Chapter 6
Streams and Urbanization

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"Urbanization" encompasses a diverse array of watershed alterations that influence the physical, chemical, and biological characteristics of streams. In this chapter, we summarize lessons learned from the last half century of research on urban streams and provide a critique of various mitigation strategies, including recent approaches that explicitly address geomorphic processes. We focus first on the abiotic conditions (primarily hydrologic and geomorphic) and their changes in streams that accompany urbanization, recognizing that these changes may vary with geomorphic context and climatic region. We then discuss technical approaches and limitations to (1) mitigating water-quantity and water-quality degradation through site design, riparian protection, and structural stormwater-management strategies; and (2) restoring urban streams in those watersheds where the economic, social, and political contexts can support such activities.

6.1 Introduction and Paradigms—How Do Streams "Work"?

6.1.1 Channel Form

The term *stream channel* means different things to different people. To an engineer, it is a conduit of water (and perhaps, sediment). To a geologist, it is a landscape feature typically constructed by the very flow of water and sediment that it has carried over many years or centuries. To an ecologist, it is an interconnected mosaic of different aquatic and riparian habitats, and the organisms that populate it. To a government regulator, it is a particular landscape feature that may impose adjacent land-use constraints and whose flow should meet certain standards for chemical composition. And to the urban public, it can be an aesthetic amenity, a recreational focus, or an eyesore (and sometimes, all three).

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In this chapter, we approach the stream channel primarily from its physical perspective, namely as the product of the primary watershed processes of water runoff and sediment delivery, together with the secondary components of large woody debris and trace (but locally critical) chemical constituents. Of course, the effects of human activity on stream channels cannot be ignored in the context of the urban water environment. Our goal, however, is to provide a basis from which to understand the influences of watershed urbanization, deliberate channel manipulations, and climate change. This is best achieved by approaching the topic through the perspective of the multi-scale processes that normally give rise to these features, and that in turn have supported the suite of biota that have evolved to thrive in these dynamic environments (Frissell et al. 1986, Church 2002).

Before embarking on a discussion of river-channel form and behavior, we must draw a distinction between two fundamentally different types of channels. *Alluvial channels* are those that have been carved by the water flow into deposits of the very sediment carried by that flow in the past, and that presumably could be carried by that flow in the future. These "self-formed" channels are free to adjust their shape in response to changes in flow, because their flows are capable (at least episodically) of moving the material that forms their boundaries (Fig. 6.1). The detailed

Fig. 6.1 View of an alluvial channel, whose boundaries are composed of the sediment previously transported by the flow under its current hydrologic regime

Fig. 6.2 View of a non-alluvial channel, whose boundaries cannot be modified under the current discharge regime (Los Angeles River, California)

hydrodynamics of how these channels establish their preferred dimensions and shape are complex and still not fully understood. However, we can recognize remarkable similarities in the behavior of these channels worldwide, readily expressing the net result of processes only imperfectly understood.

In contrast, *non-alluvial channels* are unable to adjust their boundaries, or at least not over relatively short time periods. A variety of channels express this condition to varying degrees: bedrock ravines, channels choked with landslide sediment or the debris of a catastrophic flood, channel sediment dominated by immovable boulders derived from the surrounding hillside deposit, or channels with thick and deeply rooted bank vegetation. In the urban environment, the most common non-alluvial channel is a piped or concrete-lined conduit (Fig. 6.2). In nearly all such instances, any degree of sediment movement or deposition within a non-alluvial channel will encourage that channel towards a more “alluvial” behavior. Thus these categories are not absolute but instead are gradational in both space (i.e., up and down the channel) and in time. Nevertheless, the distinction is a useful one and its recognition can save the planner or engineer from much fruitless analysis in certain types of channels and stream systems.

6.1.2 Water Discharge

In every setting, the most obvious role of a stream channel is to convey water from the contributing watershed. Flows rise and fall relatively rapidly in response to rainfall during storms or snowmelt, and they maintain a more steady discharge from the slow release of groundwater. With small contributing areas or in arid climates, stream channels may not carry any flow at all during dry weather.

A useful distinction is between the components of runoff that reach the stream channel quickly and those that arrive more slowly, often days (or longer) after the rain has stopped. If hillslope runoff reaches a stream channel during or within a day or so of rainfall, commonly following a flow path over or close to the ground surface, it causes high rates of discharge in the channel and is usually classified as *storm runoff* or *direct runoff*. Water that percolates to the groundwater moves at much lower velocities by longer paths and so reaches the stream slowly, over long periods of time. Water that follows these paths sustains streamflow during rainless periods and is usually called *base flow*. A formal distinction between these types of runoff is needed for certain computational procedures, but for our purposes a qualitative understanding is sufficient.

The relative importance of these flow paths in a region (or more particularly on each hillslope) can be affected by climate, geology, topography, soil characteristics, vegetation, and land use. The dominant flow path may vary between large and small storms. The most important discrimination, however, is based on which is larger: the rate of precipitation (known as the "rainfall intensity") or the rate at which water can be absorbed by the soil (the "infiltration capacity"). Where runoff primarily occurs in regions (or during particular storms) in which the rainfall intensity exceeds the infiltration capacity of the soil, surface runoff occurs because the ground cannot absorb all of the rainfall. This characterizes areas of "Horton overland flow regime." In contrast, a "subsurface flow regime" predominates where the rainfall intensity is typically low and so all precipitation typically infiltrates. Runoff can still occur in areas dominated by subsurface flow, but measured discharges have a much more attenuated response to rainfall because flow paths are primarily via the subsurface.

In most humid regions where the soil's infiltration has not been locally impacted, a subsurface flow regime commonly predominates. In arid and semi-arid regions, infiltration capacity is commonly limiting and rainfall, when it occurs, can be quite intense; Horton overland flow is thus the dominant storm runoff process. One common expression of these different regimes is the persistence of dry-weather (i.e., "perennial") flow in humid regions, because subsurface water is abundant and groundwater discharges continue to occur between storms.

The changing discharge in a stream is commonly displayed as a *hydrograph*, a graph of the rate of discharge at a point in a stream (or runoff from a hillside) plotted against time. Discharge is usually expressed as a volume of water per unit time (as cubic meters per second (cms) or cubic feet per second (cfs)) (Fig. 6.3).

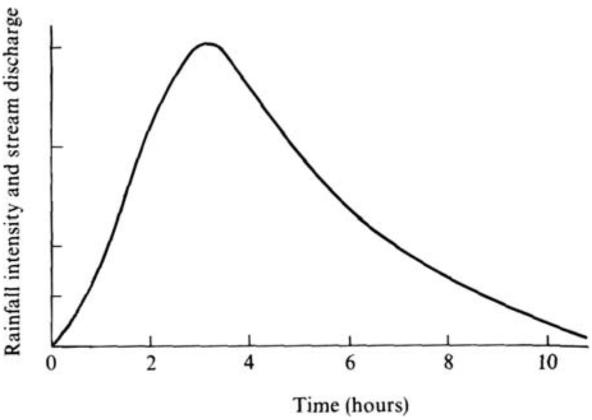

Fig. 6.3 An example of a hydrograph, showing the variation of discharge with time (modified from Dunne and Leopold (1978))

If this volume per unit time is divided by the area of the catchment in appropriate units, the runoff can be expressed as a depth of water per unit time (e.g., centimeters per hour or inches per day), which is very convenient for comparing with similarly expressed rates of rainfall, infiltration, and evaporation.

