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Urban transformation of river landscapes in a global context

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Abstract

Over the past 50 years considerable progress has been made in understanding the impacts of urban development on river processes and forms. Such advances have occurred as urban population growth has accelerated around the world. Using a compilation of research results from more than 100 studies conducted in a range of areas (58 addressing morphological change), this paper describes how urbanization has transformed river landscapes across Earth's surface, emphasizing the distribution of impacts in a global comparative context. Urban development induces an initial phase of sediment mobilization, characterized by increased sediment production (on the order of 2–10 times) and deposition within channels, followed by eventual decline that couples with erosion from increased runoff to enlarge channels. Data from humid and temperate environments around the world indicate that channels generally enlarge to 2–3 times and as much as 15 times the original size. Although research has emphasized temperate environments, recent studies of tropical areas indicate a tendency for channel reduction resulting from strong sediment erosion and deposition responses because of intense precipitation and highly weathered soils. Embryonic research in arid environments further suggests variable river responses to urbanization that are characterized by rapid morphological change over short distances. Regardless of location, the persistence of the sediment production phase varies from months to several years, whereas several decades are likely needed for enlarging channels to stabilize and potentially reach a new equilibrium. Urbanizing streams pose particular challenges for management given an inherent changing nature. Successful management requires a clear understanding of the temporal and spatial variations in adjustment processes.

Keywords: Urbanization; Channel adjustments; Stream equilibrium; River management

1. Introduction

A half century has passed since scholars convened at the International Symposium on "Man's Role in Changing the Face of the Earth" and cast sharp focus on the reality of human impacts on Earth systems (Thomas, 1956). The question explored at the symposium was: "What has been, and is, happening to the earth's surface as a result of (humans) having been on it for a long time, increasing in numbers and skills unevenly, at different places and times?" (Fejos, 1956). In relation to river landscapes, Strahler (1956) outlined erosion and aggradation as system responses when steady state is upset by human activity, and Leopold (1956) connected changes in sediment yield, driven by land-use changes, to adjustments in river channels. Significant advances have been made along those lines in the years since, with intensified research efforts producing a voluminous literature that documents a range of human impacts on fluvial geomorphology in general, and on river channels in particular (Gregory, 1977a, 1987a,b, 2006-this volume).

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This paper assesses the progress made on understanding the impacts of urban development on river landscapes, with emphasis on the distribution of such impacts in a global comparative context. Urban development has been a major driver of change across Earth's surface, accelerating in recent decades in response to population growth (Fig. 1). In the third quarter of the twentieth century alone, urban population increased over 100% worldwide and nearly 200% in less developed regions (Gupta, 1984). These rates represent an enormous number of people increasingly living in urban areas. Whereas in 1952, the largest city in the world (New York City) had a population of less than eight million, by 2001, 17 cities had eight million inhabitants, with the largest urban area (Shanghai) exceeding a population of 14 million (United Nations, 2004). As might be expected, the development of infrastructure to accommodate expanding populations

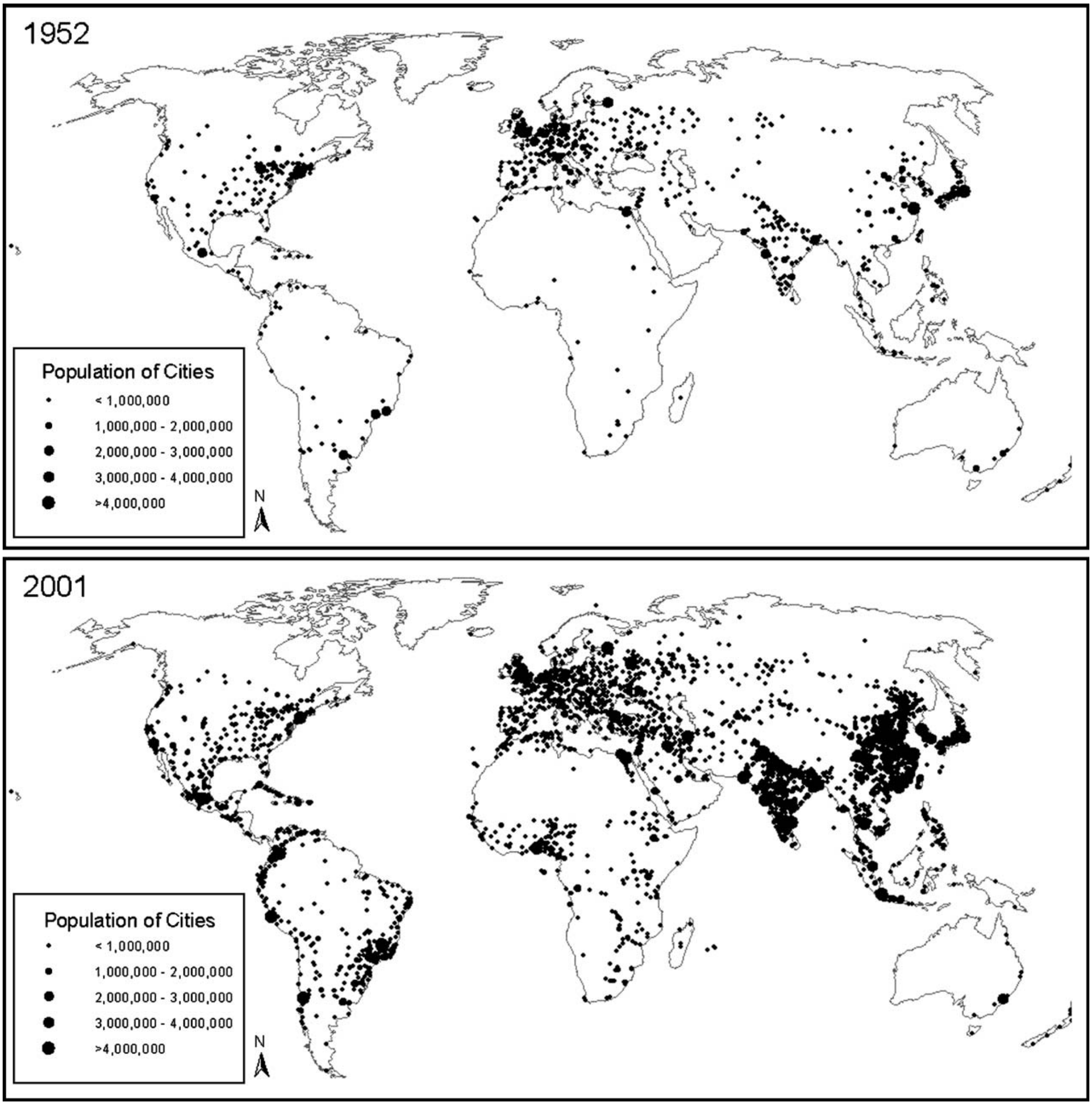


Fig. 1. Worldwide urban population change from 1952 to 2001, approximately covering the time period discussed in this paper (produced from original data: United Nations, 1952, 2004).

would pose formidable demands on river systems (Eyles, 1997; Douglas, 2005), a situation that will likely continue into the future.

This paper synthesizes research results published since 1956 in a range of world areas to answer three questions. First, what have been the impacts of urban development on river systems across Earth's surface? Second, how do these impacts vary with locale and hydroclimatic environment, to the extent indicated by empirical data? Third, how persistent are the impacts at different locales and environments, and what does that persistence indicate about whether rivers can truly adjust to the impacts of urban development? Lastly, the paper concludes by highlighting some challenges for managing urban river systems.

2. A half century of investigations

2.1. The database

Developing from the work of Gregory (1977b, 1987a,b, 1995) and Brookes and Gregory (1988), the data for this paper include results from more than 100 published studies that document urbanization impacts on river systems over the past five decades. The investigations selected report hydrologic and sedimentologic process alterations, but emphasize those quantifying morphological change within channels and watersheds (58 studies). The publications are primarily journal articles and book chapters, although much of the early work in the 1960s on hydrologic effects of urbanization were reported by the U.S. Geological Survey in the Professional Paper series, Water Supply Papers, Open File Reports, and Circulars, and some of these have been included. The studies comprise work that appeared in mainstream English language publications since 1956. Equivalent analysis of journals in other languages as well as review of unpublished materials, could expand the present effort.

From these publications, the characteristics of the study sites were recorded, followed by the hydrological, sedimentological, and morphological parameters affected by urbanization, the magnitudes and rates of change, spatial and temporal character, and techniques used in the investigations. The papers were categorized into three groups according to the aspect of the physical system investigated — hydrological, sedimentological, and morphological. Although more than one type of effect was often reported in a single study, categorizing according to a main focus enabled quantitative analyses to be conducted on the structure of the research contributions, and the progression of research themes to be identified. This approach of quantitatively analyzing large amounts of literature in research is an increasingly common and useful means of inquiry (e.g. Kondolf and Piegay, 2003). The following paragraphs describe some of the spatial and temporal attributes of these contributions and the methods employed, followed

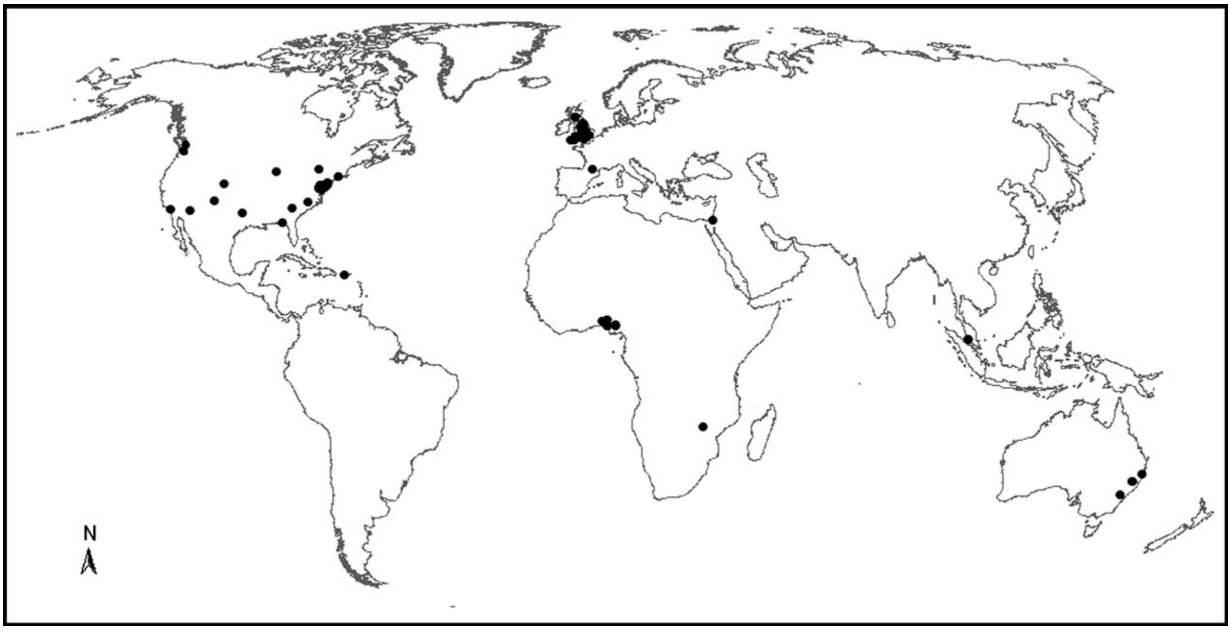


Fig. 2. Location of field sites studied in 58 investigations since 1956 reporting morphological change related to urban development.

