1

RAINWATER AS THE RESOURCE

1.1 THE WATER BALANCE AS A GUIDE FOR SUSTAINABLE DESIGN

In every portion of the planet, the cycle of water provides the same natural model: The water resource is replenished with each season and the land surface responds to this cycle of abundance or drought with a vegetative system that flourishes and diminishes with the available rainfall. The hydrologic cycle is continuous, but it is by no means constant, and every human habitat must recognize and live within the limits and constraints of this dynamic process. Over the past 4.5 million years, our species has learned to live in balance with the water cycle; or if it changes over time, migrate to other environments.

Unfortunately, over the past century, our modern society has not followed this process in the building of our current communities. As our numbers increased and spread across the land surface, we began to exploit rather than sustain our land and water resources. During the past century, our control of energy sources allowed us to neglect the principle of sustaining our habitat, and we gave little thought as to how we built our modern cities, disregarding the local environment and the natural limits of each place. Guided by a false confidence that we could conquer any constraint or natural limitation, we have stripped and sculpted the land to fit our perceived image of how we can best situate our structures. We have exploited the available water resources, without careful consideration of where we live in terms of natural topography and hydrology.

Low Impact Development and Sustainable Stormwater Management, First Edition. Thomas H. Cahill.

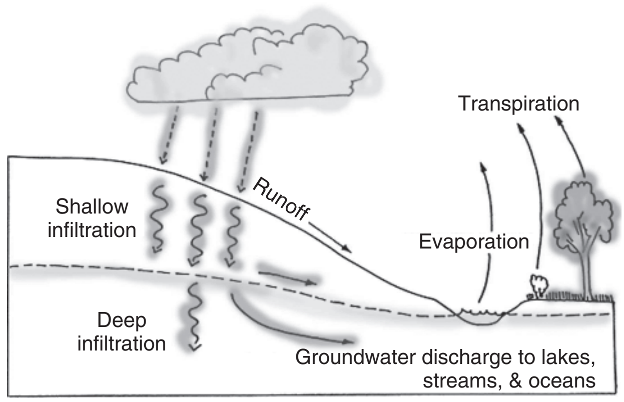

Figure 1-1 The hydrologic cycle.

The *hydrologic cycle* or *water balance* serves as a model for understanding the concept of sustainability of our water resources (Figure 1-1). The challenge of sustainability is to draw upon elements of this cycle to serve our needs without significantly disrupting the balance. With careful land use planning and water resource management, every available drop of rain can be used and reused to meet our needs without destroying the quality or affecting the character of natural streams and rivers. Many of our uses, such as drinking supply, can be largely recycled with the proper waste system design, and many other uses can be reduced in quantity if they are largely "consumptive" uses, such as irrigation of artificial landscapes. Consumptive demands of cultivation can also be reduced by methods such as drip irrigation, and energy systems can be designed that do not consume fresh water in the cooling process. All modern water supplies require energy, and most energy systems affect water. Similar to the land–water dynamic, the energy–water interrelationship requires that any system changes consider both resources.

The principle of water balance is best understood in the context of a measurable land area—watershed, drainage basin, or land parcel—that quantifies the water cycle. The rain that falls on the land surface over a period of time defines the magnitude of the resource and the quantity required to sustain the cycle. The potential demands on this balance imposed by our land development process can then be applied to this model as an initial step in understanding how the cycle should guide our activity on the land.

Perhaps the easiest way to understand the concept of the water balance is to consider a small unit area (Figure 1-2), an acre or hectare, and measure the movement of rainfall through this tiny portion of the planet. The flow begins (or continues) with rainfall, shown in the figure as the annual average for a temperate climate, the mid-Atlantic region of eastern North America. Whereas the annual amount of rainfall varies greatly from place to place across the United States (Table 1-1) and can also experience significant seasonal differences (Table 1-2), the hydrologic cycle remains a constant.

