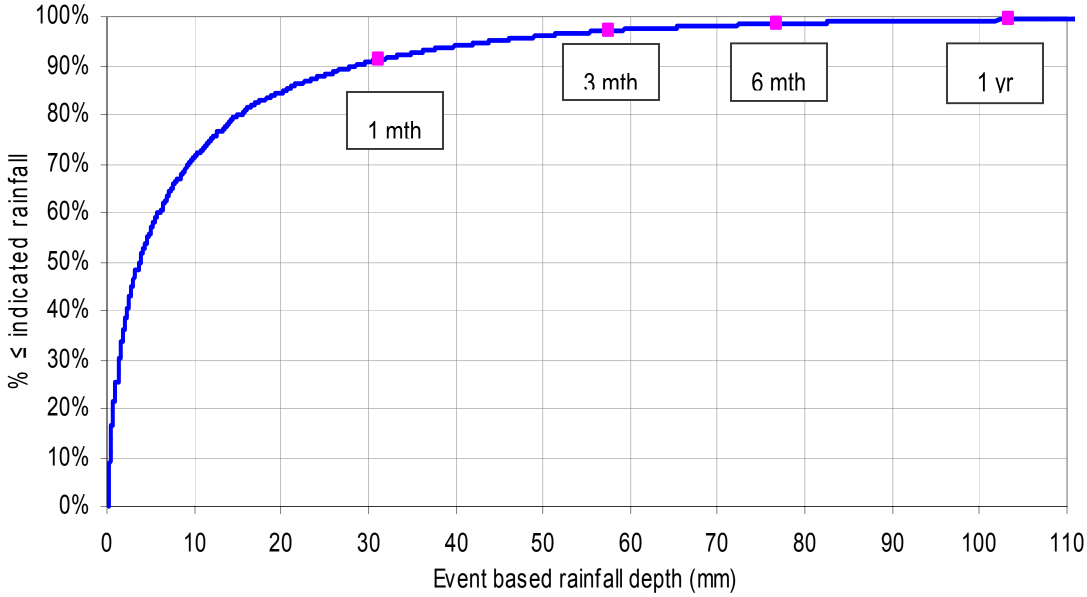


Figure 1. Event based rainfall depth in Miami, Florida:1948-2000.

About 50 years of long-term rainfall data are applied to the runoff depth estimation models. The one-hour rainfall data was collected from August 1948 to December 2000 at the Miami WSCMO Airport, Miami, Florida. The data are reported to the nearest 0.254 mm. A rainfall event is assumed to end if it hasn't rained for six consecutive hours. To calculate excess rainfall, 2.54 mm of initial abstraction is assumed for both impervious and pervious area. DCIA runoff and other runoff are estimated by developing rainfall-runoff models. The infiltration loss is calculated by subtracting the initial abstraction, DCIA runoff and other runoff from the total rainfall. A math balance equation of rainfall-loss-runoff is shown in below:

$$Rainfall = Initial\ abstraction + Infiltration\ loss + DCIA\ runoff + Other\ runoff$$

1. Residential-High Density

The Kings Creek site is a 5.95 hectare drainage basin that is part of an apartment complex in Dade County in South Florida. The impervious area is 2.62 hectares. Rainfall and runoff data for 16 storms were reported at 5 minute intervals. Key references for Kings Creek are Hamid (1995) and Hardee et al. (1979). Hamid (1995) has compared simulations using the SCS method with SWMM simulations of the study area partitioned into 13 subcatchments. Hardee (1977) presents the database for the study. The resulting rainfall-runoff relationship indicates that DCIA accounts for virtually all of the runoff for rainfalls up to about 12.5 mm. The runoff from Kings Creek was separated into two components as shown in below:

$$\textit{DCIA Runoff} = 0.441\ (\textit{Excess Rainfall}) \qquad (4)$$
$$\textit{Other Runoff} = 0.3636\ (\textit{Excess Rainfall}) - 5.542 \qquad (5)$$

The rainfall-runoff model and results of the long-term analysis are shown in Figure 2. Using the one-month rainfall of 30 mm, you see that the bulk of the runoff from 90% of the rainfall is DCIA runoff.