6.1.3 Sediment Transport

Precipitation falling on the landscape, together with the action of biological agents, breaks down rocks by weathering. Surface runoff and streamflow carry this load and transport the weathered debris. These various actions gradually move the rock debris toward the oceans, ultimately lowering the continents and depositing the materials in the sea. Successive periods of uplift ensure that the leveling process never becomes complete. But the downcutting or denudation of the land masses proceeds inexorably on all continents.

The rate of denudation seems slow but the amount of debris moved is immense. The rate is variously expressed as the spatially averaged speed at which the land surface is being lowered (e.g., in millimeters per 1,000 years), the annual amount of sediment being delivered into stream channels produced per unit area of watershed area (the sediment delivery, e.g., in tonnes per square kilometer per year), or the amount of sediment being carried past a point in a river in a given day under a given discharge (the sediment yield, e.g., in kilograms per day).

The average sediment load of a channel thus comprises the average rate at which hillslope sediment is delivered into stream channels, combined with the amount of sediment that is eroded from the bed and banks of the channel itself. Although not nearly as self-evident to the urban planner or city dweller as the water flow within the channel, the sediment load is a critical contributor to the physical, chemical, and biological conditions of an urban stream.

Fig. 6.4 A view of a stream and its adjacent floodplain, the recently constructed surface adjacent to the channel that is still episodically inundated by high flows

6.1.4 Floodplains

Most alluvial river channels are bordered by a relatively flat area or valley floor. When the water fills the channel completely (and so is at "bankfull stage"), the water level matches the elevation of this ground surface, which is called the *floodplain* (Fig. 6.4). This term is also used by both planners and engineers to identify the area adjacent to a channel that is inundated by floods of a given recurrence interval (e.g., "the 10-year floodplain"), but here we mean a distinct, observable land feature itself.

Geomorphically, a floodplain is defined as the flat area adjoining a river channel, constructed of alluvium by the river under the present climatic and land-use regimes. In natural settings, floodplains commonly are constructed by the lateral migration of channels and the subsequent deposition of sediment over a period of many hundreds and thousands of years without significant change in that channel's width or depth. This definition of a floodplain includes the concept, very difficult for the public and their elected officials to grasp, that the floodplain is an integral part of the river channel itself. It is not occupied by water as often as is the identifiable (low-flow) channel, but as a part of the river's "high-flow channel," its inundation is virtually assured over time, and its modification almost always has significant downstream consequences.

6.1.5 Water Chemistry

Just as the flow and sediment load of a stream integrates the contributions from the upstream watershed, so the chemical composition of the water reflects the contributions of both natural constituents and human-generated compounds throughout the watershed. Urbanization invariably results in a net increase in surface runoff because of soil compaction and new impervious surfaces, and so a great proportion of the water delivered to streams bypasses the cleansing influence of soil and plants. Because human activities in urban areas also increase inputs of nutrients, metals, organic compounds, and other potential pollutants to the land surface, urban storm runoff normally results in larger loads and more variable concentrations of chemical pollutants than runoff from undisturbed watersheds.

6.1.6 Biota

River water supports a world of its own. The microorganisms alone comprise a surprising variety and number of forms, while freshwater fish are often one of the most prized natural resources of a region. The *biotic health* of a stream is indicated by the variety and the composition of the population of organisms, both visible and microscopic. Although this chapter does not fully explore the details of stream ecology in the urban environment, we recognize that biology is commonly the overriding goal that drives much of the present activity in stream enhancement. The environmental planner has a large stake in the biotic health of the watercourse because it affects the perceived value of the amenity, the potential for recreation, the degree of regulatory attention, and the health of the surrounding community.

Using measures of plant and animal populations is also a particularly attractive way to assess aquatic health because organisms tend to integrate the effects, both known and unknown, of stream and watershed conditions (Karr and Chu 1999). However, a sole reliance on measures of biotic health can also limit our ability to act promptly and effectively to solve socially important problems. If freshwater fish are a major resource value, for example, then measuring their abundance will surely tell us the status of that resource, but any decline in that population will come only when degradation has already occurred and may be too late to correct.

6.1.7 Social Amenities of Urban Streams

Stream corridors in urban areas range from repulsive, polluted drainage ditches to verdant oases of biodiversity, recreation, and renewal. There is an emerging perspective that urban stream corridors should be much more than engineered conduits for fast conveyance of runoff and other discharges. Indeed, many communities are now focusing on stream and river corridors as high-value amenities not only for recreation, but as focal points for providing social, aesthetic, and educational benefits. Stream corridors are increasingly viewed not only as a “right-of-way” for floodwaters, but also as places where urban dwellers can access pedestrian and bicycle paths, go boating, experience a renewing environment, learn more about local animals and plants and whole ecosystems, and even swim. Accordingly, the management of urban stream corridors is most effective when multiple uses and functions are recognized, and policies balance human uses with practices necessary for sustaining the ecological health of the stream.

6.2 How Development Affects Stream Processes

6.2.1 Hydrologic Effects

The urbanized landscape: Modifications of the land surface during urbanization change the type and the magnitude of runoff processes. These changes in runoff processes result from vegetation clearing, soil compaction, ditching and draining, and finally covering the land surface with impervious roofs and roads. The infiltration capacity of these covered areas is lowered to zero, and many areas that remain soil-covered are trampled to an almost impervious state. Thus Horton overland flow is introduced into areas that formerly may have generated runoff only under the subsurface flow regime. Resulting increases in storm runoff rates and total volumes lead to difficulties with storm-drainage control, stream-channel maintenance, groundwater recharge, and water quality.

This fundamental change in runoff-generating processes, then, is the major hydrologic consequence of urban development. Even where Horton overland flow occurred in the undeveloped landscape, runoff rates and volumes will increase further as a result of urban development. Although the downstream impacts of those increases are not expected to be as great as where subsurface flow once occurred, they can also be quite significant.

Besides eliminating soil-moisture storage and increasing imperviousness, urbanization affects other elements of the drainage system. Gutters, drains, and storm sewers are laid in the urbanized area to convey runoff rapidly to stream channels. Natural channels are commonly straightened, deepened, or lined with concrete to make them hydraulically smoother. Each of these changes increases the hydraulic efficiency of the channel, so that it transmits the flood wave downstream more quickly and with less storage in the channel. Higher downstream flood peaks typically result.

The increase of storm runoff has many costly consequences in urban areas. Frequent overbank flooding damages houses and gardens, or disrupts traffic. The capacities of culverts and bridges may be overtaxed. Channels become enlarged in response to the larger floods, and building lots suffer erosion and reduction of their value. Biological communities are disrupted by both these physical changes and the altered flow regime itself.

The measurement and prediction of hydrologic response: The human activities accompanying development produce measurable effects in the hydrologic response of a drainage basin. Most dramatic, and most often studied, is the increase in the maximum ("peak") discharge associated with floods. Other hydrologic changes also accompany watershed urbanization, but they require relatively sophisticated methods to recognize their effects and predict their magnitude. Hydrologic models are the most common tools by which runoff changes are studied; they allow us to understand the changes wrought by urbanization and show why many of the efforts to control runoff problems have not been terribly successful.