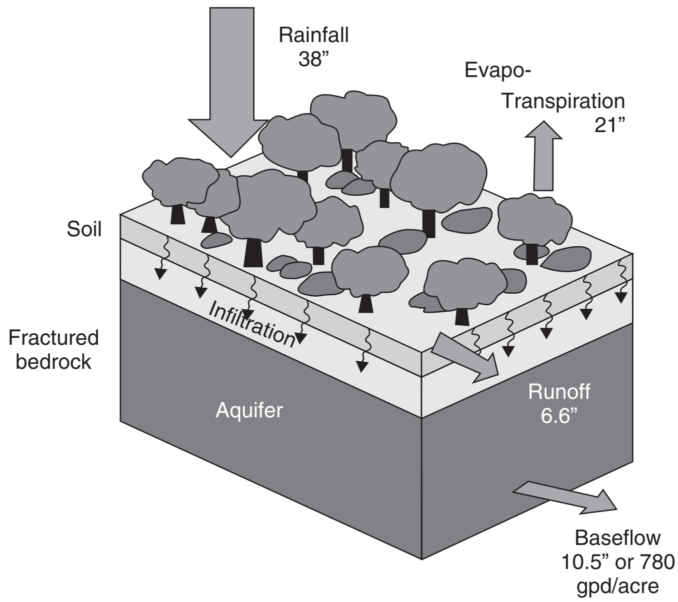

Figure 1-2 The hydrologic cycle on an undeveloped unit area (in./yr).

Table 1-1 Annual Rainfall in Major U.S. Cities

City	Annual Rainfall (in.)	Annual Snowfall (in.)
Albany, NY	38.6	64.4
Anchorage, AL	16.1	70.8
Atlanta, GA	50.2	2.1
Austin, TX	33.6	0.9
Boston, MA	42.5	42.8
Charlotte, NC	43.5	5.6
Chicago, IL	36.3	38.0
Denver, CO	15.8	60.3
Duluth, MN	31.0	80.6
Honolulu, HI	18.3	0
Houston, TX	47.8	0.4

Source: [1].

It is also possible to structure a more complicated model of this dynamic process (Figure 1-3), realizing that the water movement through all elements is continuous, while some elements, such as the soil mantle, act as short-term storage units, holding or releasing moisture from year to year. Other processes, such as evapotranspiration, vary greatly from season to season, and by location, throughout the year. Thus even this more complex graphic fails to fully describe the water balance cycle.

Table 1-2 Seasonal Variation of Rainfall in Regional Watersheds

Region	Major River Basin and City	Rainfall (in.) Spring	Summer	Fall	Winter	Total
Northeast	Delaware River	11	11.3	10.6	9.7	42.5
	Philadelphia, PA	*26%*	*26%*	*25%*	*23%*	
Northwest	Willamette River	13.8	3.5	15.7	27.2	60.2
	Portland, OR	*23%*	*6%*	*26%*	*45%*	
Southeast	St. Johns River	10	10	19.1	12.2	51.2
	Jacksonville, FL	*19%*	*19%*	*37%*	*25%*	
Southwest	Santa Anna River	4	0.4	2.7	7.5	14.6
	Los Angeles, CA	*27%*	*4%*	*15%*	*51%*	

The development of plants on the planet surface long preceded the mammals from which we evolved, and plants have fulfilled their part in the hydrologic cycle for several billion years. On those land surfaces that evolve a natural vegetative cover, especially woodlands, the trees and grasslands utilize the input of rainfall to live by *photosynthesis* [2], drawing the infiltrating moisture from the soil (or directly from the atmosphere) and transforming the water into oxygen and organic matter, a process described by the reaction

$$(6H_2O + 6CO_2) + (\text{sunlight, 48 mol}) = 6O_2 + C_6H_{12}O_6$$

This simple miracle of plant life is carried out by the role of chlorophyll in the vegetation. In addition to producing the oxygen by which all species live, this process maintains the critical balance of CO_2 in the atmosphere for the benefit of all animal life forms, including the human species. While the air we breathe is comprised primarily of 78% nitrogen with slightly less than 21% oxygen, the role of minor gases (argon, 0.93%; CO_2, 0.038%) and water (1%) is critical in maintaining the temperature at a relatively constant level over time. The rapid increase in CO_2 over the past century has played an important and causal role in global warming, specifically as the result of burning fossil fuels [3, 4]. Thus, the importance of sustaining surface vegetation, especially trees, during the land development process cannot be overstated (Figure 1-4), as it compensates for this human impact [5, 6]. It should be noted that terrestrial vegetation provides only a portion of the photosynthetic production, with marine plankton actually generating more of the balance on a global basis.

On a naturally vegetated land surface, about half of the rain that falls is returned to the atmosphere by the evapotranspiration process. The balance of infiltrating rainfall, not utilized by the vegetation or evaporated from the surface by sunlight and air currents, infiltrates or percolates slowly (or quickly) into the soil mantle. A portion of this rain drains deep into the soil and weathered rock surface, eventually reaching the zone of saturation, described as the water table (Figure 1-5), and becomes groundwater.

