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ORIGINAL ARTICLE

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Impact of urbanization on storm response of White Rock Creek, Dallas, TX

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Abstract This study documents hydrological changes resulting from urbanization of the upper sub-basin of White Rock Creek watershed in Collin and Dallas counties, Texas. The 172-km^2 watershed was transformed from 87% rural in 1961 to 95% urban in 2002, following construction of the Dallas suburbs of Richardson, Addison, Plano and Frisco. The objective of the study was to investigate changes in the storm response of White Rock Creek in terms of peak storm flow, storm flow volume and lag time. The approach employed to compare pre- and post-urbanization hydrology was to develop average unit hydrographs for each time period and use them to generate the creek's storm flow response to a set of six hypothetical precipitation events. The results suggest that substantial hydrological changes have occurred. The average infiltration capacity of the watershed was reduced by about 60% so that storm flow was generated at lower precipitation intensities in the post-urbanization period. Storm flow peak discharge and volume were more than doubled for a hypothetical 10-year precipitation event. Average lag time was about 49 min shorter in the post-urbanization period. Urbanization has significantly impacted the storm response of the creek and increased the potential for flooding. It is anticipated that similar hydrological changes will occur in other rapidly urbanizing watersheds in the Dallas-Fort Worth Metropolitan region. Watershed managers should take likely changes in storm response into account when planning future storm water management needs.

Keywords Unit hydrograph · Storm flow · Infiltration capacity · Urban growth · Texas Denton County USA · White Rock Creek

Introduction

Urbanization changes hydrological processes within watersheds by altering surface infiltration characteristics, introducing storm drainage systems and by artificial channelization of streams. Replacement of soil and vegetation by concrete and asphalt reduces infiltration and promotes surface runoff; storm drains and channelization move runoff more rapidly to and through channel networks. The expected results of these changes include decreased lag times, increased storm flow volumes and increased peak flows (Fig. 1). The consequence within, and downstream of, urbanized watersheds, is a potential for more frequent and severe flooding due to higher peak flows. This study documents hydrological changes resulting from urbanization of the upper sub-basin of White Rock Creek watershed in Collin and Dallas counties, Texas.

Study area

The 172-km^2 upper sub-basin of White Rock Creek watershed was transformed from 87% rural in 1961 to 95% urban in 2002 (Ollman 1969; North Central Texas Council of Governments 2002; Fig. 2). Hourly stream flow (m^3/s) and precipitation data (in cm/h) for the 1960s were obtained from United States Geological Survey (USGS) stream discharge gauge 08057200 and precipitation gauge 9W, both located at the intersection of White Rock Creek and Greenville Avenue, Dallas. These data were compiled in the report, "Hydrology Data for Urban Studies in Dallas, Texas" (United States Geological Society Water Resources Division, 1961–1968). Hourly precipitation data for the 2000s were obtained from a National Oceanic and Atmospheric Administration (NOAA) precipitation gauge located at Love Field Airport, Dallas (approximately 6 km west of the stream gauging station) (NOAA 2005). Hourly stream flow data for the 2000s were obtained from USGS stream discharge gauge 08057200 located on White Rock Creek, the same gauge used to record the 1960s stream flow data.

Methods

Lag times

Lag times were derived from the initial hydrographs and were defined as the time from the center of mass of precipitation (time when half the precipitation had fallen) to the peak stream flow (peak flow was assumed to occur in the middle of the hour when the highest flow was recorded, i.e., if the highest flow occurred in 15 h, it was assumed that peak flow occurred at 15.5 h (Fig. 1).

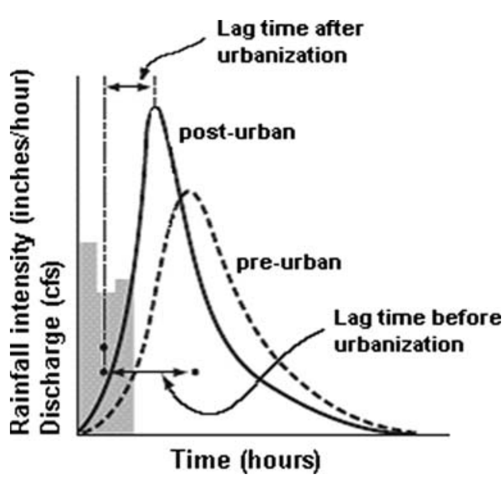

Fig. 1 Conceptual changes in hydrograph following urbanization (modified from Leopold 1968)