Decades of direct hydrologic measurements and simulation models quantify several related consequences of watershed urbanization: For any given intensity and duration of rainfall, the peak discharge is greater (by factors of 2 to 5; Hollis 1975), the duration of any given flow magnitude is longer (by factors of 5 to 10; Barker et al. 1991), and the frequency with which sediment-transporting and habitat-disturbing flows move down the channel network is increased dramatically (by factors of 10 or more; Booth 1991).

More recent assessments of hydrologic change have recognized other aspects of an altered flow regime, however, that are not expressed by traditional hydrologic metrics such as these but that may have even more significant geomorphic and ecological consequences. These include various attributes of non-extreme flows, such as the relative distribution of runoff between wet-season base-flow periods and high-flow periods (Konrad and Booth 2002) or the rate of rise or fall of individual storm hydrographs (Poff et al. 1997). As such, they may provide useful criteria for identifying flows, and entire flow regimes, that may have significant geomorphic or ecological effects on streams.

The influence of urban development on base flow will change by location and with the season, because base flow derives from different sources in different places and at different times of the year. During the wet season, base flow includes slow drainage from soils, which is likely to be lower in urban areas. During the dry season, base flow is fed from groundwater discharging from deeper aquifers, whose recharge may or may not be affected by the land-surface modifications associated with urban development. Human use of shallow groundwater or surface-water resources can reduce base flow during the dry season, whereas using water from a deep aquifer or imported from another basin to irrigate landscape during a dry season can actually increase base flows in urban streams (Konrad et al. 2005). Thus this attribute of stream hydrology, critical to both ecological and aesthetic functions, does not have a uniform response to urbanization.

Characterizing imperviousness: Although we commonly invoke "impervious surfaces" as a prime determinant of runoff changes in urban areas, not all imperviousness is created equally. Most important is the distinction between total impervious area (TIA) and effective impervious area (EIA). TIA is the "intuitive" definition of imperviousness: that fraction of the watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt, and buildings. Hydrologically, however, this definition is incomplete for two reasons. First, it ignores nominally "pervious" surfaces that are sufficiently compacted or otherwise so low in permeability that the rate of runoff from them is similar or indistinguishable from pavement (Burges et al. 1998). The second limitation of using TIA as a metric of hydrologic response is that it includes some paved surfaces that may contribute nothing to the storm runoff into the downstream channel. For example, rooftops that drain onto splashblocks that disperse the runoff onto a garden or lawn may not create any change in flow in the downstream channel at all. This metric, therefore, cannot recognize any contribution to stormwater mitigation that may result from alternative runoff-management strategies using, for example, pervious pavements or rainwater harvesting.

The first of these TIA shortcomings, the production of significant runoff from nominally pervious surfaces (Burges et al. 1989), is typically ignored in the characterization of urban development. The reason for such an approach lies in the difficulty in identifying such areas and estimating their contribution, and because of the credible belief that pervious areas will shed water as overland flow in proportion, albeit imperfectly, with the amount of impervious area. The second of these TIA shortcomings, the inclusion of non-runoff-contributing impervious areas, is formally addressed through the concept of EIA, defined as the impervious surfaces with direct hydraulic connection to the downstream drainage (or stream) system. Thus, any part of the TIA that drains onto pervious (i.e., "green") ground is excluded from the measurement of EIA. This parameter, at least conceptually, captures the hydrologic significance of imperviousness. EIA is the parameter normally used to characterize urban development in hydrologic models, although its direct measurement is difficult and commonly accomplished only by correlation to TIA.

6.2.2 Geomorphic Effects of Urbanization

Historically, human-induced alteration of stream channels was not universally seen as a problem. Dams and other stream-channel "improvements" were a common activity of municipal and federal engineering works of the mid-20th century (Williams and Wolman 1984); "flood control" implied a betterment of conditions, at least for streamside residents (Chang 1988); and fisheries "enhancements,"commonly reflected by massive infrastructure for hatcheries or artificial spawning channels, were once seen as unequivocal benefits for fish populations. Today, however, these alterations are widely recognized as commonly degrading the physical function, the biological integrity, and the aesthetic appeal of urban streams.

Even when not subjected to direct manipulation, however, urban-induced channel changes commonly do occur. As a result of hydrologic changes, channel widths and depths commonly increase throughout urban areas, and heterogeneous channel morphology becomes more simplified and uniform. Channels expand gradually in response to progressive increase in the flow regime (e.g., Hammer 1972, Booth and Jackson 1997, Bledsoe and Watson 2001). Yet this relationship, although common and intuitive, is not universal. A few studies note a reduction in channel width or depth with increases in watershed urbanization and, presumably, the discharge that accompanies it (e.g., Leopold 1973).

Although channel dimensions do commonly increase in response to gradual increases in the flow regime, changes in channel dimensions are usually sporadic and abrupt, often happening during particular storms when a single large flow can annul periods of stability that may have spanned many years (Booth and Henshaw 2001). Channels can also experience rapid and nearly uncontrolled downcutting of the stream bed, usually in response to an increase in the flow rate combined with specific combinations of gradient, substrate, and reduced in-channel roughness (Booth 1990).

The flow increases themselves can also increase the washout of in-stream woody debris or erosion of riparian vegetation, critical components of both channel stability and ecological health in forested (or once-forested) watersheds. Even under the best of circumstances, accelerated wood removal cannot be compensated by natural rates of regrowth and replacement. More commonly, however, urbanization eliminates the riparian corridor altogether, which means that in-channel wood is not replaced at all. This can result in further acceleration in rates of urban-induced channel expansion.

Change in the rate of sediment delivery into the channel network is another common consequence of urban development with potentially significant consequences for channel form. The broad relationship between stages of watershed development and resulting sediment loads have long been recognized and presented in studies such as Wolman (1967). In general, an initial phase of increased sediment delivery is associated with land clearing and soil disturbance during watershed development. As impervious surfaces such as road networks, parking lots, buildings, and compacted areas increase their footprint, sediment yield from upland areas is diminished as runoff is simultaneously increased. In terms of stream processes, the capacity to transport sediment is significantly increased even as the supply of sediment for transport may be concurrently decreased. In subsequent stages of the process, channel erosion from increased flows can provide a new source of sediment that can account for more than half of the total sediment load of an urban stream (Trimble 1997).

The observed sequence of channel responses, however, can be complex. Increased sediment loads, generated at particular stages in the forest–agriculture–urban sequence of North American land development, exert a tendency for channel aggradation that opposes the tendency for erosion that accompanies increasing discharge. The time-varying interplay of these contradictory factors probably explains much of the channel narrowing or shallowing that is sometimes measured.

Efforts to integrate the generally similar, but locally disparate, observations of channel change (see Schumm 1977, Park 1997, Thorne et al. 1998) into a unified model generally articulate a sequence of anticipated changes over time. Simon (1989), for example, evaluated the consequences of channelization and described a widely used evolutionary sequence of undercutting, bank failure, channel widening, and restabilization that closely resembles that of urbanization. Arnold et al. (1982) also recognized the interplay of spatial factors, notably upstream stream erosion and downstream deposition, that can result in multiple "responses" along the same channel, a theme of complex spatial and temporal response that is echoed by many careful studies of urban channels.