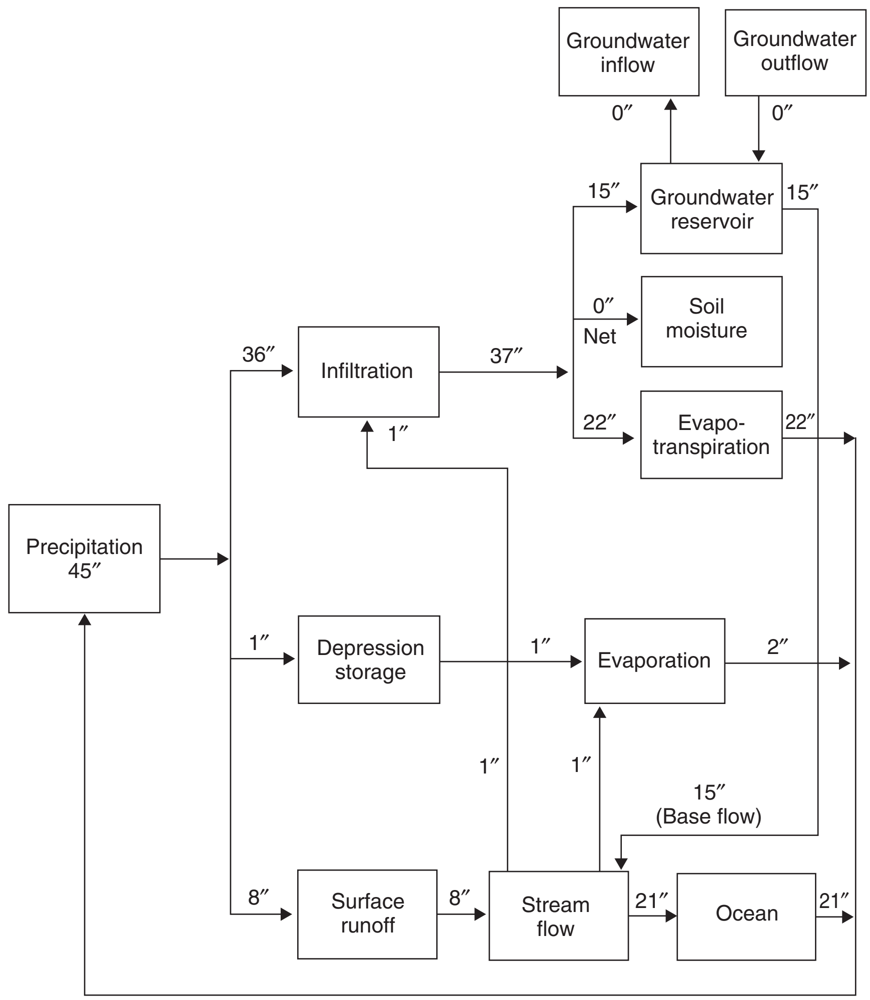

Figure 1-3 The hydrologic cycle or water balance model for a watershed in southeastern Pennsylvania: the Brandywine model project, 1984.

As each raindrop is added to this groundwater, it begins to move in the direction of available energy, created by the inexorable pull of gravity. Since the easiest pathway for displacement is through the soil (and fractures in the rock) following the surface of the land, this water eventually travels downhill, emerging as a seep or spring, flowing over the surface to a swale or steam channel. Actually, as each raindrop enters the groundwater, it displaces water from the low end of the saturated zone. A single raindrop may actually take weeks or months to complete the journey from where it falls on the land surface to the point of discharge downgradient, as it returns to the surface.