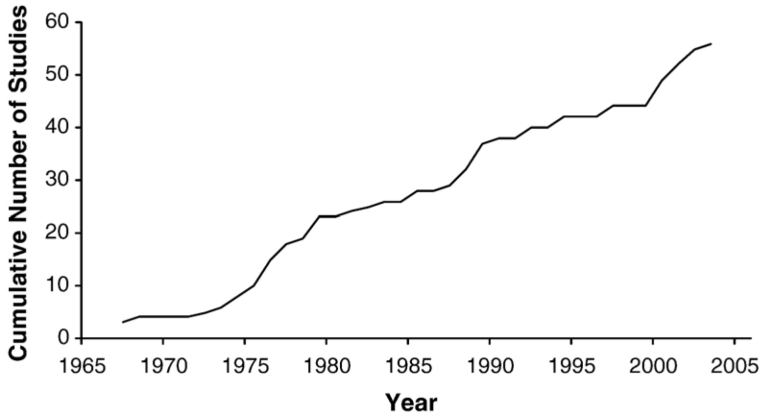


Fig. 3. Cumulative number of studies reporting urban-induced morphological change from 1956 to 2005.

by the content of the data with which to examine the three stated questions posed in this paper. The resulting database also provides reference guidance for future research.

2.2. Spatial aspects

Analysis of research investigations surveyed in this study shows that the spatial distribution of field sites has been markedly uneven (Fig. 2; Gregory, 1987b). Of the 58 investigations reporting morphological change within river systems, 27 (47%) were from the U.S., and 13 (22%) were analyses of British rivers. This concentration reflects, in part, the early influence of American fluvial geomorphologists who initiated pioneering studies in the U.S. eastern seaboard in the 1960s and 1970s, as well as a collection of British scholars who similarly spearheaded analogous research in the U.K. Theory development concerning morphologic adjustments of river systems to urbanization has, therefore, received input from relatively few geographic locations, although important studies in other countries including Australia, Nigeria, Malaysia, Canada, Singapore, Zimbabwe, France, and Israel, have now provided a broader context with which to assess magnitudes and rates of change.

2.3. Temporal trends

Examination of temporal trends in the research contributions reveals a surge of activity in the 1970s, late 1980s, and in recent years since 2000 (Fig. 3). The decade of the 1970s, in particular, saw an exponential increase in the number of studies on river channel change (Gregory, 1977a) that resulted from urban development, after an initial focus on hydrologic (e.g. Leopold, 1968) and sedimentologic (e.g. Walling and Gregory, 1970) effects. Much of this early work was conducted in the temperate environments of the U.S. and the U.K., which enabled basic theory to be formulated. As theory matured in subsequent decades with further examples and field-testing, research expanded into other geographic areas and hydroclimatic environments. Studies in the humid tropics of southeast Asia (e.g. Gupta, 1984; Douglas, 1985a,b) and Africa (e.g. Ebisemiju, 1989a,b; Whitlow and Gregory, 1989) contributed to the increase in publications in the late 1980s (Table 1). The surge of activity in the most recent period has been stimulated in part by concern over urban stream degradation and interests in stream restoration (e.g. Niezgoda and Johnson, 2005). In addition to publications that continued to provide quantitative data that document morphological change (e.g. Pizzuto et al., 2000; Table 1), this latter period also coincides with increasing efforts to develop ways to manage adjusting urban river channels (e.g. Chin and Gregory, 2005).

Table 1
Number of post-1956 English language publications that reported urban-induced morphological change by decade and study location

	1960s	1970s	1980s	1990s	2000s
U.S.	4	9	3	2	9
U.K.		8	3	2	
Australia		3	3		
Malaysia		1	1		
Nigeria			2	2	1
Zimbabwe			1		
France			1		
Canada				1	1
Israel					1
Total	4	21	14	7	12

2.4. Methods employed

Several key approaches have enabled identification of urban-induced channel change in river systems (Gregory, 1977b). Whereas streamflow records could be analyzed to detect hydrologic effects over time in urbanizing areas (e.g. Hollis, 1974), direct measurement is often required to capture detailed changes in sedimentological process associated with urbanization (e.g. Walling and Gregory, 1970). Direct monitoring through the urbanization process is also ideal for quantifying morphological change, such as illustrated by Leopold (1973) for Watts Branch in Maryland. Pre-development data are seldom available for this method to be easily applied, however, and observations are rarely conducted over a sufficiently long period for longer-term adjustments to be revealed (Leopold et al., 2005). Therefore, historical methods (Hooke and Kain, 1982) using topographic maps and surveys, or sequential aerial photographs or remote sensing imagery (e.g. Graf, 1975), in some cases analyzed in a geographic information system (Graf, 2000), have also been successful in reconstructing change in urbanizing rivers.

Where direct means are not feasible, space–time substitution or spatial interpolation techniques have been commonly applied to infer change (Wolman, 1967a). These methods, sometimes also known as applying the ergodic hypothesis, rely upon establishing relationships for un-urbanized areas so that they can be compared to actual field-measured values under urbanized conditions. The proportion between urbanized values and those estimated for pre-urban natural conditions are then calculated to indicate the magnitude of change, commonly referred to as the “enlargement”

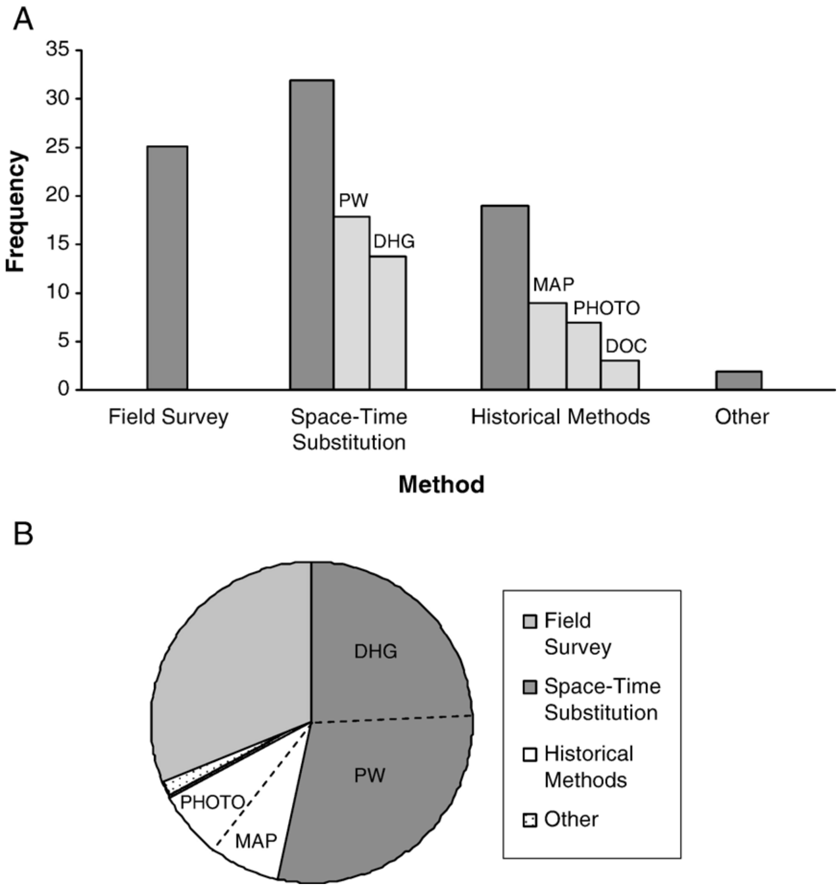


Fig. 4. (A) Number of studies of urban-induced channel adjustments using several methods. PW refers to paired watershed; DHG indicates downstream hydraulic geometry. MAP, PHOTO, and DOC represent topographic maps, aerial photos and remote-sensing imagery, and historical documents, respectively (see Gregory, 1977b). The “Other” category includes modeling and geographic information systems. This figure includes all methods used in each of the 58 investigations analyzed. The numerical totals of the lighter colored bars add up to those of the darker bars for the space–time substitution and historical methods. (B) Proportion of studies using various methods as the principal tool to investigate change. Abbreviations same as in (A).

(Hammer, 1972) or "change" (Gregory, 1977b) ratio. Variations to this approach include comparing channel geometries upstream and downstream of urban areas along a single stream (e.g. Gregory and Park, 1976a), which has been argued to be the more theoretically sound version (Park, 1977), or comparing an urbanized system with adjacent natural "control" streams (e.g. Morisawa and Laflure, 1979). Regardless of which variation is applied, use of other methods to complement space–time substitution is advisable to identify the precise location and character of change (Gregory et al., 1992) and to avoid spurious results (Richards and Greenhalgh, 1984; Ebisemiju, 1991).

Inspection of the methods used to investigate urban-induced morphological change indicates that the space–time substitution approach has been central. Thirty-two of the 58 studies analyzed applied some aspect of the spatial interpolation technique, more than field measurements (25 studies) or historical methods (19 studies) (Fig. 4a). This included 14 studies that compared hydraulic geometries upstream and downstream of urban areas (denoted DHG for "downstream hydraulic geometry" in Fig. 4) along a single stream, and 18 that used adjacent un-urbanized channels as controls (denoted PW in Fig. 4 for "paired watersheds"). If only one primary technique is considered for each study (rather than including all methods used), the reliance on space-time substitution is even more clear. Space-time substitution was a primary method used in 53% of the studies to infer morphological change (Fig. 4b), even though field survey and historical methods often provided supporting evidence. These results underscore the difficulties of obtaining direct measurements consistently over a long time period to document morphological change. They also reflect the rare opportunities available to instrument a watershed before urbanization occurred, as was done in the Rosebarn catchment near Exeter in the U.K. in the late 1960s (cf. Walling and Gregory, 1970; Walling, 1974).