Such changes to channel morphology are among the most common and readily visible effects of urban development on natural stream systems (Walsh et al. 2005). The actions of deforestation, paving of the uplands, and channelization can produce tremendous changes in the delivery of water and sediment into the channel network. In channel reaches that are alluvial, subsequent responses can be rapid, dramatic, and readily documented: channels widen, deepen, and in extreme cases may downcut many meters below the original level of their beds. Alternatively, they may fill with sediment derived from farther upstream and braid into multiple rivulets threading between gravel bars. In either case, they are transformed far beyond the range of conditions displayed at any time during their pre-urban period. They can become hazardous to any surrounding human infrastructure, and they no longer can support their once-natural populations of benthic invertebrates and fish.

6.2.3 Chemical Effects

The chemical constituents of natural streams vary widely with climatic region, stream size, soil types, and geological setting. However, small natural streams typically have relatively low levels of both dissolved and particulate constituents. As urbanization alters the pathways by which water passes over and through the ground surface, and as we introduce new chemical constituents into the near-surface environment, the chemical composition of surface and ground waters change. The worst of these problems have historically emanated from discrete sources such as a municipal sewage outfall or the cooling-water discharge of a thermal power plant. In the United States, large expenditures on existing sources and new regulations on future sources have yielded dramatic reductions in this type of “point-source” pollution during the 1970s and 1980s. Yet these gains are slowly being lost to more diffuse nonpoint sources of contaminants, which continue to change the quality of surface and ground waters almost unabated.

These changes in water quality are nearly inescapable byproducts of modern land-use development and human activities in both agricultural and urban settings. The spatial pattern of such increases, however, is quite irregular, and simple correlations between any measure of urbanization (e.g., percent watershed imperviousness) and concentrations of chemical pollutants are generally poor. Furthermore, the linkages between chemical constituents and beneficial uses are very poorly known, particularly at low but chronic levels, and the natural variability of many of these constituents often makes the identification of human effects ambiguous or very time-consuming. In areas of low or even moderate urban development, water-chemistry parameters often do not exceed water-quality standards (Horner et al. 1997). Other constituents, particularly manmade compounds with unknown but potentially significant biological activity at very low concentrations, have no health or water-quality standards at all.

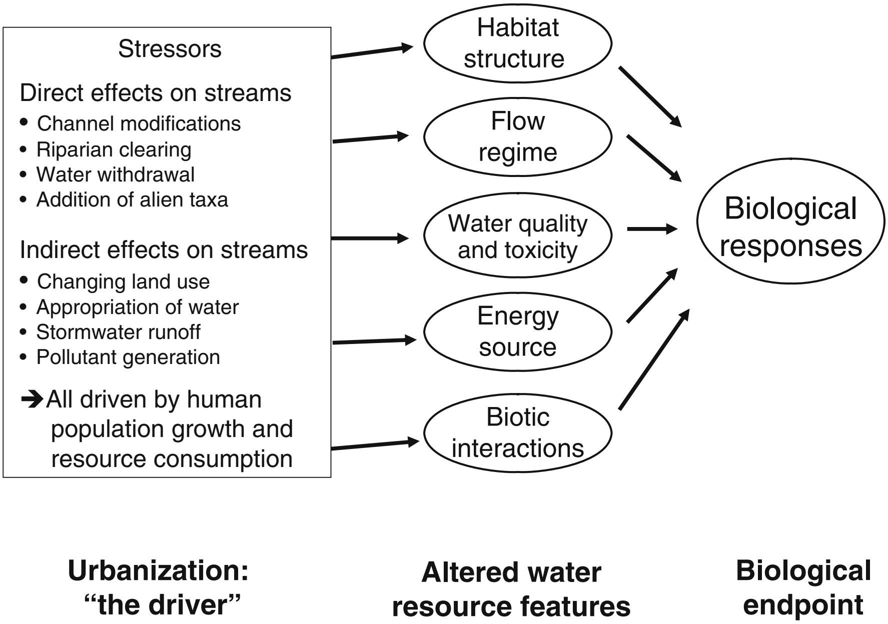

Fig. 6.5 Five features that are affected by urban development and that affect biological conditions in urban streams (modified from Karr (1991); Karr and Yoder (2004))

6.2.4 Ecological Implications

Stream biota evolves over millennia as a result of the complex interactions of chemical, physical, and biological processes. These processes and interactions can be grouped into five major classes of environmental "features" to form a simple conceptual framework (Fig. 6.5; Karr 1991, Karr and Yoder 2004). When one or more of these features is affected by human activities, the result is ecosystem degradation (Allan 2004, Paul and Myer 2001). No one feature, however, is always the limiting factor for biological condition; conversely, improving any one feature does not guarantee corresponding improvement in biology. An important corollary for our subsequent consideration of stream enhancement is that correcting or "restoring" one altered feature does not necessarily eliminate the need to correct another.

In the urban environment, changes are imposed on these features by a wide variety of human activities, via a number of pathways that operate at multiple spatial scales. So, for example, watershed-scale changes in land cover alter hydrology through stormwater inflows to streams and reduced groundwater recharge. Adjacent to stream channels, local changes to land cover can affect the input of energy via organic material and sunlight; and, at a single site, direct modification of the channel itself can disrupt the habitat structure.

Although any of the five features of Fig. 6.5 can be responsible for the loss of biological health in an urban stream, changes in flow patterns are commonly recognized as a particularly important and ubiquitous pathway by which urbanization influences biological conditions. This primacy reflects the magnitude of hydrologic change commonly imposed by urbanization (e.g., Booth and Jackson 1997, Konrad and Booth 2002) and the close correlations reported between biological health and various metrics of hydrologic alteration (e.g., Poff and Ward 1989, Poff and Allan 1995, Roy et al. 2003). Such metrics reflect interactions between flow regime and the physical characteristics of the channels upon which they are imposed. Because the frequency and erosive potential of flows that shape in-stream habitats are amplified by imperviousness, the overall intensity of habitat disturbance experienced by stream biota is often more severe after watershed development. The resulting disequilibrium between flow regime and channel form alters habitat "dynamics" and degrades biological health by reducing the quantity, quality, and diversity of available habitats.

Even where urban-modified flows have been managed and downstream channels have adjusted (or been directly modified), a "stabilized" channel should not be mistaken for a return of the channel to its natural state (Henshaw and Booth 2000), and a "stream-stabilization project" should never be mistaken for ecological restoration. A re-stabilized channel will typically be larger and less geomorphically complex than the pre-urbanization channel form. It will also have altered habitat and flow patterns, water velocities, sediment flux, and organic inputs (e.g., Jacobson et al. 2001, Roesner and Bledsoe 2002), and it may carry an ecological legacy of extirpations that precludes the return of pre-disturbance biota (Harding et al. 1998). Additional assessment and rehabilitation actions are almost always required to restore the biological integrity of the stream even after geomorphic stability is achieved, and the success of such additional efforts is by no means assured.

The inherent complexity of watershed processes makes it difficult to isolate the effects of urbanization on ecological health. Interactions between stream water quality and quantity, and year-to-year climate variability, can confound predictions regarding the ecological implications of urbanization. At present, it is usually not possible to accurately predict the specific ecological changes that will occur under alternative watershed-management scenarios. Nevertheless, the last few decades of research and management experience provide a very useful knowledge base and suite of science-based strategies for managing urban watersheds.