Unit hydrographs

The approach employed to compare pre- and post-urbanization storm response of White Rock Creek was to develop average unit hydrographs for the time periods 1961–1968 and 2002–2004 and use them to model the creek's storm flow response to a set of six hypothetical storm events. Changes in the hydrological response of the watershed between the two time periods cannot be based on individual storms (even if of approximately the same duration and precipitation amount), because other factors that influence the watershed's response are unlikely to be equal; for example, antecedent soil moisture, temperature, wind speed and season). The rationale for using average unit hydrographs is that when the response to storms of exactly the same duration and precipitation amount are modeled, and the effects of other factors such as antecedent soil moisture, are also averaged, the model output is presumably a better representation of the "typical" or "average" hydrological response of the watershed than an individual storm.

A unit hydrograph results from one inch (2.54 cm) of infiltration-excess precipitation (or surface runoff) generated by a storm of a given duration; for example, 2.54 cm of infiltration-excess precipitation generated by a storm that lasts 3 h would be a 3-h unit hydrograph. Part of unit hydrograph theory is that there is a threshold precipitation intensity that must be surpassed in order for surface runoff to be generated—this threshold is the infiltration capacity of the watershed. The steps used to derive a unit hydrograph are: (1) separate base flow from storm flow using the semi-log-plot method described by Wilson (1974), (2) calculate depth of infiltration-excess precipitation by dividing the total storm flow volume by the area of the watershed, (3) divide the storm hydrograph ordinates by the depth of infiltration-excess precipitation to derive a unit hydrograph (Fig. 3). This method also yields the infiltration capacity of the watershed, which is the threshold value used to derive infiltration-excess precipitation (Table 1).

To be selected for analysis, storms had to produce significant storm flow (a peak stream flow of at least 25 m^3/s was the arbitrary minimum) and could not be bimodal (the hydrograph recession limb had to continually recede). Five storms in the 1960s and five storms in the 2000s met these criteria. Unit hydrographs were derived for each storm, which also produced a calculated value of the unit hydrograph duration and the infiltration capacity of the watershed (Table 2).

There is considerable variability in infiltration capacity within each time period. This most likely results from differences in antecedent soil moisture preceding each storm. A z-test for comparison of two sample