3. A conceptual model of change

A first glimpse into how rivers respond to urban development was outlined by Wolman (1967a), where three stages of urbanization were described to have repercussions on river channels: 1) a stable or equilibrium pre-development stage; 2) a period of construction during which bare land is exposed to erosion; and 3) a final stage consisting of a new urban landscape dominated by houses, rooftops, gutters, and sewers. Accompanying the construction phase is an initial increase in sediment production because of erosion of bare surfaces, leading to sedimentation within channels. Central to the last stage is increasing impervious surfaces leading to greater runoff, which, together with decreasing sediment production, is followed by channel erosion and channel widening or enlargement (Fig. 5). Data from around the world have

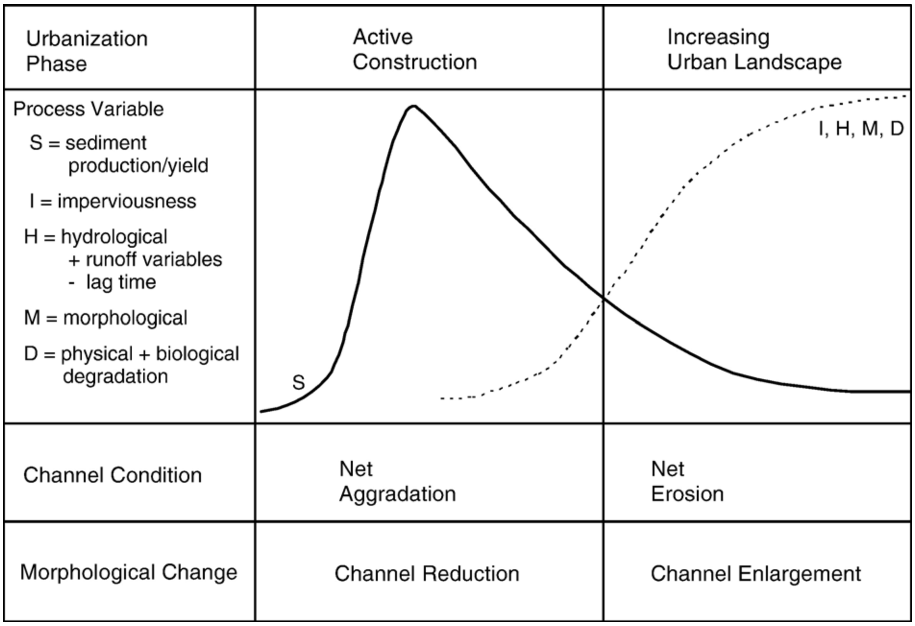


Fig. 5. General phases of urbanization with associated process changes, channel conditions, and morphological adjustments (developed from Wolman, 1967a). Curves are approximate to indicate trends but could exhibit sharp changes and considerable variation among variables.

since provided analogs for different portions of this model, prompting several questions: a) to what extent do the data provide evidence for these successive stages of urbanization; b) how do the data vary among regions to reflect differing process–response mechanisms; c) what are the time periods for the successive stages; d) what other details do the data show to fill in gaps and augment the picture?

4. Sediment production and sediment yield

Ample evidence has indicated a remarkable increase in sediment production once urbanization commences, especially for land surfaces that have been cleared for building but often remain bare for more than one year (Wolman and Schick, 1967). These surfaces can induce erosion rates up to 40,000 times pre-disturbance rates (Harbor, 1999) and produce annual sediment yields on the order of 10,000–50,000 t km^{-2} yr^{-1} (Piest and Miller, 1975), 60 times more than non-construction areas on average (Chen, 1974). Table 2a shows representative values of sediment yield for selected urbanizing areas in the U.S., where data are available from numerous studies conducted in the 1960s and 1970s. The three construction sites (Baltimore, Maryland; Reston, Virginia; Royce Brook, New Jersey) show high sediment yields ranging from 1194 to nearly 55,000 t km^{-2} yr^{-1}, representing increases of 45 to 300 times the initial background conditions. Construction sites can deliver as much as 80% of the sediment yield from an urbanizing basin (Fusillo et al., 1977). Thus, sediment yield per unit area would be higher for small areas entirely under construction or with large proportions affected (Table 2a; Walling, 1974). Sediment yield per unit area tends to decrease with increasing drainage area because of "dilution effects" (Wolman and Schick, 1967; Fox, 1976). Accordingly, sediment production for larger drainage basins, shown in Table 2a, increases two- to five-fold, as reflected in the example of Isaquah Creek in western Washington (Nelson and Booth, 2002) where only 0.3% of its 144 km^2 drainage area is under construction.

Empirical data available from other areas of the world appear comparable (Table 2b). An extreme case of an abandoned construction site in Kuala Lumpur, Malaysia (Leigh, 1982) yielded 611,100 t km^{-2} yr^{-1} of sediment (representing ~20,000 times natural conditions), but other values are within the range reported for the U.S. sites. Sediment yield increases for construction sites in Australia (Douglas, 1974) and Tahiti (Wotling and Bouvier, 2002) are higher at 120 times background values; another location in the Anak Ayer Batu basin under heavy development in Kuala Lumpur yielded sediment 30 times greater than natural conditions. On average, however, the empirical data show that increases in sediment production for urbanizing basins as a whole are on the order of 2–10 times, although concentrations may increase 20-fold and maximum load up to 80-fold during individual storms, as demonstrated by an example from England (Walling, 1974 in Table 2b).

A case may be made for greater urban-induced sediment effects in the humid tropics, given the high sediment concentrations and loads recorded at several locations in Malaysia, Singapore, and Nigeria (Table 2b). This might be expected because soils in tropical environments are deeply weathered and easily erodible (Leigh, 1982) despite high silt–clay contents. Rainfall intensities for the short, localized, but heavy downpours (Gupta, 1984) often exceed the threshold of soil erosion (Hudson, 1971), for example reaching 35–55 mm h^{-1} in Papeete, Tahiti (Wotling and Bouvier, 2002), 50–70 mm h^{-1} in Peninsular Malaysia (Dale, 1959), and up to 157 mm h^{-1} in Zimbabwe (Whitlow and Gregory, 1989). Thus, tropical rainstorms can be an order of magnitude more erosive than in temperate regions (Hudson, 1971; Gupta, 1984). These hydroclimatological characteristics may explain the very high suspended sediment concentrations of 81,230 mg l^{-1} and ~109,800 mg l^{-1} recorded during individual storms in Kuala Lumpur, Malaysia and the Ado-Ekiti urban area of Nigeria, respectively (Table 2b). Generalization is not easy, however, given limited available data (Gupta and Ahmad, 1999), and ultimately, greater quantification is needed to develop a more comprehensive understanding of the interrelationships among the potential control variables including rainfall, soils, and topographic characteristics.

Less emphasis has been given to quantifying sediment loads after development is complete. City highways and numerous urban activities can still introduce significant quantities of particulates into storm water runoff and reach urban streams. Even so, an overall reduction in sediment production is likely given the urban pavement, and negative correlations between percent built-up areas and sediment yield infer decreasing sediment loads during the latter stages of urbanization (Oyegun, 1994). Numerous qualitative descriptions have given further support to the concept of decreasing sediment production in the post built-out phase of urbanization (Kinosita and Yamazaki, 1974; Gupta, 1982). Surveys of culverts in newly completed developments in Baltimore, Maryland, for example, showed only small percentages occupied by sediment (Wolman, 1967b). Where data on sediment yield have

Table 2a
Example values of sediment concentration and yield relative to background selected urbanizing areas of the United States

	Location	Drainage area (km^2)	Sediment concentration [a] (mg l^{-1})	Increase over background [b]	Sediment yield (t km^{-2} yr^{-1})	Increase over background [b]	Remarks	References
United States	Baltimore, Maryland	0.0065			54,056	300× [c]	100% disturbed	Wolman and Schick, 1967
	Minebank Run, Towson, Maryland	0.08			30,889	140×	100% disturbed	Wolman and Schick, 1967
	Oregon Branch Cockeysville, Maryland	0.61	~30,000 [d]	20×	27,800	126×	Industrial park	Wolman and Schick, 1967
	Reston, Virginia	0.2	5930		4550	45× [c]	73% disturbed	Guy, 1974
	Royce Brook, New Jersey	0.075			1194	47× [c]	100% disturbed	Fusillo et al., 1977
		3.1			112	5×	36% disturbed	
	Kensington, Maryland	0.24			9267	30×	17% disturbed	Guy, 1963
	Meadow Hills, Denver	3.7			2913	30×	53% disturbed	Graf, 1975
	Lake Barcrost near Fairfax, Virginia	24.6			12,549	3×	7% disturbed	Holeman and Geiger, 1959
	Little Patuxent at Guilford, Maryland	98.4			236	4×	29% disturbed	Fox, 1976
	Delaware River near Trenton, New Jersey				193	>5×	Urbanized	Anderson and McCall, 1968
	Northwest Branch, Anacostia River, Hyattsville, Maryland	128			714	4×	Urban+development	Wark and Keller, 1963; Keller, 1962
	Isaquah Creek, Washington	144			44	1.5×	19% urban; 0.3% construction	Nelson and Booth, 2002

[a] Maximum value reported.
[b] Background values determined from data reported for pre-development, nearby rural/wooded, or upstream of urban condition.
[c] Construction site.
[d] Converted from original data in ppm.

Table 2b
Example values of sediment concentration and yield relative to background for selected urbanizing areas of the world

	Location	Drainage area (km^2)	Sediment concentration[a] ($mg\ l^{-1}$)	Increase over background[b]	Sediment yield ($t\ km^{-2}\ yr^{-1}$)	Increase over background[b]	Remarks	Reference
Australia	Dumaresq Creek (tributary), Armidale	83.8	1466		3829[c]	120×[d]	23% urban	Douglas, 1974
Canada	River Ottawa, Quebec	61.8				2–5×	Urbanizing	Warnock and Lagoke, 1974
Japan	Suburbs of Tokyo	0.45			25,414[c, d]		Development sites	Kinosita and Yamazaki, 1974
Mexico	Mexico City				30–60			Maderey, 1974 (reported in Wolman, 1975)
Malaysia	Anak Ayer Batu, Kuala Lumpur	3.3	81,230	75×	2120	30×	Heavy development	Douglas, 1978
	Anak Ayer Batu, Kuala Lumpur	0.063	15,343	15×	611,100	20,000×[d]	Abandoned site	Leigh, 1982
Nigeria	Ado -Ekiti area		109,799	400×				Ebisemiju, 1989a
Singapore	Near University Singapore's Bukit Tumah campus		19,000	Several order magnitude				Gupta, 1982
United Kingdom	Withycombe Brook, Exmouth	2.8		2–4× up to 11×			45% urban	Walling and Gregory, 1970
	Rosebarn Catchment, Exeter	0.26		2–5× avg. 20× indiv. storm		5–10x avg. 20–40× indiv. storm up to 82×	25% urban	Walling, 1974
Tahiti	Atiue River, Papeete	0.077 0.85			7300	120×[d]	100% disturbed 9% disturbed	Wotling and Bouvier, 2002

[a] Maximum value reported.
[b] Background values determined from data reported for pre-development, nearby rural/wooded, or upstream of urban condition; the letter x refers to the number of times of increase.
[c] Converted from $m^3\ km^{-2}\ yr^{-1}$ assuming particle density of 2.65 $g\ cm^{-3}$.
[d] Construction site.