6.3 Management Principles

Channels are problematic for people, because they are attractive but resist our efforts to manage them—they flood, they migrate, they deposit sediment, they downcut—in short, they are dynamic systems, but they spend long periods of time in quiescence that lull the unwary into approaching too closely and developing too permanently. People are problematic for channels too—we alter them directly for our own purposes, and our manipulation of the watershed's land surface affects every aspect of what combines to form a natural stream or river. As a result, channels can lose both their physical and biological functions without any intentional (but no less influential) actions on our part.

We recognize that pervasive watershed changes, notably during urbanization, fundamentally alter the rates and processes by which water and sediment are delivered to the stream channels. The channel form, in turn, changes in response to the altered delivery regime. Yet rather than address the problem at its source, namely the watershed area, most remedial efforts are expended at the final point of expression, namely the stream channel. Clearly, this is not rational.

Complete restoration of an already urbanized watershed, however, is rarely judged feasible (because of astronomical expense, daunting logistics, and limited effectiveness of available tools). However, the success of in-channel mitigation, however feasible and conscientiously applied, also is limited. This is the conundrum that faces even the most well-intentioned efforts at stream protection or enhancement in the urban water environment.

Even if achievable goals are of necessity limited, effective actions do exist and typically follow certain key underlying principles:

- hydrologic alteration is profound; hydrologic mitigation is critical;
- hydrologic mitigation must reflect both geomorphic and ecological principles;
- protecting riparian zones provides synergistic benefits; and
- goals, objectives, and evaluation are all needed for successful urban-stream enhancement.

These principles are enumerated in the following sections.

6.3.1 Hydrologic Alteration Is Profound; Hydrologic Mitigation Is Critical

As a consequence of urban-induced runoff changes, which in turn cause flooding, erosion, and habitat damage, jurisdictions have long required some degree of stormwater mitigation. The most common historic approach has been to convey stormwater runoff as rapidly and efficiently as possible away from developed areas to minimize the consequences of standing water. As this conveyance becomes more effective, however, the receiving downstream channels become subject to increasing peak discharges and consequent flooding of their own.

Thus, the first recognized hydrologic consequences of urbanization were those associated with peak-flow increases (i.e., "more flooding"). Careful analysis, culminating in a synthesis of many separate studies (Leopold 1968, Hollis 1975), showed how two factors, watershed percent imperviousness and watershed percentage with storm sewers, increased the peak discharges of floods. Large, infrequent floods were increased less than smaller, more common events; in general, Hollis found peak-flow increases of two- to three-fold are common for the moderate-sized floods in moderately urbanized watersheds. These general results have been replicated in both empirical and modeling studies, on many dozens of watersheds throughout the United States. Although there is a consistent pattern of peak-flow increase associated with increased watershed imperviousness, differences in "styles" of development (e.g., connectivity of imperviousness surfaces and drainage infrastructure) as well as climatic and geologic contexts contribute to high variability among regions and watersheds (e.g., Bledsoe and Watson 2001, Poff et al. 2006).

The first (and still most common) approach in reducing the magnitude of peak discharge has been through the use of detention ponds (Fig. 6.6a), which are placed downstream of the developed area (from which runoff is drained rapidly and efficiently) and upstream of areas prone to urban-increased flooding or erosion from high flows. These facilities can be designed to various levels of performance, depending on the desired balance between achieving downstream protection and the cost of providing that protection. A "peak" standard, the classic (and least costly) goal of detention facilities, seeks to maintain post-development peak discharges at their pre-development levels (Fig. 6.6b). This approach addresses the concern of flooding, for which the "peak" discharge is the only important parameter. Even if this goal is achieved successfully, however, the aggregate duration that such flows occupy the channel must increase because the overall volume of runoff is greater,

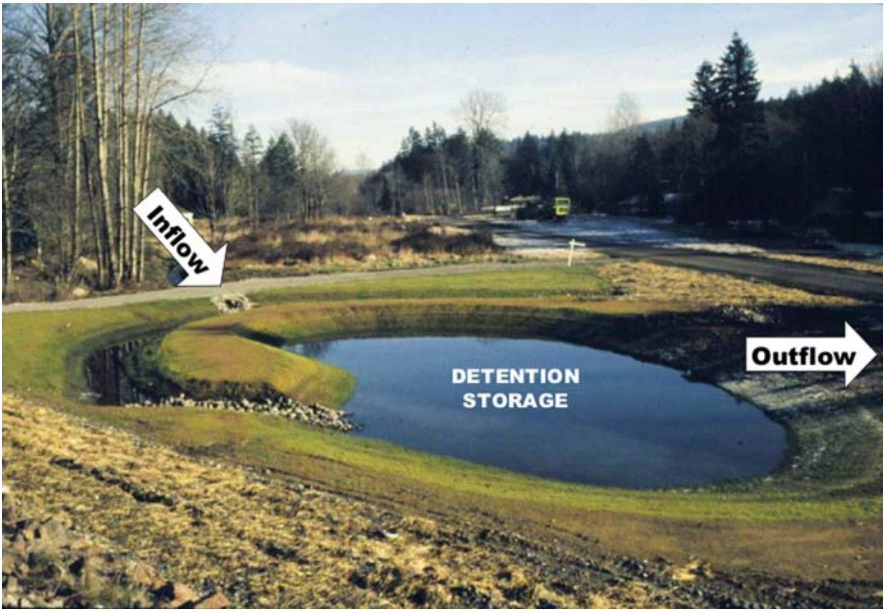

Fig. 6.6a A detention pond, designed to capture and temporarily store runoff from the adjacent residential development before releasing the water to the downstream channel (King County, Washington)

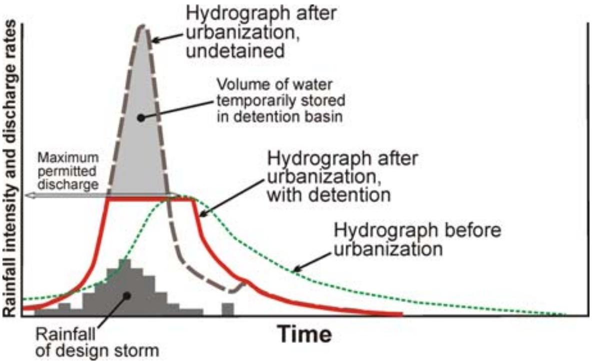

Fig. 6.6b Idealized hydrograph of a detention pond, showing the presumed rainfall from a chosen "design storm" (low gray bars) and comparing the three alternative hydrographs (pre-development, post-development without detention, and post-development with detention) that result. The maximum permitted discharge from the detention pond is normally set by the peak discharge from the pre-development watershed (modified from Dunne and Leopold (1978))

resulting in substantial stream-channel erosion (McCuen 1979, Booth and Jackson 1997, Roesner et al. 2001). If the channel is erosive, or if it supports biota with a particular suite of flow-related needs, significant damage may still result.