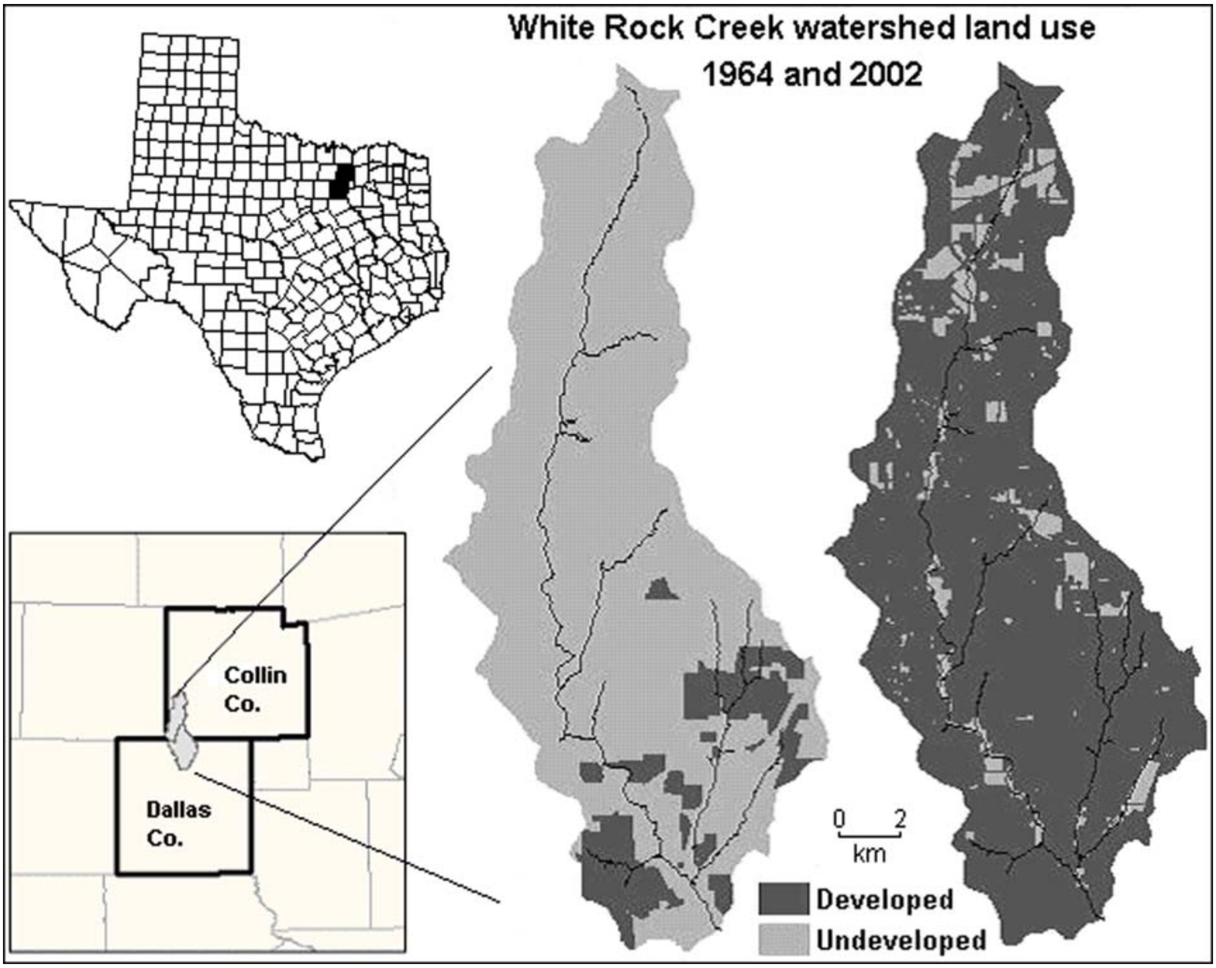

Fig. 2 Location of the upper sub-basin of White Rock Creek watershed (north of Greenville Avenue) in north-central Texas and extent of urbanization in 1964 and 2002

means indicates that the difference in average infiltration capacity between the two time periods is significant at the 94% confidence level.

Because the 10 unit hydrographs had durations varying from 1 to 5 h, the *S*-curve technique (Chow et al. 1988) was used to change all durations to an intermediate value of 3 h. The *S*-curve is developed by continually lagging a unit hydrograph by its duration and adding the ordinates. For example, an *S*-curve developed for the 1-h unit hydrograph derived from the April 28th 1966 storm was lagged by 3-h. The difference between the two curves is a hydrograph representing 7.62 cm of infiltration-excess precipitation occurring over 3 h (2.54 cm of infiltration-excess precipitation/h for 3 h). The ordinates of this hydrograph are divided by three to produce a 3-h unit hydrograph (Fig. 4).

The five 3-h duration unit hydrographs from each time period were then averaged to derive a "typical" or "average" unit hydrograph for each period (Fig. 5).

Modeling storm response

The average infiltration capacities (Table 2) and the average unit hydrographs (Fig. 5) were used to model the storm runoff response to a series of hypothetical storms ranging up to the 500-year flood event of 1,599 m^3/s (FEMA 2004, Table 3).

A total of six scenarios were used:

1.27 cm/h for 3 h
2.54 cm/h for 3 h
3.81 cm/h for 3 h
5.08 cm/h for 3 h
6.35 cm/h for 3 h
7.62 cm/h for 3 h

The amount of surface runoff generated by each scenario depends on the average infiltration capacity calculated for each time period; for example, scenario 3–3.81 cm/h for 3 h—would generate 1.12 cm/ h of surface runoff in the 1960s (3.81–2.69) to total 3.36 cm of surface runoff over 3 h, and 2.62 cm/h of surface runoff in the 2000s (3.81–1.19) to total 7.86 cm of