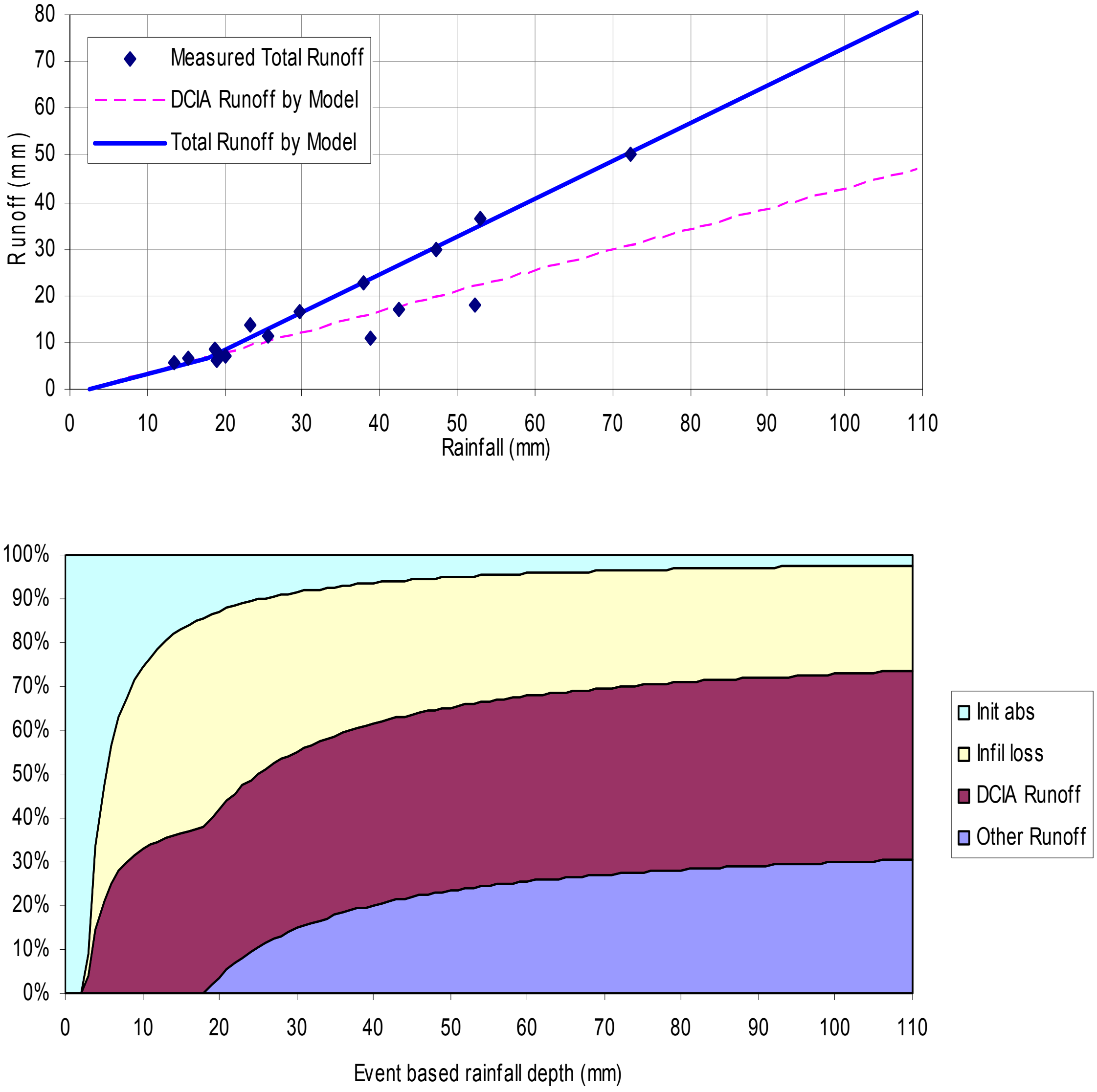


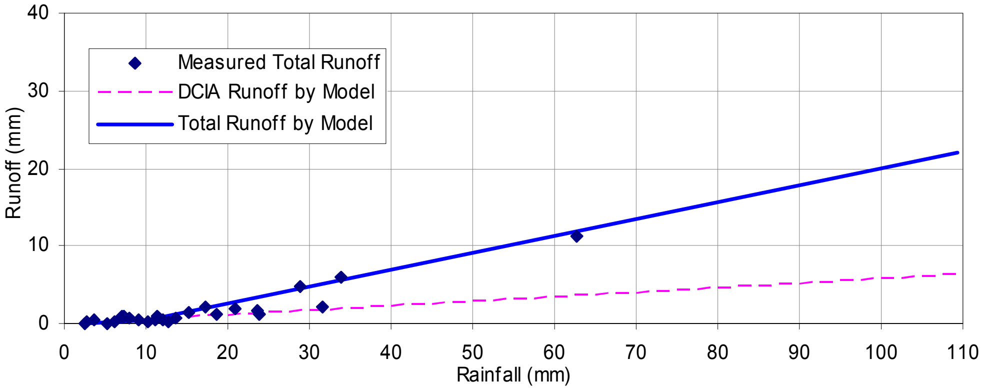
Figure 2. Rainfall runoff relationship and long-term analysis at the high density residential site in Miami, Florida.