Table 3
Sediment yield comparisons for developing and developed basins

	Forested/rural basin(s)	Basin(s) under active construction		Development complete/urbanized basin(s)		Reference
	Sed. yield ($t\ km^{-2}\ yr^{-1}$)	Sed. yield ($t\ km^{-2}\ yr^{-1}$)	Approx. increase	Sed. yield ($t\ km^{-2}\ yr^{-1}$)	Approx. increase	
Papeete, Tahiti	Matatia: 59	Atiue: 713	12×	Vaiami: 142	2.4×	Wotling and Bouvier, 2002
Maryland, U.S.	Broad Ford Run: 4.2	Little Falls Branch: 896	~ 200×	Stony Run: 21	5×	Wolman, 1967a
Maryland, U.S.	Avg: 21.8	Avg: 337	16×	Avg: 37	1.7×	Fox, 1976

been available, a clear trend is also evident between basins undergoing construction and those where development is complete (Table 3). The example basins in Tahiti and Maryland under active development produced sediment 12 to ~200 times at of the forested or rural counterparts during the time of study, whereas sediment yields for the already urbanized basins were considerably less, on the order of 2–5 times greater than rural basins, and these increases could be contributed mostly by channel erosion (e.g. Trimble, 1997; Nelson and Booth, 2002).

The comparative values provided in Table 3 underscore the significance of time in evaluating the magnitude and direction of change associated with urbanization. Depending on when measurements are conducted during the evolutionary sequence of change accompanying urbanization (Fig. 5), the magnitudes of the impacts can be small or large. The direction of change can also be increasing or decreasing, aggrading or eroding, contracting or enlarging. Thus, it is critical to specify where on the sediment curve a particular system undergoing change is being studied to understand its behavior and possible future adjustments. The comparative values given in Table 3 also reinforce the reliance on the classic approach of space–time substitution to infer change over time, because of limited temporal data available to make these assessments directly within single systems.

5. Imperviousness and runoff

Hydrologic changes associated with urbanization have been extensively studied, and results from these studies have clearly shown that urban development leads to larger and more frequent floods (e.g. Leopold, 1968). The main parameters demonstrated to have changed are peak discharge, lag time, flood frequency, and total runoff or water yield (see Poff et al., 2006-this volume, for a sub-continental analysis of runoff responses to urbanization). A sample of the early work from the U.S. and U.K. (Table 4) indicates that peak discharge commonly increases two to four times following urban development; lag times decrease correspondingly to one-half to one-fifth of the former values. Streamflow hydrographs have also been documented to occur more frequently, for example increasing from 171 per year in 1969 to 423 per year in 1972 in the Rosebarn catchment near Exeter (Gregory, 1976), with an overall effect of increasing runoff volume or water yield on the order of two to four times (Table 4). As well, urbanization has been demonstrated to affect runoff from small summer storms the most. During large storms, saturated catchments respond as those in urban conditions whether in urban land use or not (Hollis, 1974), and during winter, saturated soils similarly respond more like urban paved surfaces (Hollis, 1977). Amounts of winter runoff, therefore, increased only by 1.5 times on average compared to an increase of 2.8 times for summer floods in the Rosebarn catchment (Gregory, 1974).

Consideration of other runoff and streamflow variables over annual to decadal timescales has added further details to understanding of hydrologic changes. For example, comparing a highly urbanized stream with less urbanized ones in the vicinity of Atlanta, Georgia, USA, Rose and Peters (2001) found that the storm recession period was more rapid for the urban stream (1–2 days less) and the baseflow recession constant was 35–40% lower. Low flow was also 25–35% less in the urban basin. Elsewhere in the Puget Lowland in Washington, modeling and monitoring efforts have shown that 44–48% of the annual precipitation becomes runoff in a zero-ordered urbanized basin compared to 12–30% in a forested catchment (Burges et al., 1998). Konrad et al. (2005) also concluded that urban streams have lower inter-annual variability in annual maximum streamflow and short duration of frequent high flows. These changes could have important ecologic implications in addition to geomorphologic consequences, because biota often respond to the degree of flow fluctuations rather than to the magnitude of flood peaks (Konrad and Booth, 2005).

Table 4
Example hydrological changes caused by urbanization for selected areas of the U.S. and U.K.

Location	Peak discharge	Lag time	Floods (frequency)	Seasonality/individual storm effects	Total runoff/ water yield	Reference
Washington D.C.	+2–6× (80%)	−	+mean annual floods 1.8×			Carter, 1961
Long Island, New York	+123% direct runoff			+5% baseflow		Sawyer, 1963
Santa Clara County, California					+1.18× 1945; +1.70× 1958	Harris and Rantz, 1964
Sacramento, California				Summer baseflow 0.7×; January 4.1×	+2.29×	James, 1965
Jackson, Mississippi	+4.5× mean annual flood					Wilson, 1967
Pennsylvania	+2–3× mean annual Q est. (50% paved)	−				Leopold, 1968
Long Island, New York	+; at least 250%>than forested	−flood peak widths			+direct runoff 27%	Seaburn, 1969
Detroit, Michigan	+3–4×	−1/5				Brater and Sangal, 1969
NE Exeter, Devon	+2x	−1/2		+1.5× winter, 2.8× summer; small storms affected more	+%runoff>0.92	Gregory, 1974
Harlow, Essex	+220% max monthly flood		+3× summer floods			Hollis, 1974
NE Exeter, Devon		−1/2	+(171/yr 1969 to 423/yr 1972)			Gregory, 1976
Harlow, Essex				+low flow, +summer flows	+water yield	Hollis, 1977
NE Exeter, Devon	+2–4×				+2–4× storm runoff volume	Walling, 1979
Atlanta, Georgia	+			+total in wet yr; −total and low flows in dry yr		Ferguson and Suckling, 1990
San Francisco Bay area	+2×	−				Leopold, 1991

Driving these hydrologic changes at the core is an increase in impervious surfaces (Fig. 5), so that the percent of impervious cover correlates with many hydrologic as well as geomorphologic variables. These include water yield (Hollis, 1977), peak discharge (Seaburn, 1969), bankfull discharge (Booth and Jackson, 1997), daily discharge (Jennings and Jarnagin, 2002), lag time (Carter, 1961; Leopold, 1968), baseflow (Klein, 1979), channel enlargement (Hammer, 1972; Hollis and Luckett, 1976; Roberts, 1989), and channel stability (Booth and Jackson, 1997; Bledsoe and Watson, 2001). A reduction in perviousness of impacted surfaces, such as by conversion of forest to pasture or grass (Booth et al., 2002), has also been demonstrated to increase runoff potential (Harbor, 1994). For a rapidly urbanizing watershed in Indiana, USA, application of a model that uses the curve number method of the Soil Conservation Service to estimate changes in surface runoff showed that average depth of annual runoff increased by more than 60% from 1973–1991 (Grove et al., 2001). Direct runoff was affected the most in this basin, shown by an increase in the ratio between direct runoff and total runoff from ~49% to 65% during this period (Choi et al., 2003).

Recent work has also related the percent of impervious surfaces to chemical and biological stream characteristics (reviewed in Paul and Meyer, 2001), where increasing impervious cover leads to progressive stream degradation (Fig. 5; May et al., 1997; May, 1998; Wang et al., 2000; Morley and Karr, 2002; Ourso and Frenzel, 2003). Stream impairment (i.e. fish species diversity dropped from good to fair) was detected when impervious cover reached 12% in a study conducted in the Piedmont province of Maryland (Klein, 1979). Similarly, in lowland streams in western Washington, the quality of fish habitat was observed to degrade at ~10% effective impervious area (impervious surfaces with direct hydraulic connection to the downstream drainage system) (Booth and Jackson, 1997). This level of urbanization was also related to declining fish species and biologic conditions in southeastern Wisconsin streams, as measured by the index of biotic integrity (IBI) (Wang et al., 2000). Observations such as these have led to the view that thresholds of stream degradation exist at generally 10–15% impervious cover (e.g. Klein, 1979), although Booth et al. (2002, 2004) have argued that any threshold effect is likely a function of the imprecision of the metric rather than an intrinsic characteristic of the stream system. Substantial biological degradation has certainly been documented at lower levels of impervious cover (e.g. Karr and Chu, 2000). Morley and Karr (2002) have further found that the percent of urban area more strongly correlated with stream IBI scores than percent impervious cover.

Regardless of the metric used to represent the intensity of urbanization (McMahan and Cuffney, 2000) or to predict urban impacts (Arnold and Gibbons, 1996; Schueler, 2000; Tang et al., 2005), it is clear that an important part to the third stage of urbanization (Fig. 5) is *what happens with increasing imperviousness*. Not only does runoff increase along with other hydrologic and sedimentologic changes, as Wolman (1967a) initially envisaged, but a range of ecological effects is now additionally being recognized, including declines in the richness of algal, invertebrate, and fish communities (Paul and Meyer, 2001). Biologic degradation often occurs long before physical change is detected; these morphologic adjustments will be reviewed in the next section.

6. Morphological adjustments

6.1. The magnitude, direction, and parameters of change

Morphological adjustments in the river system can be considered in terms of changes in the channel cross-section, reach and planform, and network and basin (Gregory, 1987a,b). These changes have been examined for a range of human impacts, including reservoir and dam construction, catchment land use changes, channelization, and urbanization (Gregory, 1987a,b; 2006-this volume). In relation to urban development, such examination can be extended to include a detailed accounting of the morphological parameters reported to have changed in the 58 investigations that provided data for this paper (Table 5). Such a tabulation shows that changes in channel cross-section have been reported the most, with 66% of the studies documenting adjustments in channel capacity, 50% in width, and 34% in depth. Of these, a large majority (60–86%) indicated an increasing direction of change. That is, data from around the world have collectively provided clear evidence for larger channels in urbanizing rivers (Fig. 6). Typical channel enlargement ratios range from 1.0–4.0 (Gregory, 1987a), with the average for the entire dataset analyzed in this study being 2.5 (Table 5).