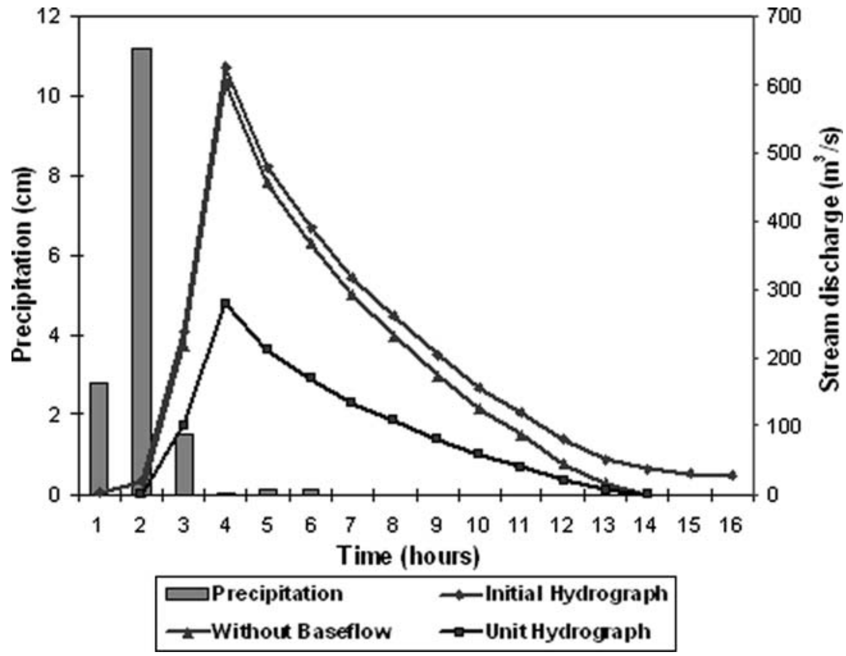

Fig. 3 Procession from initial hydrograph to storm hydrograph to unit hydrograph, for a storm occurring on April 28, 1966. In this example the total storm flow volume divided by the watershed area produces a depth of infiltration-excess precipitation of 5.46 cm. The storm flow hydrograph ordinates are divided by 5.46 to produce a unit hydrograph, representing 2.54 cm of infiltration-excess precipitation

Table 1 Derivation of infiltration capacity and unit hydrograph duration based on depth of infiltration-excess precipitation

Time (h)	Precipitation (cm)	Infiltration capacity (cm)	Infiltration-excess precipitation (cm)
1	2.79	5.69	0
2	11.18	5.69	5.49
3	1.47	5.69	0
4	0.05	5.69	0
5	0.13	5.69	0
6	0.13	5.69	0

In this example (April 28, 1966) the infiltration capacity is 5.69 cm/h and the duration of infiltration-excess precipitation is 1 h

Table 2 Storm events included in analysis, calculated unit hydrograph durations and watershed infiltration capacities

Time period	Storm events	Unit hydrograph duration (h)	Infiltration capacity (cm/h)	Average infiltration capacity (cm/h)
1960s	Nov. 22, 1961	1	2.54	1960s 2.69
	April 27, 1962	5	0.38	
	Sept. 8–9, 1962	3	1.45	
	April 28, 1966	1	5.69	
	Aug. 13–14, 1968	1	3.35	
2000s	Dec. 30, 2002	1	1.70	2000s 1.19
	April 23–25, 2003	1	2.31	
	June 11–12, 2003	3	0.10	
	Dec. 12, 2003	3	0.38	
	June 9–10, 2004	3	1.04	

surface runoff over 3 h. The ordinates of the average unit hydrographs were multiplied by the total depth of surface runoff to model storm hydrographs for each scenario. Values of storm flow volume and peak storm flow were obtained from the resulting storm hydrographs.

Results

Lag times

Average lag time decreased from 3.27 h in the 1960s to 2.45 h in the 2000s—a reduction of about 49 min (Table 4).

Although a reduction in lag times was expected, a *z*-test for comparison of two sample means indicates that the difference in average lag time is only significant at the 77% confidence level; this relatively weak significance level probably results from the small sample size and coarse resolution of the 1-h precipitation and stream flow data.

Storm flow volumes and peaks

Modeled storm hydrographs for each of the six scenarios are shown in Fig. 6. Table 5 contains storm flow volumes and peaks derived from the modeled storm hydrographs.