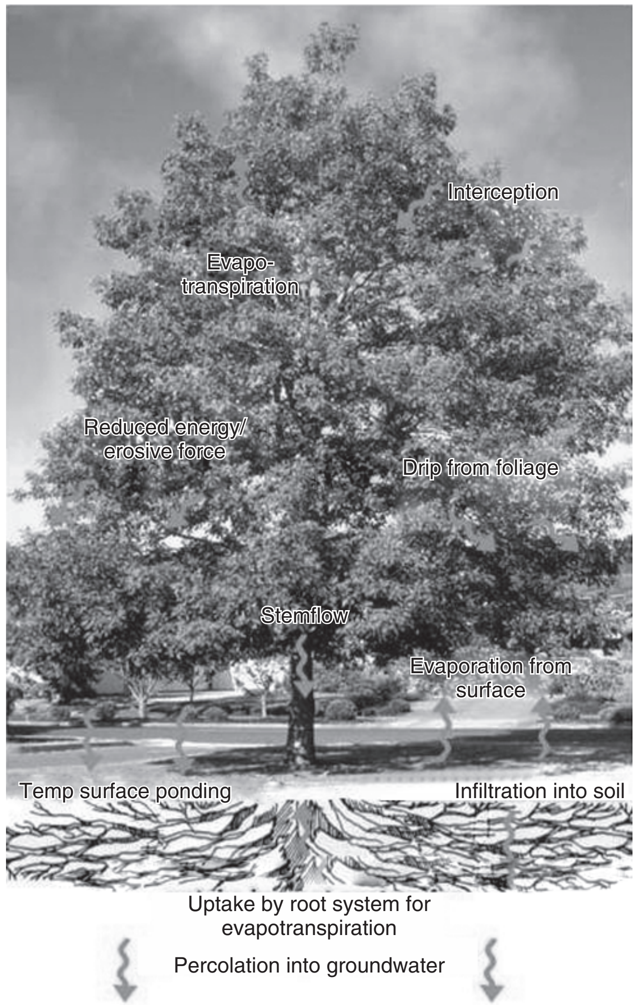

Figure 1-4 The perfect LID measure for stormwater management: a tree.

Of course, not all infiltrating rainfall follows an identical pathway of movement in the subsurface, and the complex layering of the soil in different horizons, each with a very different permeability, can make this journey lengthy and circuitous. Where highly impervious layers exist in the soil mantle, infiltrating rain will move across this surface, again following the energy gradient. The underlying bedrock also influences the speed and direction of groundwater movement, in both the unsaturated zone and deep below the water table. If the underlying rock is comprised of soluble carbonates, it includes open solution channels or subsurface flow pathways that formed hundreds of millions of years ago and now provide an underground river network, carrying the rainfall many miles from the

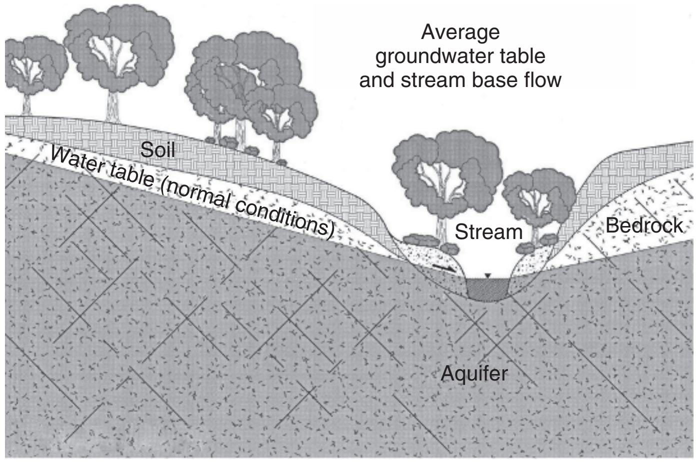

Figure 1-5 Groundwater recharge feeds the local surface waters and sustains base flow.

initial point of infiltration. In coastal watersheds, the groundwater may discharge directly to estuary systems, never reappearing on the land surface.

In some physiographic regions, a fraction of the infiltrating rain enters into deeper aquifers and does not reappear at the surface, but may remain stored for centuries. In active seismic regions, geothermal sources may actually bring some of the deep water to the surface. This vertical flow of groundwater may comprise a portion of surface systems, such as the Snake River tributary in the Columbia River system, originating from the "hot spot" that forms the geysers of Yellowstone (Figure 1-6). However, for most of the developed regions of the United States, the simple model illustrated by Figure 1-2 is a valid representation of this complex water balance.

While the full hydrologic cycle includes water movement on a global basis, the consideration of stormwater management is limited to the freshwater portion of the total resource, a fraction of the world's water (about 2.5%). Most of that fresh water is currently contained in ice (although the future is quite uncertain) and represents 77.2%, with an additional 22.6% contained in the subsurface as groundwater, leaving only 0.32% in surface rivers and lakes, 0.18% as soil moisture, and 0.04% in the atmosphere, for a total "available" water resource of 0.54% [8]. All of the following discussion is concerned with this sum of these small portions, although it amounts to the trillions of gallons of water that sustain the human biosphere.

1.2 THE WATER BALANCE BY REGION

Although the most obvious measure of the water resources available in a given region of the country is the average annual rainfall received, this statistic can be deceiving if we do not recognize the potential variability in this measure,

Figure 1-6 Deep groundwater is discharged by geothermal vents (Yellowstone). (From [7].)

especially in arid regions such as the Southwest, where the extremes of "wet" and "dry" years can result in a system that experiences a crisis under both cycles. It is the extremes of the cycle that create the greatest stress in every community, and the duration of individual droughts or flood-creating rainfall periods that measure how well or poorly we have built our communities.