Although these data suggest worldwide trends, great variability does exist. For example, the largest capacity change ratio (Gregory, 1977b) of 15.3 was recorded in west Bathurst, Australia along Esrom Creek (Hannam, 1979), and the lowest value of 0.13 was also registered in Australia, along Dumaresq Creek in northern New South Wales (Gregory, 1977c; Table 5). Such contrasts

Table 5
Morphological parameters reported to have changed from 58 investigations (after Gregory, 1987b and Downs and Gregory, 2004); +/− indicate increasing or decreasing trends; n = sample size

	Parameter reported	Frequency of citations (%)	Direction of change [a]	Magnitude of change [b]			
				Min	Mean		Max
					−(n)	+(n)	
Channel cross section	Capacity	66	74% +	0.13	0.40 (5)	2.5 (17)	15.3
	Width	50	86% +			1.5 (8)	7.4
	Depth	34	60% +	0.73	0.75 (3)	2.3 (4)	2.8
	W/*D* ratio	14	100% +				4.0
Reach and planform	Channel pattern/migration	12	57% + /braiding				
	Sinuosity	10	100% −	0.59			0.92
	Slope	5	+ and −				
	Bed material	10	50% + (coarser)				
	Bedforms/roughness (sand bars/dunes)	10	50% +				
Network and basin	Drainage density (including storm drains)	12	71% +	−58%			+133% (+808%)
	Other changes	7	+floodplains +riparian zones −large woody debris				270%

[a] Including results that did not give quantitative values.
[b] Summary of quantitative results.

are consistent with the notion that change is often spatially discontinuous, so that the precise character and location of change need to be considered in addition to the general trend (Gregory et al., 1992). Whether and how much channels are enlarging also depend on sediment loads being carried and, therefore, the time period of study following development, as noted earlier. In some cases, sediments have been reported to be flushed out of the river system in 5–7 years (Wolman and Schick, 1967), whereas in others, channels still remained smaller after 20 years (Leopold, 1973).

In addition to the channel enlargement often emphasized in urbanization studies (Fig. 5), researchers have now also quantified other urban-induced channel changes that include reductions in sinuosity, a tendency for bed material to coarsen, and an overall

Fig. 6. A channel enlarging because of urban runoff, Monks Brook, Eastleigh Hampshire, U.K. Tree indicates original location of channel bank (see Gregory et al., 1992; photograph by K.J. Gregory).

increase in drainage densities (Table 5). Reduced sinuosities commonly result from artificial straightening (Fig. 7). Along the River Bollin in Cheshire, sinuosity decreased from 2.34 to 1.37 in 1935–1973 (Mosley, 1975); urban streams in southeast Pennsylvania are also 8% less sinuous than rural counterparts (Pizzuto et al., 2000). Bed materials often coarsen (Arnold et al., 1982; Finkenbine et al., 2000) from scouring of fines (Douglas, 1985b) and increased competence because of higher peak flows (Finkenbine et al., 2000), although this is not always the case (Pizzuto et al., 2000), as large quantities of sand and silt can be introduced into river channels during urbanization (Fox, 1976). Sand bars and sand dunes can, therefore, also increase (Wolman, 1967a; Wolman and Schick, 1967) to 1.5 times the previous value (Fox, 1976), and floodplains can expand by 270% because of sedimentation (Graf, 1975). Drainage densities have initially decreased as much as 58% (Department of Interior, 1968) when small channels have been paved over during urban development (Meyer and Wallace, 2001), but subsequently, introduction of roads (Gregory and Park, 1976b) and stormwater drains (Hannam, 1979) can increase drainage densities by 50% (Graf, 1977) and sometimes up to 808% (Whitlow and Gregory, 1989). Therefore, although specific adjustments depend on location and time periods following urbanization, the overall empirical data indicate that urbanized landscapes are characterized by larger and straighter channels, with higher drainage densities resulting from an artificial network, and generally coarser materials because of removal of fines and armoring.

6.2. Spatial variations

Given that great variability exists in channel adjustments, with 26% of reported cases nevertheless undergoing channel reduction (decreasing direction of change in Table 5), channel-change ratios were mapped for various regions of the world to assess the extent to which spatial patterns can be discerned. At first glance, Fig. 8 gives the overall impression that urbanization has enlarged river channels across Earth's surface. Mean enlargement ratios are consistently on the order of 2–3. Although the capacity ratios for southeast Australia appear larger initially, the mean is affected by the one extreme value of 15.3 from west Bathurst (Hannam, 1979). Closer examination, however, does suggest possible regional differences. First, channel adjustments in British rivers generally occur more in the depth dimension than those in the U.S. and elsewhere. Thus, British rivers tend to become deeper and narrower as enlargement occurs (Park, 1977; Fig. 8). This is likely a function of relatively low sediment loads for most British rivers on a world scale (Knight, 1979), as well as more cohesive local bed and bank materials and vegetation characteristics compared to other sites studied. Second, the data contained in Fig. 8 suggest regional variations related to hydroclimatic effects that could be explored. Whereas research on the impacts of

Fig. 7. Avondale Stream in Harare, Zimbabwe, illustrating how artificial manipulation of urban streams commonly results in reduced sinuosities (see Whitlow and Gregory, 1989; photograph by K.J. Gregory).

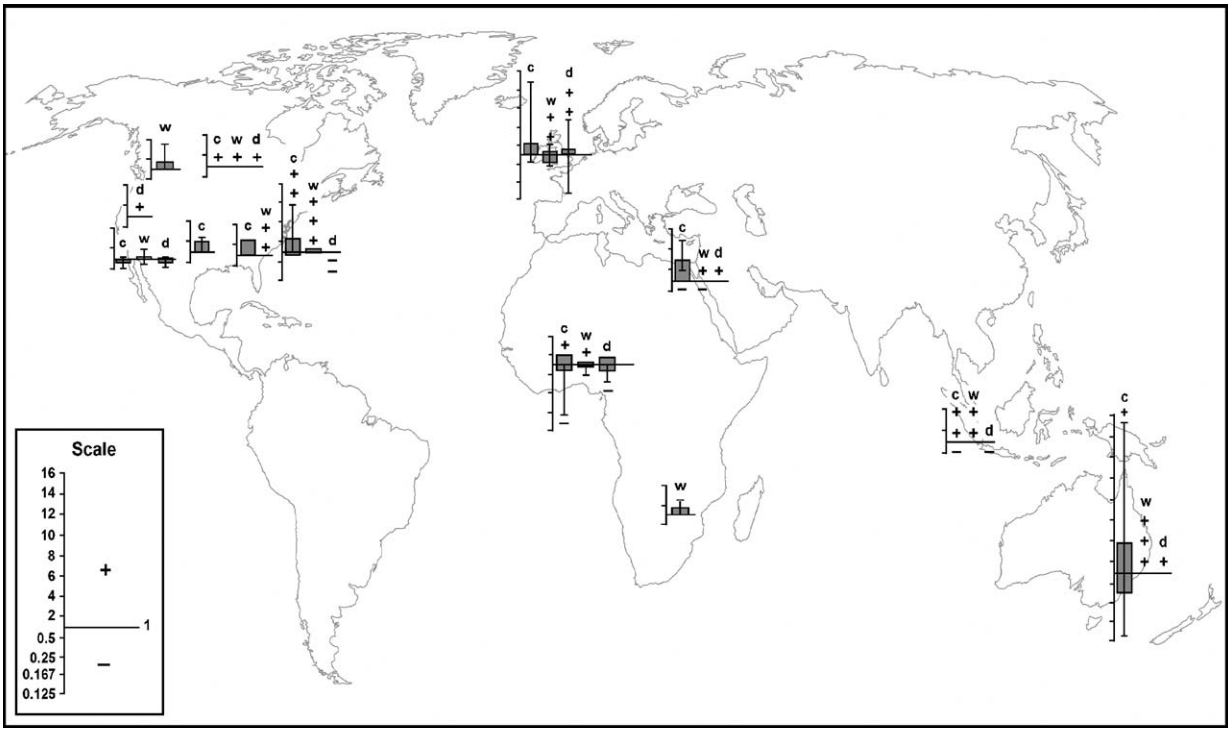


Fig. 8. Urban-induced changes in channel capacity (c), width (w), and depth (d) worldwide. Bar graphs illustrate average change ratios for locations where data are available. Some represent data from a group of studies. Grouped sample sizes: 13 for U.K.; 6 for U.S. eastern seaboard that includes Philadelphia, Baltimore, and Washington D.C.; 4 for Nigeria; and 4 for southeastern Australia. Horizontal lines represent change ratios of 1, demarcating channel enlargement and reduction. Vertical lines indicate minimum and maximum values. Symbols "+" and "−" represent increasing or decreasing trends where comparable quantitative values were not given.

urbanization on river channels have emphasized temperate environments (Fig. 2), studies in the humid tropics of Africa (e.g. Ebisemiju, 1989a,b) and southeast Asia (e.g. Douglas, 1974, 1985b), along with recent work in arid regions of Arizona (Chin and Gregory, 2001) and Israel (Laronne and Shulker, 2002), now give a rudimentary basis for comparison according to hydroclimatic environments, as described below.

6.2.1. Response in tropical environments

Quantitative data available from Nigeria suggest that channel changes have more commonly involved a reduction in channel capacity rather than enlargement (Ebisemiju, 1989a; Odemerho, 1992; Fig. 8), and that the magnitude of these changes has generally been smaller than in temperate environments. Although a dramatic case of channel enlargement was documented along the Ekulu River within the urban area of Enugu (capacity ratio = 1.91, width ratio = 1.34, depth ratio = 1.65; Jeje and Ikeazota, 2002), most other studies in Nigeria reported smaller urban river channels. These include downstream sections of the Ekulu (capacity ratio = 0.79; Jeje and Ikeazota, 2002), channels along the headwaters of Elemi River through the village of Igede (capacity ratio = 0.81; Ebisemiju, 1989a), and in the Ikpoba River in Benin City (Odemerho, 1992). Reductions in channel capacity of 47% were also reported for the Elemi River through the Ado-Ekiti urban area (Ebisemiju, 1989a). Hydraulic geometry further showed variable and insignificant relations in the Ado-Ekiti area, suggesting that channels were undergoing adjustment at the time of measurement (Ebisemiju, 1989b).