Thus, mitigating the erosive potential of increased runoff requires control of the *duration* (not just the magnitude) of flows across a wide spectrum of sediment-transporting discharges. A "duration" standard for detention-pond performance thus was developed in several jurisdictions to maintain the post-development duration of all discharges at pre-development levels (e.g., King County 1990, MacRae 1997). Duration standards are motivated by a desire to avoid potential disruption to the downstream channels by not allowing any flow changes that might increase sediment transport beyond pre-development levels. Without infiltration of runoff, however, the total volume of runoff must still increase in the post-development condition, and so durations cannot be matched (or reduced) for all discharges—below some discharge rate, the "excess" water must be released. This is accomplished by determining (or otherwise assuming) a threshold discharge below which sediment transport, or any other disruptive conditions, in the receiving channel is presumed not to occur.

The flow-duration control approach is a significant improvement over the "peak-shaving" standard, but it is not a panacea. Reductions in sediment delivery to stream channels may result in accelerated channel erosion and, therefore, habitat degradation, even if the pre-development flow characteristics are largely maintained (Bledsoe 2002). This occurs because the flow becomes more "hungry" for channel-forming sediment and the stream consequently compensates for the reduction in the watershed sediment supply through local boundary erosion. Moreover, additional analyses have shown that other measures of flow variability with likely biological importance, such as the seasonality of peak discharges or the time between sediment-transporting events, are not well maintained by such flow-mitigation approaches in the face of watershed urbanization (e.g., Konrad and Booth 2005). In other words, maintaining sediment-transport capacity is not an adequate surrogate for protecting the full universe of flow-related attributes of a stream.

6.3.2 Hydrologic Mitigation Must Reflect both Geomorphic and Ecological Principles

Native biological communities are adapted to and tolerate a range of aquatic habitat conditions that may become less available or completely disappear as a consequence of land-use changes. Watershed urbanization alters the interactions between flow, sediment and channel form that fundamentally control the quality, quantity, and spatial distribution of stream habitats (e.g., Jacobson et al. 2001, Roesner and Bledsoe 2002, Walsh et al. 2005). As such, there is broad consensus among river scientists that sustaining biological communities, and especially sensitive biota, requires maintaining flow and habitat dynamics within some range of natural variability (e.g., Bunn and Arthington 2002). Thus, hydrologic-mitigation practices derived from an understanding of both geomorphic and ecological processes are a prerequisite for maintaining stream ecological integrity. Because flow regime is the "master variable" controlling erosion, habitat availability, and ecological processes, the stormwater-management practices that are the most protective of stream health are those that minimize changes in the magnitude, frequency, duration, and variability of streamflows.

6.3.3 Protecting Riparian Zones Provides Synergistic Benefits

Urban development not only increases rates of water and sediment delivery but also encroaches on the riparian corridor. With the clearing of streamside vegetation, less wood enters the channel, depriving the stream of stabilizing elements that help dissipate flow energy and usually (although not always) help protect the bed and banks from erosion (Booth et al. 1997). Deep-rooted bank vegetation is replaced, if at all, by shallow-rooted grasses or ornamental plants that provide little resistance to channel widening. Furthermore, the overhead canopy of a stream is lost, eliminating the shade that controls temperature and supplies leaf litter that enters the aquatic food chain (Roberts et al. 2008).

Abundant research has demonstrated the ecological importance of preserving riparian zones, even where other measures have not been taken to mitigate the effects of urbanization. For example, Morley and Karr (2002) documented an increase in biological health from "very poor" to "fair" over <2 km along a single suburban Puget Lowland stream channel, finding that the variability was strongly explained by riparian land cover but not by overall catchment land cover. Good correlations between physical condition of channels and frequency of stream-road crossings are shown by a variety of studies (e.g., Avolio 2003, McBride and Booth 2005). Over two decades ago, Steedman (1988) showed the importance of both watershed disturbance and riparian corridor integrity in supporting a healthy fish population in streams of the American Midwest.

6.3.4 Goals, Objectives, and Evaluation Are Needed for Successful Urban-Stream Enhancement

Most urban streams are managed in a piecemeal, reactionary fashion. Managers often find themselves in a perpetual cycle of treating the symptoms of urban degradation with small-scale "band-aids" that are largely divorced from any sort of strategic planning for streams within their watershed context. Many managers perceive that social attitudes and values around urban-stream amenities are rapidly evolving in their jurisdictions, but most programs and activities are not rooted in stakeholder preferences or clearly defined goals.

Goals for enhancing and sustaining urban stream amenities are generally most useful and achievable when they grow out of an envisioning process that proactively garners input from the full spectrum of watershed stakeholders. The envisioning process necessarily involves planners, engineers, ecologists, and social scientists to connect alternative management strategies to probable future states defined in terms of valued amenities. That is, the process involves developing predictive scientific assessments (in the sense of Reckhow 1999) that integrate modeling, expert judgment, extensive communication, and developing the institutional commitments requisite for achieving a long-term vision for the stream systems within a particular jurisdiction. They also require a list of tangible activities that can make concrete progress towards these overarching goals.

This progress must be measured and assessed, lest the entire effort become meaningless. Even where basin-planning programs have identified and implemented practices aimed at achieving a particular long-term vision, stream-enhancement activities are rarely monitored and assessed (Wohl et al. 2005, Palmer et al. 2005). As such, the practice of managing urban streams suffers from a paucity of information and, therefore, knowledge, regarding which policies and tools are effective for placing a given type of urban stream on a desired trajectory.

Despite substantial knowledge gaps, a critical examination of the last few decades of research and monitoring suggests that it is plausible that integrated programs of hydrologic mitigation, riparian zone conservation, and pollution controls can potentially sustain aquatic biodiversity and valued social amenities in urban streams. Systematic monitoring and assessment of pre- and post-urban processes and conditions are essential for understanding the extent to which integrated management can maintain ecosystems that closely resemble pre-impact structure and function, as opposed to yielding new types of regional stream ecosystems (Westman 1985). Without such information, the goal of identifying sustainable management strategies becomes unattainable, and the rapidly growing population of urban streams will never reflect the aspirations of the people who inhabit their watersheds.

6.4 Technical Approaches to Urban Stream Enhancement

6.4.1 Hydrology and Geomorphology

Although the physical "channel design" is a common element of stream enhancement or stream restoration, a true alluvial channel is ultimately the product of its water and sediment regime. Although a set of design drawings or engineering plans can establish the initial template for channel form, the long-term morphology will reflect the hydrologic regime and the sediment load that passes down the channel. Conversely, if the channel is not designed to adjust then the interplay of channel form, flow regime, and sediment load will determine whether or not the outcome is "stable" or "successful."

In each of these circumstances, the role of hydrology is paramount, and there is no substitute for accurate hydrologic predictions. Current computer models use hourly (or more frequent) precipitation data as input to simulate many years of hydrologic response, keeping a running account of the amount of water within various hydrologic storage zones, both surface and subsurface. Individual storm "events" are not discriminated; the actual rainfall record, over time, determines how the hydrologic system responds. This approach is necessary to achieve the overarching goal of recognizing relationships between flow and biota, because much of the biotic response depends not on the characteristics of an individual storm but on the timing and the relationships of flows arising from multiple storms, and the sequence and distribution of those flows throughout the year. These critical factors cannot be explored in any other way.