Most large river basins in the United States have experienced significant human alteration or structural intervention over the past two centuries. It is interesting to consider the net effect of human activities on the regional watershed, although we have no baseline (pre-disturbance) flow data to compare with current conditions. However, we can compare the net runoff generated in these large systems with the rainfall experienced within the watershed (Table 1-3). Also shown is a reference city, usually situated at the downstream reach of the river basin. In the Santa Anna basin draining to Los Angeles, the inflow from three diversion canals affects these statistics significantly.

Table 1-3 Water Balance by Region and River Basin

Region and Percent of Area	River Basin and Reference City	Basin Size (m^2)	Mean Discharge (ft^3/sec)	Alteration	Rainfall (in) City	Rainfall (in) Basin	Runoff (in.)
NE 60%	Delaware Philadelphia, PA	12,757	14,902	NYC diversion	42	42.5	25.6
NW 63%	Willamette Portland, OR	11,478	32,384	Dams/lakes	37	60.2	38.2
SE 23%	St. Johns Jacksonville, FL	8,702	7,840	Lakes	52	51.6	11.8
SW 2.3%	Santa Anna Los Angeles, CA	2,438	60	Diversions	15	13.4	0.3

Source: Derived from [9].

Whatever the average annual rainfall or variability of this volume in a given location, the design of structures or systems to convey or mitigate the impacts of this volume (and flow rate) of surface runoff have always focused on individual storm events. These "design storms" are events during which the intensity, duration, and amount of rainfall produce the most severe impacts.

We remember the most extreme rainfall events, especially when they are the result of cyclonic storm patterns produced in both the Atlantic and Pacific oceans that approach the mainland in the form of hurricanes or cyclones. We even identify them by name when they reach a given magnitude or anticipated wind speed, assigning a category of intensity that can change during the approach. Most recent memory cannot help to identify hurricane Katrina (Figure 1-7), which devastated the Gulf coast in September 2005, but other names and memories are shared by communities throughout the country. Most periods of prolonged rainfall do not receive this recognition or nomenclature, but have produced dramatic flooding impacts in large and small watersheds.

The statistic of rainfall that has the most common usage in defining severe rainfall events is the 100-year storm, which is the rainfall that occurs during a 24-hour period with a frequency of once in 100 years. This figure cannot, however, convey the full impact on a local watershed of more severe and intense rainfalls. For example, in July 2004 the Rancocas Creek in southern New Jersey was visited by a rainfall pattern [10] that dumped some 13 in. in some portions of this small (250 m^2) watershed (which has a 100-year rainfall frequency of 7.2 in.), in a pattern that was anything but uniform. The net result was the destruction of some 22 small earthen dams, built for various purposes, and significant property damage (but no loss of life).

This type of localized event can be visited on any portion of the country, regardless of our statistics and classification of storms, and is repeated all too frequently all across the globe. While the total rainfall is a given period and

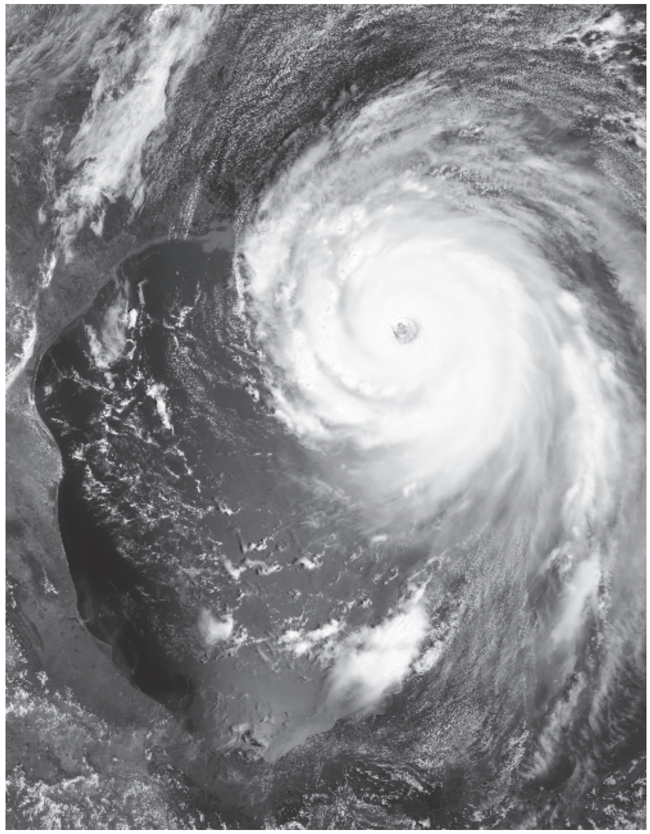

Figure 1-7 Hurricane Katrina strikes the U.S. Gulf coast.

the intensity of that precipitation have much to do with the resulting impact, the hydrologic response of any given watershed is also a function of land cover conditions, especially vegetation, and season, with frozen ground producing some of the most severe runoff conditions during early spring in mountainous regions.