Because the precipitation intensities in scenarios 1 and 2 are lower than the 1960s average infiltration capacity, no surface runoff was generated and there are no storm hydrographs for the 1960s. In scenario 3, the

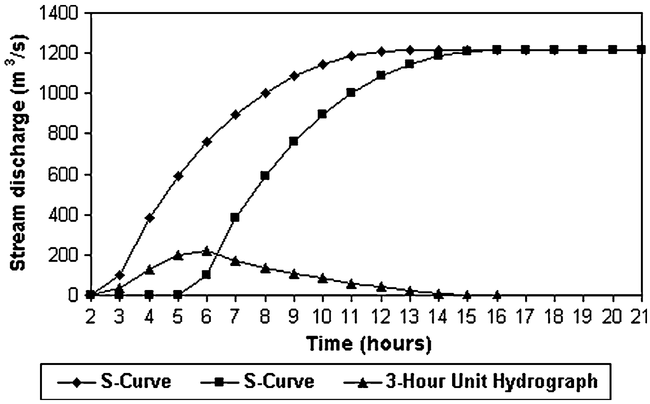

Fig. 4 A 3-h unit hydrograph derived from the April 28, 1966 storm event

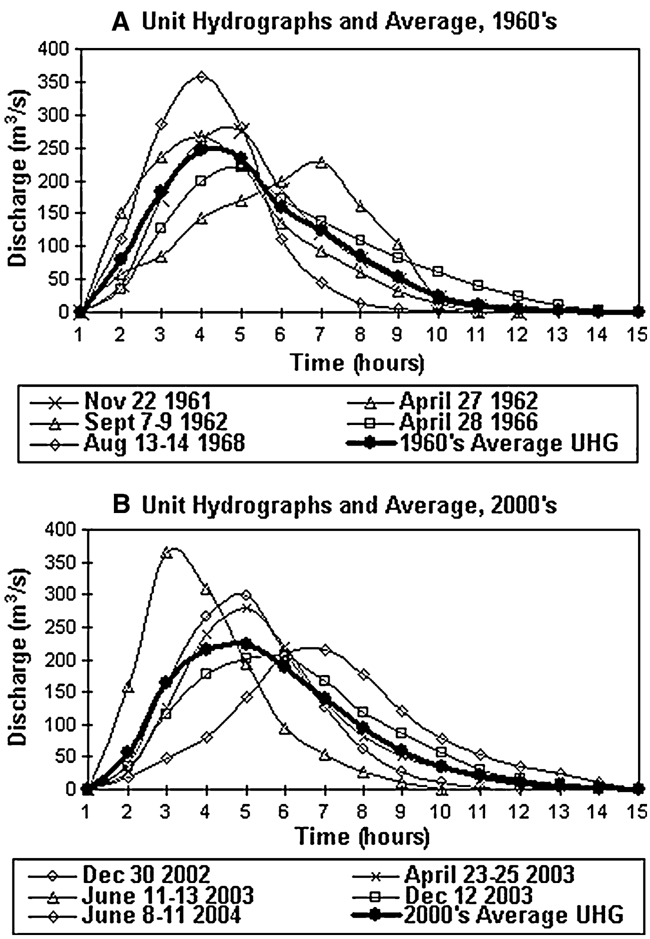

Fig. 5 **a** Unit hydrographs and average unit hydrograph in the 1960s. **b** Unit hydrographs and average unit hydrograph in the 2000s

precipitation intensity (3.81 cm/h) is greater than the average infiltration capacity for both the 2000s and the 1960s and so surface runoff and a storm hydrograph was

Table 3 Flood-frequency data for White Rock Creek watershed, 2004

Peak stream flow (m^3/s)	Flood event	Percent chance of occurrence
708	10-year	10
1,053	50-year	2
1,211	100-year	1
1,599	500-year	0.2

Table 4 Lag times derived from initial hydrographs

Storm event	Center of mass of precipitation (h)	Peak flow (h)	Lag time (h)	Average (h)
Nov. 22, 1961	6.59	9.5	2.91	1960s 3.27
April 27, 1962	5.3	10.5	5.2	
Sept. 7–9, 1962	23.19	27.5	4.31	
April 28, 1966	2.45	4.5	2.05	
Aug. 13–14, 1968	19.59	21.5	1.91	
Dec. 30, 2002	15.5	16.5	1	2000s 2.45
April 23–25, 2003	21.5	24.5	3	
June 11–12, 2003	25.63	25.5	−0.13	
Dec. 12, 2003	16.54	20.5	3.96	
June 9–10, 2004	18.06	22.5	4.44	

generated for both time periods (Fig. 6). For scenarios when storm hydrographs are generated for both time periods (scenarios 3–6), the difference in storm flow volumes between the 2000s and the 1960s stayed approximately the same (about 8,207,000 cubic meters higher in the 2000s). Differences in storm peak flows are greatest in scenario 3 (385 m^3/s higher in the 2000s) and progressively decrease, reaching a difference of 284 m^3/s (higher in the 2000s) in scenario 6 (Table 5).