One-size-fits-all practices based on "single-factor" ecology or extrapolation across all stream types is not likely to protect stream amenities. Streams differ in their resilience and response to the effects of urbanization (Montgomery and MacDonald 2002). A channel that naturally contains extensive bedrock control or very resistant boundary materials, for example, will be less physically susceptible to the hydrologic changes typical of urbanization than a fully alluvial stream in relatively erodible material. This suggests that stream-management activities aimed at mitigating the effects of hydrologic modifications will be most effective when tailored to different stream types.

Identifying simple thresholds that can be used to broadly prescribe stormwater policy will continue to be an attractive goal (e.g., $\leq$10% total watershed imperviousness, Schueler 1994)), but the outcomes of such an approach will be constrained and difficult to predict. Instead, a linked modeling framework that combines continuous hydrologic simulation, sediment delivery, and channel erosion models is probably necessary to protect fully the physical habitat characteristics of streams that are susceptible to geomorphic impacts (Richards and Lane 1997). Such a framework can provide a process-based, albeit uncertain, foundation for envisioning alternative future states of streams. Identifying appropriate predictive and assessment tools, and designing management practices that are demonstrably effective in conserving ecological integrity is an ongoing challenge that begs for improved interdisciplinary collaboration between engineers and ecologists.

6.4.2 Riparian-Zone Conservation and Restoration

Protecting and restoring riparian zones is a cornerstone of stream conservation. Although riparian corridors often constitute less than 5% of the total watershed area, they have a profound and disproportionate influence on the ecological integrity of streams (Gregory et al. 1991, Naiman et al. 2005). Protected streamside zones, sometimes called "buffers" in a regulatory setting, support stream health by moderating temperatures, filtering pollutants, providing food and cover, and preventing excessive channel erosion. There are many excellent resources that describe management strategies for riparian zones, including information on multi-purpose designs, model ordinances, and overcoming implementation issues (Lowrance et al. 1995, Schueler 1995, Center for Watershed Protection (CWP) 2008).

One of the key challenges in urban watersheds is restoring riparian zones along streams that have been engineered for drainage conveyance, or where channels have incised and have become disconnected from their floodplain, lowering the water table of the surrounding landscape (Fig. 6.7). Restoration of riparian corridors in these contexts requires careful prioritization of activities and multidisciplinary design teams of geomorphologists, engineers, and ecologists. Increases in channel and floodplain roughness associated with reestablishment of vegetation, debris inputs, and adjustments in stream morphology are generally at odds with the traditional approach to drainage infrastructure that emphasized "fast conveyance" of floodwaters. In many contexts, enhancing stream riparian corridors will require engineers and environmental planners to transcend the tension between encouraging fast conveyance versus establishing functional (and hydraulically rough) riparian corridors, in part by strategically identifying locations where riparian enhancement is feasible within the constraints of existing infrastructure and floodplain encroachment.

6.4.3 Low Impact Development and Land-Use Planning

Low Impact Development (LID) is a strategy for stormwater management that uses on-site natural features integrated with engineered, small-scale hydrologic controls to manage runoff by maintaining, or closely mimicking, pre-development watershed hydrologic functions (U. S. Environmental Protection Agency (USEPA) (1999), Puget Sound Action Team (PSAT) (2005). It is achieved most effectively at multiple scales—land-use planning at the scale of an entire watershed to identify and preserve key elements of the hydrologic system, together with engineering and site-design elements that are implemented at the scale of individual parcels, lots, or

Fig. 6.7 Modestly incised urban channel, with likely lowering of the water table beneath the adjacent and now-disconnected floodplain (Juanita Creek, Kirkland, Washington)

structures. In combination, these actions seek to store, infiltrate, evaporate, or otherwise slowly release stormwater runoff in a close approximation of the rates and processes of the pre-development hydrologic regime.

Most applications of LID have several common components:

- Preserving elements of the natural hydrologic system that are already achieving effective stormwater management, recognized by assessment of a site's watercourses and soils; channels and wetlands, particularly with areas of overbank inundation; highly infiltrative soils with undisturbed vegetative cover; and intact mature forest canopy.
- Minimizing the generation of overland flow by limiting areas of vegetation clearing and soil compaction (Arendt 1997); incorporating elements of urban design such as narrowed streets, structures with small footprints (and greater height, as needed), use of permeable pavements as a substitution for asphalt/concrete surfaces for vehicles or pedestrians; and using soil amendments in disturbed areas to increase infiltration capacity.
- Storing runoff with slow or delayed release, such as in cisterns or distributed bioretention cells, across intentionally roughened landscaped areas, or on vegetated roofing systems ("green roofs"). Runoff storage in LID differs from traditional stormwater management, notably the latter's use of detention ponds, primarily

by its scale—namely small and distributed in LID, large and centralized in traditional approaches.

These objectives are achieved through five basic elements that constitute a "complete" LID design (Coffman 2002):

1. Conservation measures—maintaining as much of the natural landscape as possible.
2. Minimization techniques—reducing the impacts of development on the hydrologic regime by reducing the amount of disturbance when preparing a site for development.
3. Flow attenuation—holding runoff on-site as long as possible, without causing flooding or other potential problems, to reduce peak discharges in the downstream channel.
4. Distributed integrated management practices—incorporating a range of integrated best management practices throughout a site, commonly in sequence.
5. Pollution prevention measures—applying a variety of source-control, rather than treatment, approaches.

Although these five elements can be applied to virtually any development, the specific manner in which they are used must be determined by the local climate and soils. Native soils, in particular, play a critical role in storage and conveyance of runoff. In humid regions, one to several meters of soil, generally high in organic material and relatively permeable, commonly overlie less permeable substrates of largely unweathered geologic materials. While water is held in this soil layer, solar radiation and air movement provide energy to evaporate surface-soil moisture and contribute to the overall evapotranspiration component of the water balance. Water not evaporated, transpired or held interstitially moves slowly downslope or down gradient as shallow subsurface flow over many hours, days, or weeks before discharging to streams or other surface-water bodies. In arid regions with relatively lower organic-content soils and vegetation cover, precipitation events can produce rapid overland flow response naturally; however, the principles of LID remain: retain native soils, vegetation, topography, and the various elements of the hydrologic system to preserve aquatic ecosystem structure and function.

6.5 Next Steps

6.5.1 Rivers and Streams Are Focal Points for Urban Renewal: These Are Systems Worth Restoring

Over one hundred years ago, urban designs were deliberately linked to water systems. As discussed later in this book, we have only recently rediscovered the fundamental idea that cities can express the multiple purposes of the urban water environment. Urban streams are neighborhood amenities that inspire passion and ownership from their nearby residents, and they can support self-sustaining biotic communities, even though those communities depart significantly from pre-disturbance conditions. This combination is particularly timely as we address the dual challenges of climate change and sustainability of our modern cities.

6.5.2 Define Realistic Goals for Urban-Stream Restoration

Functioning stream systems and watershed urbanization are not mutually exclusive, but seeking a direct analog to undisturbed aquatic systems ignores the profound alteration to water and sediment fluxes that are the hallmark of urban watersheds and the streams that result. Based on nearly a half-century of studies of urban streams, the challenges of establishing a self-sustaining trajectory towards aquatic function and health are seemingly insurmountable. Even if a natural flow regime could be reestablished through effective, watershed-wide application of site-scale runoff management, natural geomorphic processes of sediment delivery and channel change are incompatible with most adjacent urban land uses. These processes, however, are the very agents of habitat creation and rejuvenation, and they ensure the persistence of the channel form through dynamic, short-term adjustments to floods and droughts. These adjustments are rarely tolerable in urban landscapes. Particularly in climatic regimes such as the American Southwest, where large discharges are many times larger than "typical" flows, the immediate consequences on the surrounding terrain can be quite dramatic.