If we were to measure all of the rainfalls at a given location over a century, we would find that the vast majority were of very small magnitude (Figure 1-8). The pie chart in the figure shows rainfall distribution for southeastern Pennsylvania, with a total annual rainfall of 44 in./yr. The relative distribution is the same for most other regions, with most of the storms less than 3 in. in total rainfall, and offers insight as to the defining statistic for a stormwater volume reduction management strategy.

While the traditional focus of concern has been the extremes of rainfall or drought, the major portion of our precipitation actually occurs in smaller, more frequent events. In fact, in almost every major physiographic or climatologic region, the 2-year-frequency rainfall serves as the defining statistic for the stormwater management designs that are outlined in this book. This rainfall and

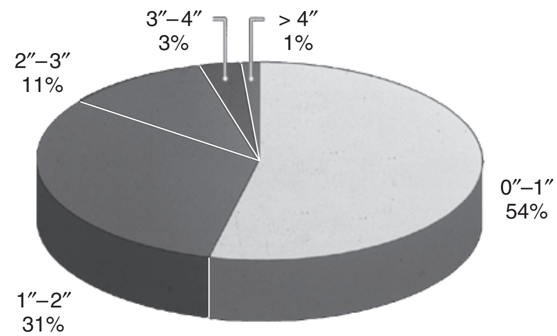

Figure 1-8 Frequency and magnitude of rainfall events, southeastern Pennsylvania. Most rainfall occurs in small storms, less than the 2-year frequency.

Table 1-4 Two-Year-Frequency Rainfall Event

U.S. Region	City	Two-Year Rainfall (in. in 24 hr)
Northeast	West Chester, PA	3.3
Northwest	Seattle, WA	3.2
Southeast	Chapel Hill, NC	3.6
Southwest	Los Angeles, CA	2.9
Central	Minneapolis, MN	2.5

that of all the storms of lesser magnitude represents about 95% of the total rainfall volume over a prolonged period of decades, and so better defines the efficiency of any proposed mitigation measure. Since this statistic has great significance as a basis for the design of most of the measures described in this book, it is important to compare the variation in this type of rain event in different portions of the country. Table 1-4 shows the 2-year-frequency rainfall in major regions, and the values are quite similar. Figure 1-9 illustrates the intensity of this type of storm over a 24-hour period (as well as the 100-year rainfall) for a mid-Atlantic watershed. This is described by an S-curve, developed by the Soil Conservation Service of the U.S. Department of Agriculture during the 1960s [11]. Of course, nature never cooperates with our assumptions concerning climate conditions such as rainfall patterns, but this type of distribution is assumed because it will produce the most extreme runoff conditions.

1.3 ARID ENVIRONMENTS: THE SOUTHERN CALIFORNIA MODEL

To be sustainable, low-impact design (LID) must consider all human demands on the hydrologic cycle that result from the land development process. This means that we begin our site planning with the issue of water supply, the single

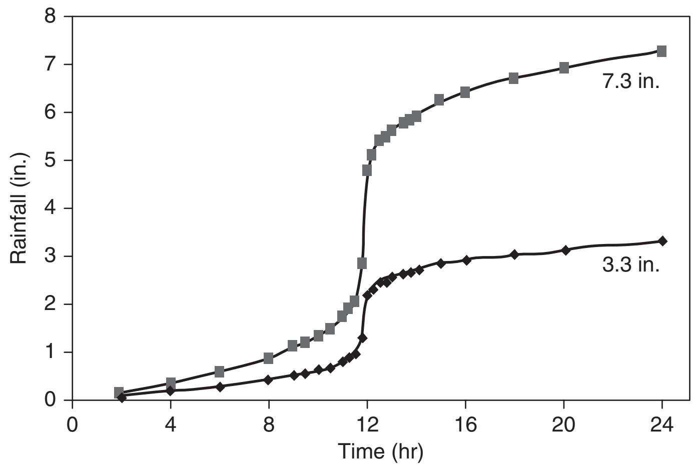

Figure 1-9 The S curves of assumed rainfall intensity and distribution; 2- and 100-year-frequency storms in southeastern Pennsylvania.

most critical aspect of site development. When this basic need is satisfied, we consider the return of this water to the cycle, containing all of the pollutants we have added during our use. The need for increasingly efficient pollutant removal processes during the past century has resulted largely from the increase in population and density in our land development, as we realized that the sewage from one community is the water supply for downstream residents.