2. Residential-Low Density

The low-density residential neighborhood has only 5.9% DCIA. It is almost exclusively swale drainage. Even in this extreme case, the runoff from storms up to about 10 mm is primarily from the DCIA. For larger storms, the other areas begin to contribute. The results are shown in Figure 3 and the runoff estimation model is shown in below:

$$\textit{DCIA Runoff} = 0.059\ (\textit{Excess Rainfall}) \qquad (6)$$

$$\textit{Other Runoff} = 0.1579\ (\textit{Excess Rainfall}) - 1.203 \qquad (7)$$



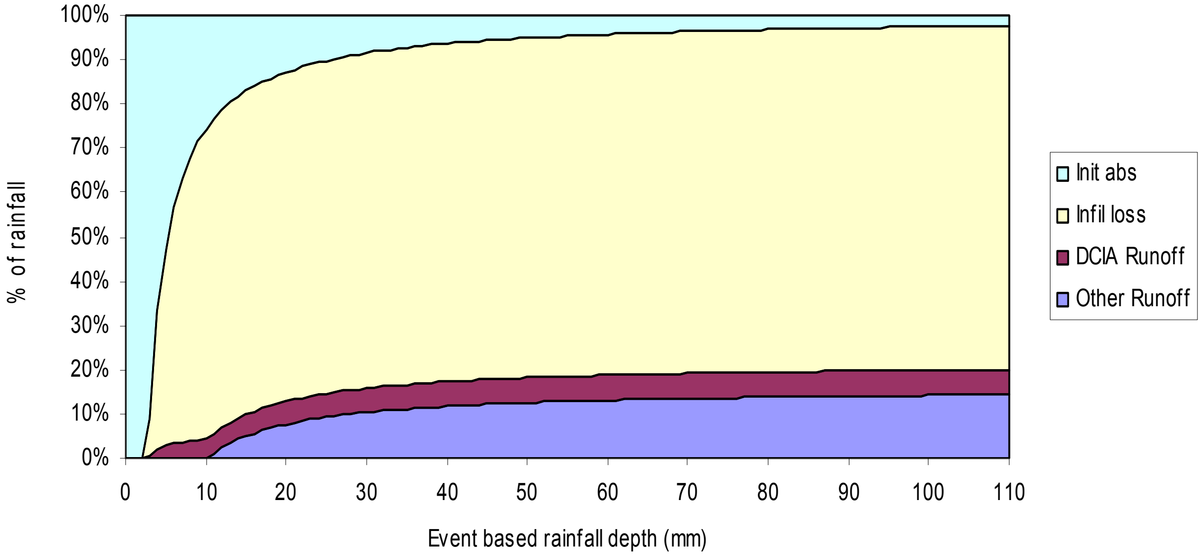


Figure 3. Rainfall runoff relationship and long-term analysis at the low density residential site in Pompano Beach, Florida.

3. Commercial Site

The results for the commercial area with a very high DCIA of 98% indicate virtually a one to one relationship between rainfall and runoff. The results are shown in Figure 4. They indicate a simple rainfall-runoff response with no significant infiltration due to the complete DCIA system.