As a result, we expect that the paradigm for a "restored" urban stream must combine the recovery of certain natural processes with a respect for the unyielding constraints and multiple objectives of the urban setting. Channels will not meander across the landscape, and so entire categories of key habitat features may not exist. Sediment will not pass down the channel as freely or as efficiently as in pre-development time, because the morphology of the channel will be constrained, and urban infrastructure (e.g., road crossings) will impose immutable constraints (Chin and Gregory 2001). A riparian corridor may (and should) be present, but its species composition will probably not mimic pre-human conditions, and the exclusion of people and domestic animals cannot be assured—indeed, their active use of this space will probably be encouraged to achieve other goals set for these watercourses.

Short-term, local-scale actions can improve the condition of urban streams and are generally feasible under many different management settings. They are unlikely to produce permanent effects, however, because they do not incorporate the reestablishment of self-sustaining watershed processes. Such actions include riparian fencing and planting, water-chemistry source control, fish-passage projects, and certain in-stream structures. Short-term actions address acute problems typical to stream channels in urban and urbanizing catchments; they are commonly necessary, but not sufficient, to restore biotic integrity.

In contrast, if restorative actions are intended to achieve sustainable ecological goals, they would need to effectively address all five elements of disturbed stream ecosystems (Fig. 6.5). These actions might include various types of land-use planning (e.g., preserves and zoning), avoiding road and utility crossings of the channel network or minimizing their footprint, upland hydrologic rehabilitation (e.g., stormwater infiltration or on-site retention) and erosion control, re-establishing the age structure of riparian vegetation communities, and reconnection of floodplains with their associated channels (Booth 2005). Because streamflow is a key element of ecological conditions and driver of habitat-forming processes, reestablishing streamflow patterns is almost certainly necessary for restoration of an aquatic ecosystem. Given the constraints common to cities and the challenges of watershed-scale hydrologic rehabilitation in a built-out catchment, this goal may not be realistic for many urban watersheds. However, nearly half of the urban development projected for the United States for the year 2030 has not yet been built (Nelson 2004), and so opportunities to achieve better stormwater management through both new development and redevelopment still abound.

Short-term actions alone, and even some well-intentioned and well-reasoned long-term actions, will not achieve broad ecosystem protection in the urban environment. At best, biological communities in urban streams may be diverse and complex, but they will depart significantly from pre-development conditions. These streams can be neighborhood amenities and provide their nearby residents with a connection to a place, and they can support a self-sustaining and self-regulating biological community. If we articulate these goals and work towards them, such outcomes for urban streams should be achievable even without fully reestablishing natural hydrologic processes or hydrologic conditions.

6.5.3 Climate Change and the Uncertain Coupling Between Human and Environmental Systems

Climate change is an impending threat to aquatic ecosystems, urban and non-urban alike, but the particular constrains of the urban water environment are likely to amplify some of the most serious consequences. Increases in water temperatures as a result of general warming will alter the geographic distribution of aquatic plant and animal species. Although some species can migrate as the climate changes, the barriers to migration and fragmentation of habit at that commonly accompanies urban development will likely result in local and regional extirpation, absent extensive and innovative restoration approaches.

Changes in precipitation will alter streamflows, with the most commonly anticipated change being an increase in extreme events and a corresponding increase in channel-scouring flows and flooding. The urban infrastructure is generally not tolerant of increased magnitudes or frequency of flooding, and the most common responses to increased flood risk are costly and further damaging the aquatic ecosystems. Future actions will need to do better! Those actions that will improve the resiliency of urban streams to such changes include maintaining riparian forests, reconnecting floodplains and other overbank areas, reducing pollution, restoring already-damaged systems, and minimizing groundwater withdrawal (Poff et al. 2002).

6.5.4 Lessons from Prior Efforts, Guidelines for the Future

Failure of the last century's management of hydrologic alteration should not condemn us to the same future. Instead, it underscores the need for new approaches to stormwater management that integrate multiple scales of watershed planning, site layout, and infrastructure design. Full, or at least partial, long-term restoration of some hydrologic and geomorphic processes, with subsequent biological recovery, may be possible even in highly disturbed urban environments. The absence of abrupt thresholds in biological responses to urbanization (e.g., Thomson et al. 1996, Morley and Karr 2002) suggests that even incremental improvements can have direct, albeit modest, ecological benefits. Urban streams can be self-sustaining to biotic communities, even though those communities depart significantly from pre-disturbance conditions. Last, urban streams should also retain the possibility, however remote, of one day benefiting from the long-term actions that can produce greater, sustainable improvements. Current costs, uncertainties, or sociopolitical constraints are no excuse to continue building urban developments or traditional rehabilitation projects that permanently preclude future long-term stream improvements.

The scientific literature and numerous case studies demonstrate the value of following ten principles to achieve sustainable stream health and resiliency in urbanizing watersheds. Conversely, our many failures can commonly be traced back to ignorance of one or more of these elements (Williams et al. 1997, Frissell 1997). We offer them as a summary of this chapter's lessons and a checklist for the management and enhancement of streams in the urban water environment:

1. Address problem causes, not just symptoms: focus on ecosystem processes rather than a specific, tangible form.
2. Recognize many scales, in both time and space. A long-term, large-scale, multidisciplinary perspective that includes both ecological history and future changes is critical.
3. Work with, rather than against, natural watershed processes, and reconnect severed linkages—the only channels that persist on the landscape without continuous human intervention are those with an intact set of watershed processes that sustain their form and features.
4. Clearly define goals and make both sustainability and enhancing ecological integrity explicit goals.
5. Utilize the best available science in predictive assessments that are risk-based and decision-oriented, acknowledging the desired outcomes of interest to all

stakeholders: Human health and safety, clean water, productive fisheries, other valued biota, reliable water supply, recreation, and aesthetics.

6. Honestly identify and openly debate the key knowledge gaps and uncertainties, but adopt an action-oriented principle that ensures that the decision-making exercise will lead to results.
7. Make decisions in a transparent, organized framework that:
    - structures the problem clearly;
    - provides a ranking of the options even though the uncertainties may not be resolved in the foreseeable future;
    - involves affected stakeholders;
    - documents and justifies the decision process to all stakeholders; and
    - provides research priorities by showing whether resolving particular uncertainties would affect the preferred option(s).
8. Watershed-restoration projects are as much a social undertaking as an ecological one; understand social systems and values that support and constrain restoration while establishing long-term personal, institutional, and financial commitments.
9. Some strategies will work, some will not, and some will take many years to assess. Learn through careful long-term monitoring of key ecological processes and biotic elements. Reevaluate and update management strategies based on monitoring, recognizing that every “restoration” effort is actually an experimental treatment that requires evaluation and future modification to achieve its stated goals.
10. The best strategy is to avoid degradation in the first place. The highest emphasis should be placed on preventing further degradation rather than on controlling or repairing damage after it has already occurred.

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