Channel reductions in the Nigeria examples were accomplished principally in the depth dimension (Ebisemiju, 1989a; Odemerho, 1992) and indicated aggradation of the stream bed in contrast to the examples of degradation from Britain. Channel aggradation has been attributed to excessive production and delivery of sediment in humid tropical environments, rapid deposition of suspended sediments, and low competence (Ebisemiju, 1989a). These interpretations are consistent with the very high suspended sediment loads reported for tropical urban catchments in Nigeria (Ebisemiju, 1989a), Malaysia (Douglas, 1974, 1978, 1985b), and Singapore (Gupta, 1982, 1984), reviewed in Tables 2a and 2b. Accordingly, high sediment yields have also caused the aggradation of stream bed and reductions in channel capacity in Malaysia along the Sungai Kelang (Douglas, 1974) and Sugai Anak Ayer Batu (Douglas, 1985b) in Kuala Lumpur. In addition to construction activities that introduce vast quantities of sediment into stream channels (Douglas, 1974), bank erosion is a significant source of sediment (Douglas, 1985b) under high intensity rainfall (e.g. Gupta, 1984), even though humid tropical rivers may be expected to exhibit lower erosive characteristics (Jeje and Ikeazota, 2002) because of high silt–clay contents. Thus, channel widening has been documented along the Sungai Anak Ayer Batu downstream of the town of Jalan Damansara (Douglas, 1985b). In Zimbabwe, the growth of Harare also caused channel widening of 1.7 times and involved a bank erosion rate of 0.33 m/year (Whitlow and Gregory, 1989). Overall, data from tropical environments available thus far suggest channel adjustments in response to high sediment loads and intense precipitation inputs. Channels may indeed enlarge in time to similar magnitudes as in temperate environments, but empirical data are not yet sufficient to demonstrate the full extent of channel adjustments in tropical areas, and more time is likely needed for channel adjustments to fully occur in those regions.

6.2.2. Adjustments of arid ephemeral streams

At the other end of the hydroclimatological spectrum are the arid-region rivers undergoing urbanization. Dryland rivers have particular dynamics that may induce urbanization effects different from those in temperate regions. In some ways similar to tropical rivers, ephemeral streams also typically carry high suspended loads (Reid and Frostick, 1987) and bedload (Laronne and Reid, 1993) because of ample supplies of sediment from unvegetated hillslopes and channel banks (Leopold and Miller, 1956). Dryland environments also exhibit extreme spatial and temporal variability in precipitation input and response mechanisms (Graf, 1988), with channel morphology subject to rapid and irregular changes (Rendell and Alexander, 1979). Urbanization impacts on dryland river channels are, therefore, likely to be less predictable, more localized, and more variable then in humid–temperate streams. Although drylands cover almost 50% of Earth's surface and contain about 20% of the world's population (Tooth, 2000), very few investigations have addressed urbanization effects in dryland settings (Cooke et al., 1982).

Data from Arizona and Israel support the hypothesis that morphological adjustments in desert rivers are more variable than previously reported for humid temperate regions (Fig. 8). Studying several towns in the Mediterranean coastal zone of Israel that included the northern Negev Desert, Laronne and Shulker (2002) found a variable channel response consisting of channel narrowing and capacity reduction as well as dramatic enlargements up to five-fold in magnitude. Elsewhere in the Sonoran desert of Arizona, development of the town of Fountain Hills, since the early 1970s, has also caused a variable morphologic response (Chin and Gregory, 2001) that included a slight overall downstream widening trend accompanied by reductions in depth and capacity during the early stages of urbanization (Fig. 8). More significantly, introduction of wide roads that directly cross stream channels has fragmented the river system into channel segments, inducing local, reach-scale variations in channel adjustment. By the year 2000, runoff from road surfaces had incised channels downstream of crossings, so that these channel cross-sections are characterized by low width–depth ratios (Fig. 9). In contrast, upstream cross-sections are 1.7 times wider as well as shallower from accretion. Because roads in desert cities are commonly built directly across streambeds as cost-effective storm drainages (Schick, 1974), as demonstrated also in Tucson, Arizona (Resnick et al., 1983) and elsewhere in Israel (Schick, 1979, 1995; Schick et al., 1999), such spatially varied responses may be characteristic of arid urban river channels. Therefore, understanding local spatial variations in channel responses may be more significant in desert settings than deciphering the overall direction and magnitude of change. Further research is also needed to more fully understand the impacts of urbanization in arid environments.

6.2.3. Effects of local conditions

At the local scale along individual river channels, channel adjustment does not necessarily take place uniformly because of variations in boundary materials or direct disturbances to river channels. Changes in lithology that cause slope and resistance to vary could result in differential erosion and enlargement. This was shown in north central Texas, U.S., where chalk channels have higher rates of enlargement compared to shale (Allen and Narramore, 1985). Channel slope and geologic materials are also critical parameters in defining susceptibility to incision in King County in Washington, U.S. (Booth, 1990), where streams erode far out of proportion to the increased discharge that initiated them, contrary to quasi-equilibrium channel enlargement. Similar local incision has been triggered by direct disturbance to the channel boundary, such as realignment and building of road crossings in urban

Fig. 9. Representative channel in Fountain Hills, Arizona, crossed by repeating system of roads. The spatially varied response is characterized by incised river channels downstream of road crossings with low width–depth ratios, and aggraded wide and shallow cross sections upstream (see Chin and Gregory, 2001; photograph by A. Chin).

catchments near Armidale, New South Wales, Australia (Neller, 1989). These incisions were also identified near a gully in Devon in the U.K. (Gregory and Park, 1976b) and in small streams in Georgia (Hayden, 1988) and Arizona (Chin and Gregory, 2001; Fig. 9) in the U.S. Bridges have additionally caused localized effects (Douglas, 1985b), including erosion that was much greater in the vicinity of the crossing than farther downstream in the New Forest, Hampshire, U.K. (Gregory and Brookes, 1983). In New England, U.S., Arnold et al. (1982) further identified areas that experienced increased erosion and caused undercut trees to topple into Sawmill Brook. Undercutting and slumping were also among reasons for spatially varied channel adjustments in Avondale Stream through Harare, Zimbabwe, as it evolved from an extensive dambo system (Whitlow and Gregory, 1989).

Because capturing detailed spatial variations in channel adjustments requires methods beyond space–time substitution, Gregory et al. (1992) suggested the simultaneous use of topographic maps, field indicators to quantify morphological changes at particular channel locations, and detailed field mapping of continuous stream reaches. These methods documented spatially discontinuous channel changes in the Monks Brook basin in central southern England (Fig. 6), which displayed variable capacity, width, and depth changes over relatively short distances. Field surveys of continuous urbanizing channel reaches in Fountain Hills, Arizona (Chin and Gregory, 2005) also identified segments in various stages of adjustment (Fig. 10), where some reaches were adjusting to urbanization but others were affected to such an extent that adjustment was no longer possible (e.g. channelized reaches). Such analysis of detailed spatial variations in channel adjustments is particularly useful for management purposes (Gregory, 2002; Gregory and Chin, 2002) because it enables flexible management decisions to be made for each channel segment according to the stage of channel adjustment.

6.3. Time periods of adjustments

Data from around the world have now provided evidence for successive sedimentological and hydrological changes associated with urbanization, along with spatially varied morphological responses, leading to the next questions: how long do these processes take place, and how long does it take for urban channels to reach a new equilibrium presumably adjusted to the changed regimes? Until recently, few investigations have explicitly addressed the issue of time for urban stream channel adjustments. As more urban areas become mature after several decades of post built-out conditions, however, the issue of a new stability regime becomes

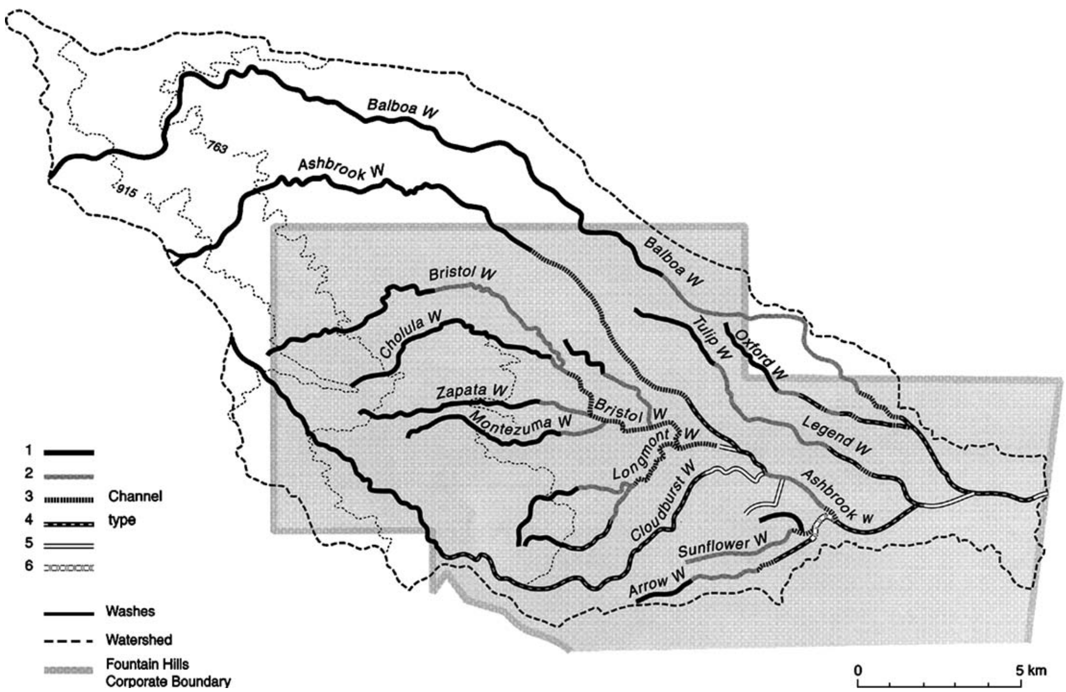


Fig. 10. Spatial variations in channel adjustments in northern wash system of Fountain Hills, Arizona (see Chin and Gregory, 2005). Stages of adjustment indicated by channel types; 1: near natural; 2: adjusting, able to recover; 3: adjusting, unable to recover naturally; 4: channelized, channel altered; 5: channelized, engineered; 6: channelized, culverted.