$$\textit{DCIA Runoff} = 1.0\ (\textit{Excess Rainfall}) \tag{8}$$

$$\text{Other Runoff} = 0.0 \tag{9}$$

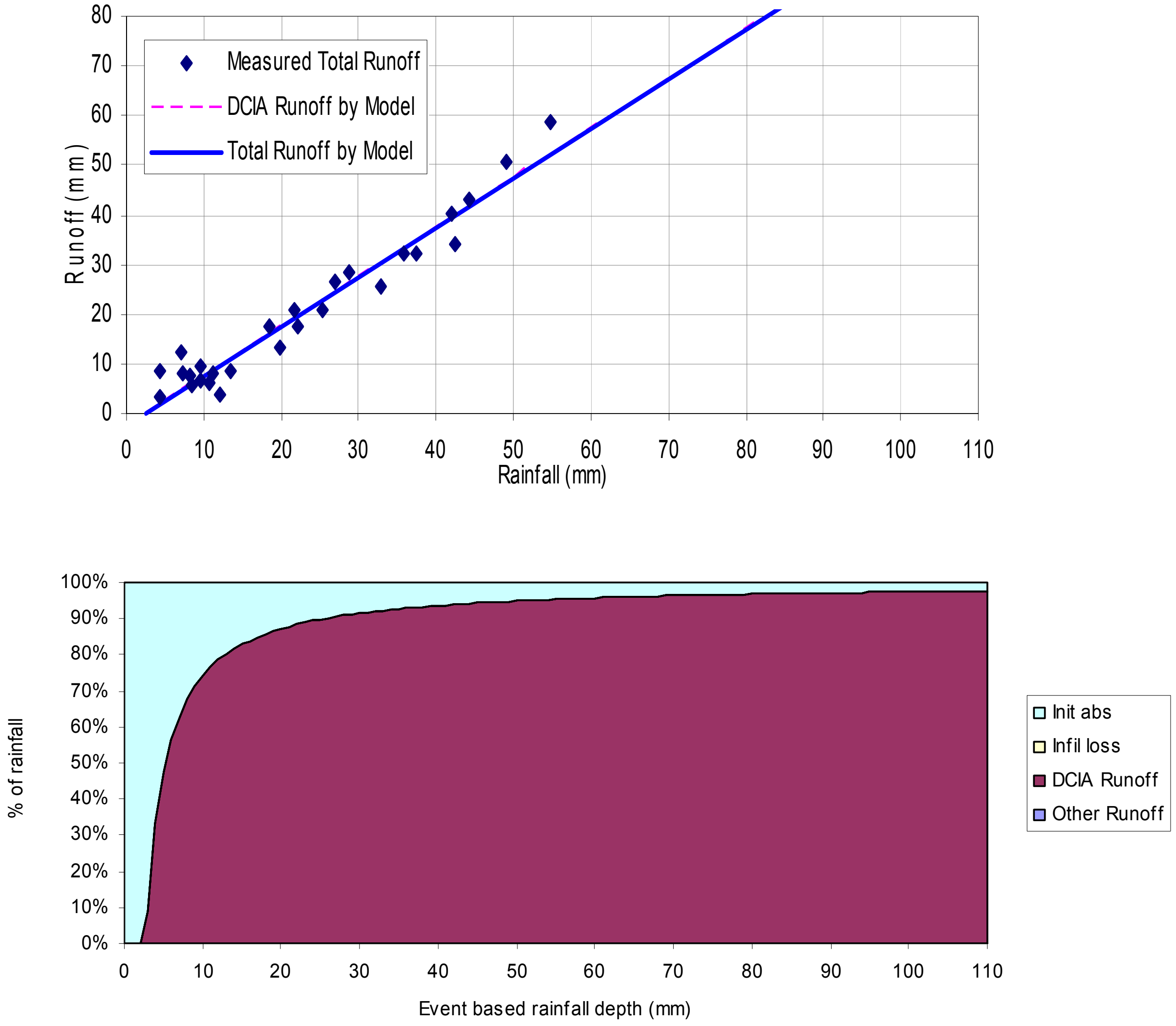


Figure 4. Rainfall runoff relationship and long-term analysis at the commercial site in Fort Lauderdale, Florida

4. Highway Site

Rainfall and runoff data are available for 25 storm events for the highway runoff site in Pompano Beach, Florida. The highway site is partially curb and gutter and partially swale drainage. Using DCIA only to estimate the rainfall-runoff relationship provides nearly identical results as one gets when the total area and a runoff coefficient are used. The results are shown in Figure 5. The non-DCIA area begins to contribute runoff for larger rainfalls only.