Stormwater has been regarded as a nuisance, to be drained away from our developments as quickly as possible following a rainfall. In arid environments, the value of rainfall to support our continued occupation of habitat is an unutilized resource, especially when the available water supply is limited and runoff is discharged to coastal waters. Nowhere is this lack of water resource management more apparent than in southern California. In these coastal watersheds, land developments draining to the Pacific coast and to inland waters and reservoirs have generated significant increases in stormwater runoff volume, which in turn has contributed to the discharge of pollutants into receiving waters, degraded aquatic habitat, affected the recreational use of these waters, and interfered with their use as water supply. Through implementation of LID practices, these pollutant discharges can be reduced significantly, so that the quality of these coastal and inland waters can be restored and sustained.

But the potential of LID goes well beyond reducing the volume of polluted stormwater runoff. This rainfall can also be understood as a lost resource in the semiarid environment of southern California, where increasing demand for fresh water requires costly importation of water supplies to sustain ever-growing communities. Interestingly, the quantity of water imported into southern California is almost equal to the net loss of stormwater runoff to coastal waters (Table 1-5), referred to as the *salt sink*.

Table 1-5 Water Balance in Southern California, 2000 (1,000 Acre-Feet)

Supply		Use (Demand)	
Precipitation	7,500	Evapotranspiration	7,441
Imported	2,991	Consumptive use	1,819
Depletion of groundwater	1,245	Outflow to the salt sink	2,498
Total supply	**11,752**	**Total use**	**11,758**

Note: The runoff lost to the ocean is almost equal to the required import.

Could LID practices such as capture and reuse of stormwater runoff significantly reduce the need for importation of water supply to the region? These practices offer the possibility of working to redress at least some of the water cycle imbalances that confront southern California communities, but will require a significant rethinking of existing stormwater and water supply system designs.

Central to the concept of watershed sustainability is the water cycle and its balance, very roughly defined as the matching of water inputs ("supply") to water outputs ("demands"). Any watershed, physiographic region, or land area that can be well defined in terms of water supply and use, both natural and human, can also be evaluated in terms of water cycle. Analysis of the existing water balance for southern California demonstrates that the natural water resources are insufficient to meet the demands of the existing 19 million residents in the 11,000-square mile region from Ventura to San Diego, with 5 million additional residents projected to arrive by 2020 [12].

The deficit in natural water resources has been met over the years by three aqueducts (Figure 1-10), which convey imported water hundreds of miles to the region. Table 1-5 provided a simplification of this water resource balance for the year 2000, with both supply and demand (use) summarized from more detailed statistics. In 2000, rainfall provided only 72% of the total water supply use or demand, again with the quantity of runoff to the ocean [2,498 thousand acre-feet (TAF)] close to the water importation (2,991 TAF).

The depletion of groundwater is especially troublesome in this "balance." Although a number of large aquifer systems lie beneath the surface of the region and are constantly being replenished by recharge from surface sources, their capacity has been exceeded during most years. The Los Angeles area receives over 40% of their current water supply from these aquifers, utilizing spreading grounds to recharge both runoff and recycled effluent, based on the concept of "conjunctive use." However, year after year, the groundwater reservoirs are further depleted, despite our plans.

The Energy Demand for Water in Southern California

It requires over 10,200 kilowatthours (kWh) for every million gallons (MG) of water imported into southern California, 40 times greater than the national average and 20% of total residential energy usage for the region, as shown in