Discussion

In all six hypothetical storm scenarios, both storm peak flow and storm flow volume increased in the 2000s compared to the 1960s. At lower precipitation intensities (1.27 or 2.54 cm/h), modeling produced no surface runoff for the 1960s because these precipitation intensities are below the calculated average infiltration capacity for the 1960s watershed surface. At the higher precipitation intensity of scenario 3 (3.81 cm/h), both storm flow volume and storm peak flow more than doubled in the 2000s compared to the 1960s (Table 5). This finding highlights the critical role of watershed infiltration capacity in generating a storm response. The approximately 60% reduction in infiltration capacity (from 2.69 to 1.19 cm/h) presumably was caused by the effects of urbanization.

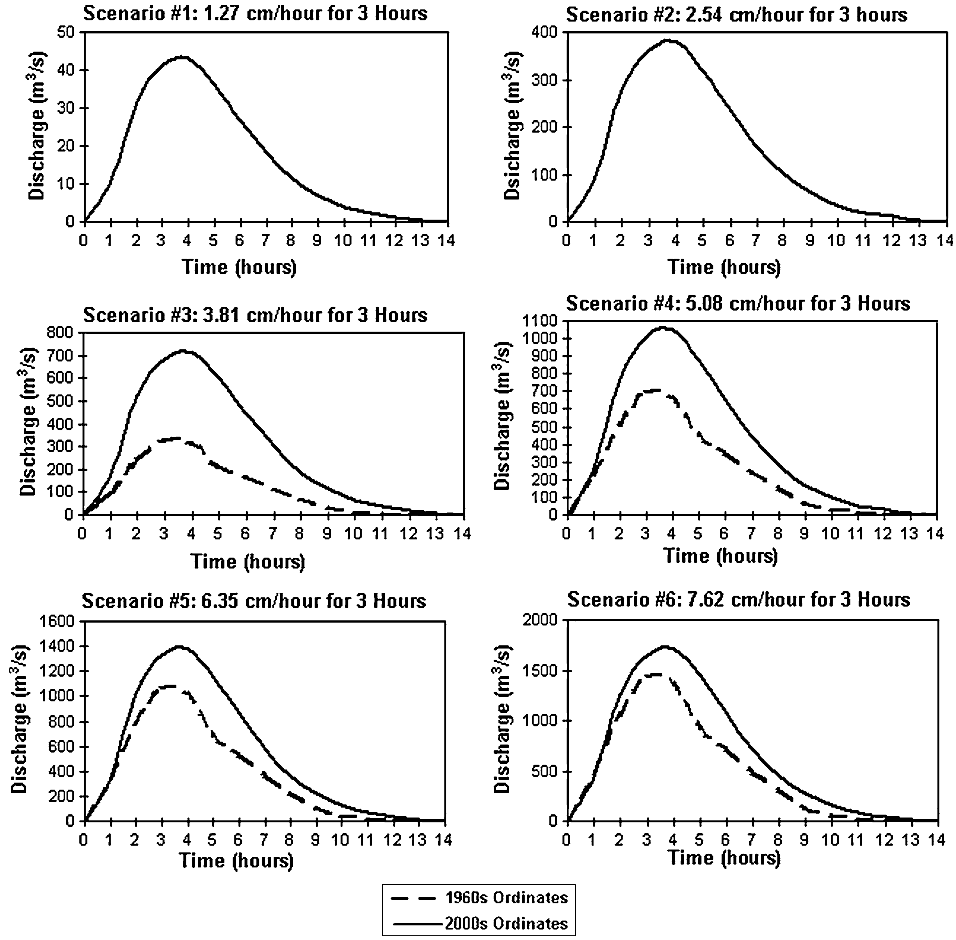

Fig. 6 Modeled storm hydrographs

At the highest precipitation intensities (scenarios 4–6) the difference in storm flow volumes between the 2000s and 1960s stays approximately constant at about 8,207,000 cubic meters. This is also a consequence of the reduction in infiltration capacity, because for any precipitation intensity that generates surface runoff in both time periods, the 2000s watershed surface will produce 1.5 cm (2.69–1.19) more depth of surface runoff than the 1960s watershed surface. Over the area of the watershed, this will produce approximately an additional 2,575,300 cubic meters of storm flow and over the 3-h duration of all scenarios, approximately an additional 8,000,000 cubic meters of storm flow volume.