$$\textit{DCIA Runoff} = 0.180\ (\textit{Excess Rainfall}) \tag{10}$$

$$\textit{Other Runoff} = 0.0636\ (\textit{Excess Rainfall}) - 0.485 \tag{11}$$

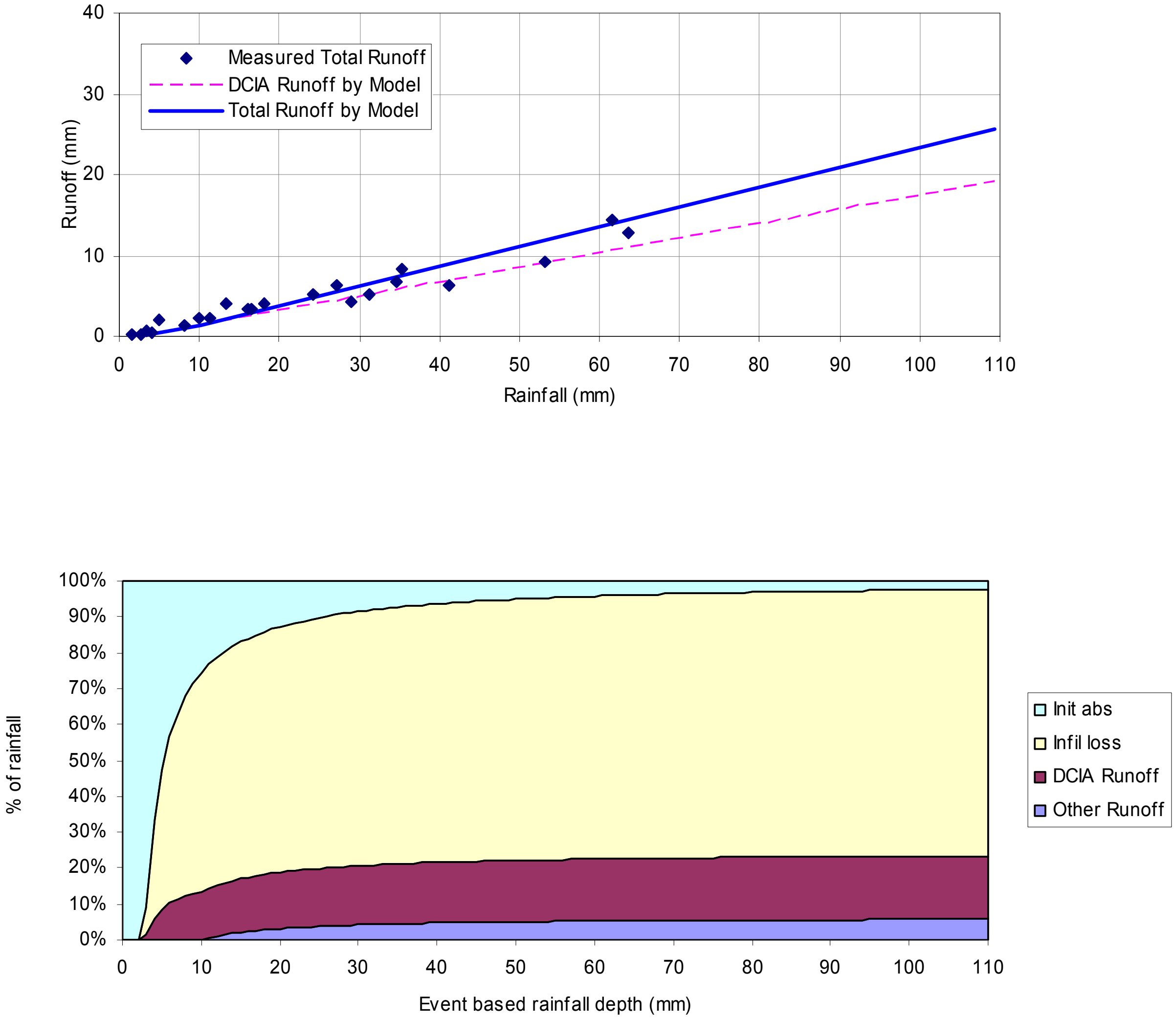


Figure 5. Rainfall runoff relationship and long-term analysis at the highway site in Pompano Beach, Florida.

Summary of long-term rainfall-runoff analysis for the entire period

The results of long-term rainfall-runoff analysis are summarized in Table 2 for the entire period. A total of 7,204 precipitation events occurred during this 52.4 year period. About 43 % of these events are less than or equal to 2.54 mm. Runoff from non-DCIA areas occurs only for the larger storms. The statistics for the runoff events are shown in Table 3. They indicate that 50 to 100 percent of the runoff is from the DCIA. The relative importance of each land use in terms of depth is shown in Table 4. DCIA runoff exceeds other runoff for all of the sites except the low-density residential site. The disproportionate importance of DCIA is evident in Figure 6. For example, while DCIA represents about 6% for the low density residential, it contributes about 36% of the total runoff. Similarly, over 80% of the highway runoff is from DCIA even though it is only 18% of the total area.

Table 2. Summary of results based on rainfall events.