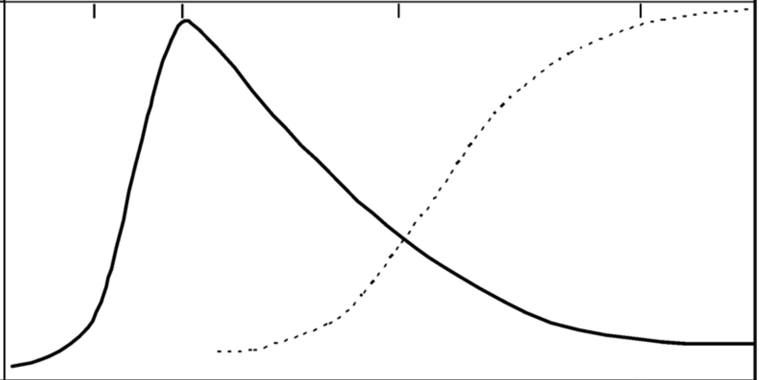
increasingly relevant (Watershed Protection Techniques, 2000; Henshaw and Booth, 2000; Finkenbine et al., 2000). Fig. 11 evaluates the time periods of adjustment for urbanizing rivers in various parts of the world, where the successive stages can be described as including a reaction time and relaxation time (Graf, 1977; Simon, 1989), leading potentially to a new equilibrium. The *reaction time* (period a in Fig. 11) represents a lag in the system between disturbance by urbanization (land clearing for construction) and the onset of a morphological response. The *relaxation time* incorporates the sequences of increasing sediment production followed by reduction and an erosive regime encompassing channel enlargement (periods b, c, d in Fig. 11). Presumably, after a larger channel has been constructed to accommodate the increased urban runoff, flow velocity and accompanying shear stresses decrease (Morisawa and Laflure, 1979), the stream is no longer erosive, and a *new equilibrium* is achieved (period e in Fig. 11).

Despite the paucity of empirical data documenting long-term channel adjustments, results from research studies do indicate the following time periods for the successive adjustment stages for urbanization. First, the lag time is short (period a in Fig. 11), from months to several years, for the urbanization sequence to be initiated once development commences. This was documented by Hannam (1979) in New South Wales in Australia, where it took five to six months for siltation to occur following land clearance for construction and for an increased concentration of suspended sediment to be recorded in Esrom Creek. Elsewhere in Denver in the U.S. (Graf, 1975), large quantities of sediment introduced in the channel system during urban development were documented to expand floodplains within two years. In College Station, Texas, urban drainage from a new master-planned residential subdivision caused the development of a stream channel within two years following installation of the drainage system (Fig. 12). The timescale for observing the start of a morphological response is presumably related to the spatial scale, that is, distance from disturbance to the channel (e.g. Fig. 12) and the size of the basin (Fig. 11).

Second, the time it takes for sediment yield to increase and for the high sediment loads to be flushed out of the system varies considerably from years to decades (periods b and c in Fig. 11, representing net channel reduction). Wolman (1967a) and Wolman and Schick (1967) observed that excessive sediment loads are removed within 5–7 years in Baltimore streams, supported also by the analysis of Hammer (1972) for the Philadelphia area. Following urbanization in Watts

Time Periods/ Phases of Adjustment	Reaction Time	Relaxation Time			New Equilibrium
	a	b	c	d	e

a) Lag time from commencement of construction to morphological change
b) Period of increasing sediment production and yield (channel reduction)
c) Phase shift from aggrading to eroding regime (sediments flushed out)
d) Period of channel enlargement
e) Stability/ new equilibrium achieved



Reference	Location	Years from urban development → (a)	(b)	(c)	(d)	Adjusted?* (e)
	U.S.					
Graf 1975	Denver[1]	< 2				
Hammer 1972	Philadelphia[2]			> 4	~ 30	yes
Wolman 1967	Baltimore			5-7		
Leopold 1973	Maryland[1]		13	> 20 †		no
Fox 1976	Maryland[3]			1-50		no
Arnold et al. 1982	Connecticut[4]				> 40 †	no
Trimble 1997	S. California[5]				> 50	no
Chin & Gregory 2001	Fountain Hills, Arizona				> 30 ‡	no
Henshaw & Booth 2000	Puget Sound, Washington[6]				1-2 decades	6 yes; 6 no
	U.K.					
Hollis & Luckett 1976	Harlow, Essex[7]			> 17 †		no
Roberts 1989	British rivers				several decades	likely
	Australia					
Hannam 1979	W. Bathurst	~ 0.5				
Neller 1988	Armidale				5 yrs after urbanization complete	yes
	Canada					
Finkenbine et al. 2000	Vancouver[8]				~ 20	yes
	Malaysia					
Douglas 1985	Kuala Lumpur		17	> 17 †		no
	Nigeria					
Ebisemiju 1989 a,b	Ado-Ekiti					1 yes; 6 no
Jeje & Ikeazota 2002	Enugu				> 50 (est.)	no

*at time of study; †adjustment phase incomplete; ‡spatially varied response more complex than simple channel enlargement; drainage area (km^2): [1]10, [2]3-16, [3]2410, [4]18, [5]288, [6]5-35, [7]21, [8]1-27

Fig. 11. Time periods of adjustment for example urbanizing rivers in various parts of the world. Solid and dashed curves represent sediment production/yield and runoff with associated hydrological changes, respectively, as in Fig. 5.

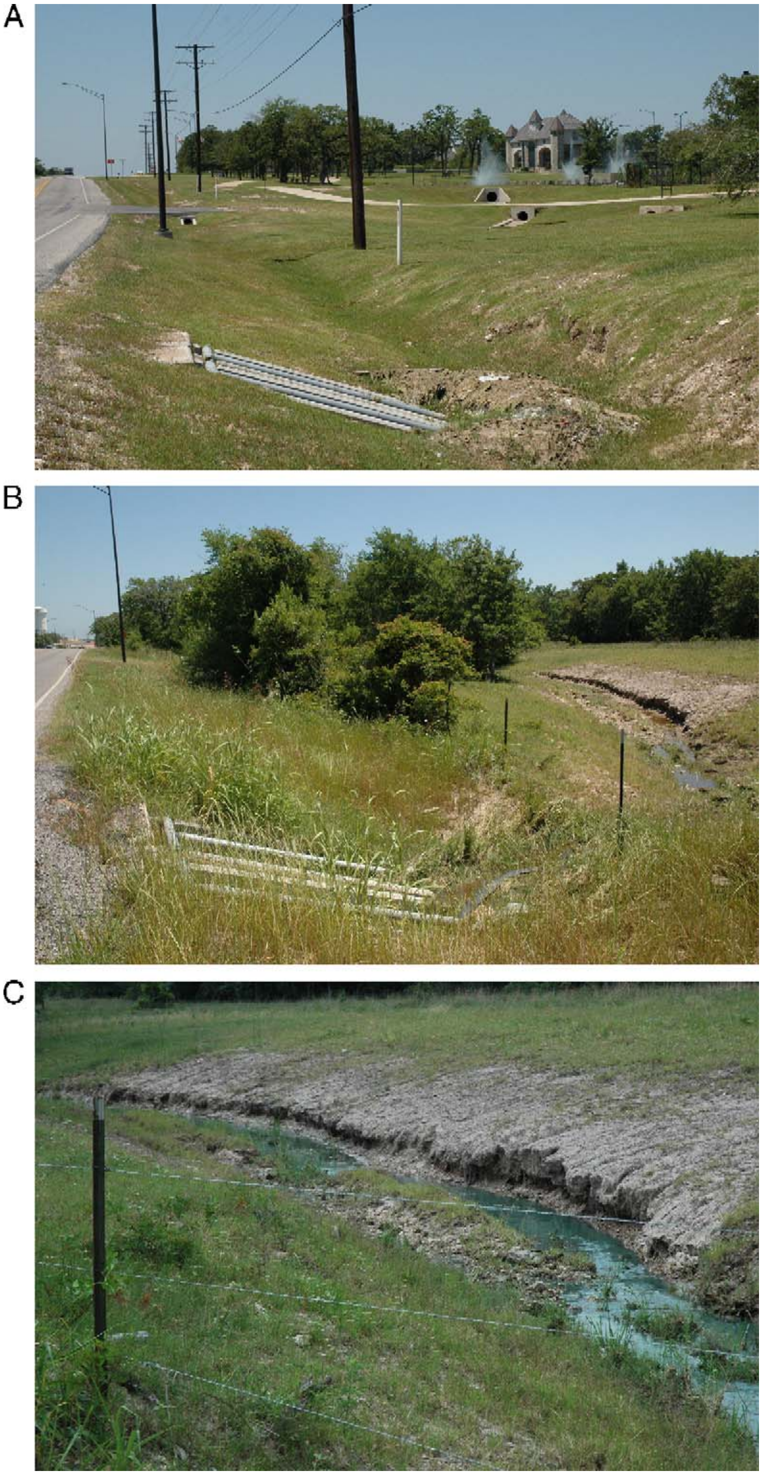


Fig. 12. A channel forming from urban drainage following development of a residential subdivision in College Station, Texas. A) drainage from subdivision is collected to drain (foreground) and siphoned under road to the left of the photograph (view is "upstream"); B) drain outlet (foreground) empties water from underneath road, causing development of a channel (view is "downstream"); C) rapid downcutting and enlargement are evident at time of photograph (April 2006 by A. Chin); maximum height of channel bank is ~0.3 m.

Branch, Maryland, however, continuous detailed surveys from 1953 to 1972 by Leopold (1973) documented 13 years of sedimentation in the system. This was followed by a shift to erosion as the increased urban runoff took effect, although the channel remained smaller after 20 years even though channel capacity was increasing relative to the peak sedimentation period. Further surveys did document increasing channel widths in subsequent decades (1973–1993; Leopold et al., 2005). Hollis and Luckett (1976) and Douglas (1985b) similarly concluded that the enlargement phase had not yet been reached 17 years following urbanization for Harlow, Essex in the U.K., and Kuala Lumpur in Malaysia, respectively. In the case of Kuala Lumpur, it took 17 years for the river to simply decrease its sediment load (period b in Fig. 5) and to shift from an aggrading to an erosive system, so many more years would be required for sediments to be completely flushed out. The long time period for the sedimentological adjustment phase for Kuala Lumpur is consistent with high sediment loads (Tables 2a and 2b) and associated bed aggradation and channel reduction documented for tropical areas (Fig. 8), as was discussed earlier.