The greatest difference in peak flows between the two time periods occurs in scenario 3, when the 2000s watershed produces a storm flow peak of 712 m^3/s,

Table 5 Storm flow volumes and peaks resulting from the six hypothetical storm scenarios

Scenario #	Time period	Storm flow volume (m^3)	Difference (2000s–1960s)	Peak storm flow (m^3/s)	Difference (2000s–1960s)
(1) 1.27 cm/h	1960s	0	841,333	0	43
	2000s	841,333		43	
(2) 2.54 cm/h	1960s	0	7,389,690	0	378
	2000s	7,389,690		378	
(3) 3.81 cm/h	1960s	5,780,103	8,157,945	327	385
	2000s	13,938,048		712	
(4) 5.08 cm/h	1960s	12,289,229	8,197,176	695	352
	2000s	20,486,405		1,047	
(5) 6.35 cm/h	1960s	18,798,354	8,236,408	1,063	318
	2000s	27,034,762		1,381	
(6) 7.62 cm/h	1960s	25,307,480	8,275,640	1,431	284
	2000s	33,583,120		1,716	

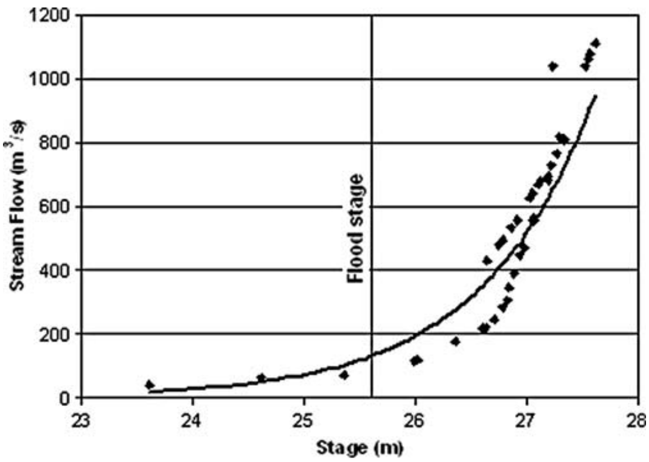

Fig. 7 Relationship between stream flow and stage, 1962–2005

equivalent to a 10-year storm event in 2004 (Table 3). This flow is 385 m^3/s higher than the peak flow for the 1960s (327 m^3/s), a 118% increase. Storm flow peaks converge at higher precipitation intensities, so that by scenario 6 (equivalent to a 500-year storm event in 2004), the peak storm flow for the 2000s is only about 20% higher than the peak storm flow for the 1960s (1,716 m^3/s compared to 1,431 m^3/s, Table 5).

Higher storm peak flows in the 2000s increase the potential for flooding. At USGS stream discharge gauge 08057200, flood stage is 25.6 m (USGS, 2006; gauge datum is 122 m). Based on stream flow and stage data from 1962–2005, flood stage is exceeded at flows above about 142 m^3/s (Fig. 7). The study findings suggest that flooding will occur at lower intensity precipitation in the 2000s and that the height of flooding will be greater at higher intensity precipitation. For example, under scenario 3, the 1960s peak storm flow of 327 m^3/s produces a depth of flooding about 0.91 m above flood stage, but the 2000s peak storm flow of 712 m^3/s produces a depth of flooding about 1.83 m above flood stage (Table 5, Fig. 7).

Conclusions

Results suggest that urbanization profoundly impacted storm response of White Rock Creek, more than doubling peak discharge and storm runoff volume for a hypothetical 10-year storm event. Average lag time decreased by about 49 min, although the confidence level of this finding is relatively low, probably reflecting the small sample size and coarse resolution of the data. The increase in peak flows implies that the potential for flooding has also significantly increased. The results indicate that flooding occurs at lower precipitation intensities in the 2000s and reaches a greater height at higher intensities, compared to the 1960s. A critical factor highlighted by the study is the importance of the watershed's infiltration capacity. The findings suggest it was reduced by about 60% between the 1960s and 2000s, presumably due to urbanization. Many other watersheds in North Texas are undergoing rapid urbanization; these watersheds should also be expected to undergo substantial changes in storm response and flooding potential. Plans for storm water management in these watersheds should take into account likely changes in storm response of streams following urbanization.

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