	HD Residential	LD Residential	Commercial	Highway
Total Events	7,204	7,204	7,204	7,204
No Runoff	43.1%	43.1%	43.1%	43.1%
DCIA Runoff only	39.8%	28.7%	56.9%	28.7%
Runoff from everywhere	17.1%	28.1%	0.0%	28.1%

Table 3. Summary of results based on runoff events.

	HD Residential	LD Residential	Commercial	Highway
Runoff Events	4,098	4,098	4,098	4,098
DCIA Runoff only	70.0%	50.5%	100.0%	50.5%
Runoff from everywhere	30.0%	49.5%	0.0%	49.5%

Table 4. Summary of results based on rainfall depth.

	HD Residential	LD Residential	Commercial	Highway
Rainfall (mm)	77,809	77,809	77,809	77,809
Init. Abs.	17.6%	17.6%	17.6%	17.6%
DCIA Runoff	36.3%	4.9%	82.4%	14.8%
Other Runoff	14.0%	8.5%	0.0%	3.4%
Infiltration	32.1%	69.0%	0.0%	64.1%

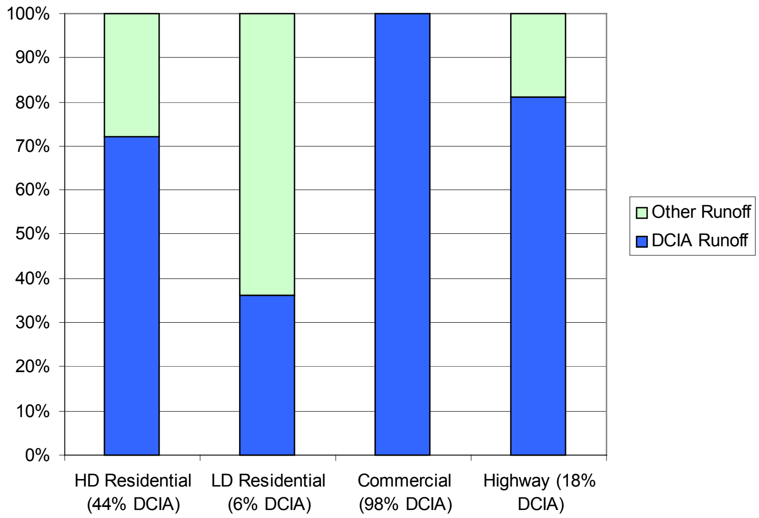


Figure 6. Summary of results based on runoff depth.

Use DCIA to Estimate Water Quality Impacts?

The oldest and still most widely used method for storm drainage design is the Rational Method (Mays 2001). The method was firstly introduced by the Irish engineer Mulvaney (1850), the American Kuichling (1889), and the British Lloyd-Davies (1906). While Mulvaney worked on agricultural areas, Kuichling and Lloyd-Davies described rainfall-runoff relationships in urban area. The basic assumptions of the Rational Method are that the rainfall intensity during the time of concentration is steady, and the frequency of peak runoff and the rainfall causing it are the same. While the American Rational Method uses the runoff coefficient according to rainfall characteristics and total land area ($Q_p = CiA$), the British Lloyd-Davies method only considers 100 percent runoff from the directly connected impervious area (DCIA) ($Q_p = iA_{DCIA}$). The results of this analysis indicate that the decision to convert land into DCIA has the greatest impact on stormwater runoff from the frequent events that are of concern in protecting water quality. Alternatively, minimizing DCIA is a very good way to protect stormwater quality. Current evaluation methods do not make this vitally important distinction between impervious area and directly connected impervious area. They also rarely separate out the right of way area as a separate land use even though it is the cause of most of the DCIA.

CONCLUSIONS

The purpose of this paper is to evaluate the importance of directly connected impervious area (DCIA) in generating urban runoff from the smaller events that are most critical for urban wet-weather flow management. Rainfall-runoff data from four sites in South Florida were evaluated. The results indicate that virtually all of the runoff from smaller storms is from DCIA. Even for larger storms it is a primary source of stormwater. This DCIA runoff moves relatively rapidly to the nearby receiving water with little or no attenuation of its pollutant load. Thus, the decision to use DCIA instead of other drainage options has a profound effect on urban storm water quality.

ACKNOWLEDGEMENTS

This study was made possible because of the high quality data collected by the USGS in South Florida as part of the Nationwide Urban Runoff Program (NURP) over 25 years ago. It remains one of the best databases in the world for evaluating the impact of urbanization on urban stormwater quality. We thank the USGS team for their excellent work. Members of the USGS team include Jack Hardee, Ron Miller, and Hal Mattraw.

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