Third, the time it takes for river channels to complete the enlargement phase and reach a new equilibrium is also variable and ranges from several years to decades (period d in Fig. 11). On one end of the scale, the adjustment process could be completed after five years, as demonstrated for Armidale streams in New South Wales, Australia (Neller, 1988). For most other locations, the time required seems to be several decades. For the Philadelphia area in the U.S., Hammer (1972) found that channel enlargement leveled off after 30 years. Channel restabilization of watersheds in the Puget Sound lowlands of Washington was also found to occur generally within one or two decades of constant land use (Henshaw and Booth, 2000). Finkenbine et al. (2000) similarly concluded that streams in the Vancouver area in British Columbia achieved a new equilibrium 20 years after urbanization. The relaxation times are apparently also on the order of several decades for lowland British rivers (Roberts, 1989). At longer adjustment timescales, however, geomorphic change was still occurring rapidly in Sawmill Brook in Connecticut after 40 years following urbanization (Arnold et al., 1982), signifying that adjustment was not yet complete. Similarly, dramatic channel erosion in a southern California river system was still taking place some 40–50 years following development, furnishing two-thirds of the total sediment yield (Trimble, 1997), although land use may not have been constant in this area. Except for one fully urbanized basin (Ebisemiju, 1989a,b), streams investigated in Nigeria were also estimated to require more than 50 years to adjust to new hydrologic conditions (Ebisemiju, 1989a,b; Jeje and Ikeazota, 2002). MacRae and DeAndrea (1999) further calculated that channel enlargement may take 50–75 years to complete once development starts, supporting the conclusion that most fluvial systems may take several decades to adjust to the process of urbanization and reach a new equilibrium, if such equilibrium can be observed at all.

6.4. Equilibrium urban streams

A final issue related to time periods of adjustments is whether rivers can fully adjust to the impacts of urban development and achieve a new stability regime. Several key factors are especially relevant to determining possible adjustment paths toward a new equilibrium. First, construction must obviously cease and sediment sources must stabilize for the adjustment process to proceed toward a new equilibrium. Until then, even if floods were to wash away excessive sand deposits, they will likely rebuild again (Fox, 1976). Channels observed to be cleared of urban sediments over short time periods may be, therefore, only temporary and not necessarily adjusted conditions. Second, impervious surfaces and the artificial drainage network must also be completed for the runoff regime to stabilize. Continuing urbanization (both on the urban fringes and within the urbanized area) also makes steady state conditions difficult to achieve. If these watershed-scale processes can become steady, morphological adjustments can potentially be completed, with channels reaching new equilibriums and capable of accommodating the altered flow and sediment regimes.

A stable urban runoff-sediment regime does not, however, guarantee adjusted urban channels. Henshaw and Booth (2000) pointed out that, in the Puget Sound lowlands, some creeks have not stabilized even after 20 years of virtually unchanging land use, and others can restabilize in far less time even while land cover continues to change. Therefore, thirdly, the responsiveness to change must also depend on the local geomorphic and network context, such as the location within the watershed (Roberts, 1989; Montgomery and Buffington, 1997), mobility of channel materials (Chin, 1998), and the geologic substrate and vegetation characteristics that influence erosive resistance (Henshaw and Booth, 2000). For example, aggradation may persist for a longer time if urbanization occurs on an alluvial fan compared to an upland location, where the adjustment may not all occur within alluvial deposits. Fourth, in cases where urbanization induces catastrophic incision (Nanson and Young, 1981; Neller, 1989) leading to dramatically larger gully-like channels (Gregory and Park, 1976b; Booth, 1990), the adjustment process will likely be more complex, and timescales are also expected to increase. Fifth, climate change and variability adds a further confounding variable to understanding channel adjustments to urbanization, adding to the challenges of observing new equilibriums except in broad terms (Goudie, 2006-this volume). Lastly, whether rivers can fully adjust to urbanization effects further depends on the extent to which they can freely change. Thus, direct manipulation and management practices can dictate how channel adjustments will occur (Brookes et al., 2004; Fig. 13).

Investigations of urban-impacted streams over the past several decades in various parts of the world enable conclusions to be reached or inferred regarding the equilibrium status (Fig. 11). Clearly, some river systems were observed to reach new equilibriums following urbanization, evidenced by channels that were stable (Henshaw and Booth, 2000), no longer enlarging (Hammer, 1972), or containing excessive fine sediments (Finkenbine et al., 2000). Many urbanizing streams, however, were still undergoing adjustment at the time of study. These were characterized by channel reductions (Leopold, 1973; Hollis and Luckett, 1976) reflecting high sediment loads (Fox, 1976; Douglas, 1985b), variable downstream channel geometries (Ebisemiju, 1989a,b; Odemerho, 1992; Chin and Gregory, 2001; Jeje and Ikeazota, 2002; Laronne and Shulker, 2002), and rapid geomorphic changes (Arnold et al., 1982) including channel enlargement (MacRae, 1997; Trimble, 1997). These results reinforce the notion that, even though new equilibriums following urbanization are theoretically possible (Leopold et al., 1964; Graf, 1977) and observed in some examples (Fig. 11), they can be truly difficult to achieve given complex and changing process interactions. The results also highlight challenges of monitoring urbanizing systems over sufficiently long time periods to be able to observe such equilibriums directly within single systems.

7. Managing and restoring urban rivers

Because urbanization is largely an irreversible process that changes Earth surfaces, urbanizing stream channels are necessarily changed through the adjustment process, regardless of how well they can adjust. Managing urban river channels poses particular challenges because, as seen in Fig. 11, most are undergoing adjustments at one stage or another. Thus, how can changing urban rivers be properly managed and potentially restored? A full treatment of this topic is beyond the scope of this paper and can be found elsewhere (e.g. Riley, 1998). Nevertheless, an assessment of the urban transformation of river landscapes would be incomplete without noting some of the key challenges for managing and restoring transformed urban rivers.

The synthesis provided in this paper suggests that understanding the temporal stages of change and recognizing where along the adjustment process a

Fig. 13. Tilmore Brook, Hampshire, U.K., an example of a managed urban stream (see Brookes et al., 2004; photograph by A. Chin).

particular system may lie is especially important. Such understanding can assist decision making, even if the magnitude of change cannot be predicted precisely (e.g. Neller, 1989; Watershed Protection Techniques, 2000). For example, recognizing that channel enlargement is a requisite adjustment process to bring about eventual stability means that it may not be necessary, practical, or well-advised to impose immediate management to physically stabilize urbanizing channels (Henshaw and Booth, 2000). Understanding the evolution of urban rivers can also help to determine "what is natural" in restoration efforts (Graf, 1996), because the pre-urban channel state often can no longer be sustained under the changed hydrological conditions. Thus, different management goals are probably appropriate for watersheds at varying stages of development (Booth et al., 2002) and at varying degrees of adjustment (Chin and Gregory, 2005). In this context, identifying which channels are suitable for protection (least disturbed), rehabilitation (improving moderately degraded channels), or stewardship (maintaining the channel but improvement unlikely) could wisely guide restoration efforts (Booth et al., 2004).

Recognizing spatial variations in channel adjustments within and between areas is also important to developing appropriate management schemes for changing urban rivers. Variations within watersheds mean that different strategies may be required for different channel segments to handle spatially distributed response mechanisms (Chin and Gregory, 2005). Consideration of spatial variations in a larger holistic catchment context also accords with the general philosophy of employing softer and more sustainable engineering methods in river restoration (Brookes, 1995; Hey, 1997). The emerging trends in the adjustment of urban river channels among different hydroclimatic regions further suggest that it may be possible to develop general guidelines for urban stream management and restoration for different environments in the future.

8. Conclusions

Analysis of research results from more than 100 studies (58 morphologic investigations) conducted across the world and published in the English language since 1956 permit answers to the three questions posed in this paper. First, urban development has transformed river landscapes across Earth's surface by changing hydrologic and sedimentologic regimes, causing a range of morphological adjustments. Empirical data have shown that these changes generally accord with the conceptual model outlined by Wolman in 1967, where a phase of sedimentological response, characterized by increased sediment production on the order of 2–10 times, is followed by eventual decline that couples with erosion from increased runoff to produce channel enlargement. Channel enlargement was reported in ~75% of the studies recording morphological results (see also Gregory, 2006-this volume), with cross-sectional areas generally increasing 2–3 times and as much as 15 times. A range of other changes have also been documented, including decreases in sinuosity, increases in bed material size and in drainage density, along with other chemical, biological, and ecological effects. Some of these changes may be transient, such as the increased sediment production and sediment loads that are part of the river landscape only until they are flushed away, but others are more lasting, especially channel enlargement or incision. In this regard, urban development does leave permanent imprints on river landscapes.

Second, although the impacts of urbanization are more easily summarized in terms of averages, considerable variability occurs between and within locales. Within areas, spatial variation in morphological responses results from differences in lithology, vegetation, slope, and urban structures, including road crossings and channelization. Between areas, regional trends are emerging for various hydroclimatic environments. Whereas most research on urbanization impacts on river systems has emphasized temperate environments, data now accumulated for tropical settings indicate a stronger sedimentological response in the tropics because of the intensity of precipitation and highly weathered soils, and thus channel reduction is more commonly observed in those areas. At the other end of the climatological spectrum, embryonic research in arid environments suggests more variable morphological responses to urban development, characterized by rapid changes over short distances and spatial patterns related to desert road crossings. These responses are perhaps not surprising given the high variability governing precipitation input and fluvial responses in desert areas, along with infrastructure particular to arid regions.

Third, the persistence of urban-induced impacts can be conceptualized as time periods of adjustments for the various stages, characterized by the lag time, reaction time, and relaxation time (Graf, 1977; Simon, 1989). Available data indicate that the lag time from the start of urban development to a sedimentological response could be as short as several months. On the other hand, several years to decades seem necessary to clear construction-related sediments, with longer time periods expected for humid tropical systems that carry greater sediment loads. The time required for rivers to complete the enlargement phase is variable and ranges from several years to cases where systems were still unstable 40–50 years following adjustment. Average relaxation times are probably on the order of several decades, although a case-by-case assessment is required to determine specific time periods of adjustment, as generalities are not easy to apply, especially in cases where catastrophic responses occur.

Considerable recent interest in the published literature has focused on the question of whether urban streams can truly adjust to changed hydrologic conditions and reach new stability regimes. The range of research investigations has demonstrated that this is indeed possible for most rivers, given the degrees of freedom with which to adjust, albeit over longer time periods in some. The result is an urban stream that, while possessing different characteristics (i.e. larger dimensions, coarser bed materials, straighter channels), is presumably adjusted to the prevailing flow and sediment regimes imposed by the urbanized watershed. The evolution of these streams is difficult to observe and rarely documented within single systems, highlighting the rare opportunities that may be available to monitor urbanizing streams over sufficiently long periods dating to pre-urban conditions. Nevertheless, streams in urban areas pose particular challenges for management given an inherent changing nature. Effective management requires a clear understanding of the temporal stages of change and the spatial variations in channel adjustment. The time is opportune to meet such challenges from a multitude of perspectives (Nilsson et al., 2003), as research investigations from a range of world areas over the past half century have clearly provided a solid foundation with which to apply, and upon which to further build.

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