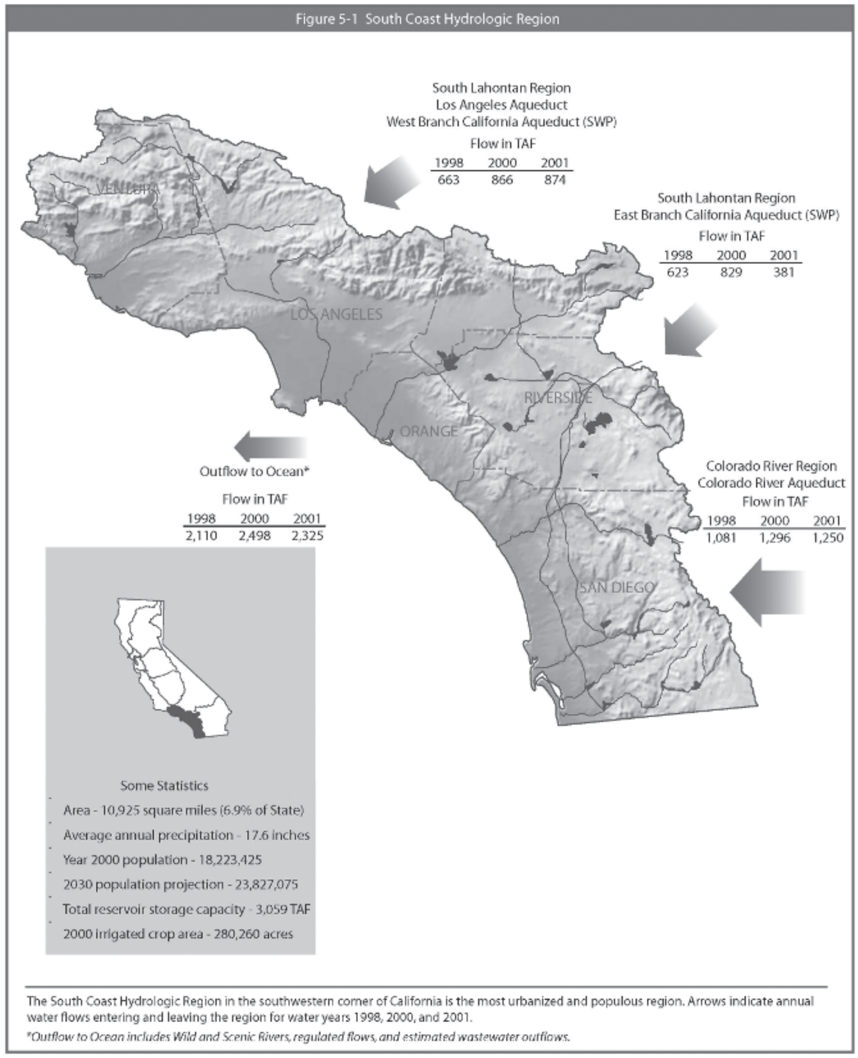

Figure 1-10 South coast hydrologic region of southern California. The imported water equals the runoff lost to the ocean.

Table 1-6. This can be compared with the national average of 250 kWh/MG. Any significant reduction in importation of water to the region can be expected to translate into significant energy savings.

What does energy demand have to do with LID? When we consider the application of sustainability concepts to land development, we must include the impact on both water and energy, and in this region the shortage of both resources is critical. If we can capture the rainfall and at the same time reduce the amount of

Table 1-6 Energy Demand of Water Supply in Southern California

Supply and conveyance	8,900 kWh/MG
Treatment and disposal	1,300 kWh/MG
Total	10,200 kWh/MG
National average	250 kWh/MG

Source: [13].

energy required to deliver imported water supplies, we will address both issues with one set of design solutions.

In southern California, this water cycle varies considerably. For example, in terms of annual precipitation, the total amount of rain received by the major communities in southern California varies dramatically; relatively wet Pasadena in the northern portion of the region receives twice the rainfall of semiarid San Diego in the southwest (20 in Pasadena, 16 in./yr in Riverside, 15 in./yr in Los Angeles, and 10 in./yr in San Diego). This variability is reflected in the size of storm events, which is so important in stormwater management calculations and therefore important to LID design. For example, the 2-year-frequency storm varies from 1.6 in. of rain in 24 hours in San Diego to 3.5 in. in Pasadena. This frequency rainfall comprises some 93 to 95% of all the rain that occurs in a century, so it is a defining statistic. Within that rainfall pattern is an equally varied difference, on both an annual and seasonal basis, with a well-defined "wet" and "dry" season. Such natural variability in the hydrologic cycle within the region makes stormwater management that much more challenging.

Of course, the fact that water is limited in southern California does not preclude the occurrence of coastal storms from the Pacific causing rainfall events that drop almost the total annual average rainfall over a period of a few days, as occurred during mid-January 2010. From the 18th through the 22nd, a total of 8 in. of rain fell in the Los Angeles region, causing widespread flooding, erosion and mud slides, evacuations, and most significantly, the structural failure of a number of residences perched precariously on hillsides. The local building codes allow the placement of buildings in locations that would not be considered sustainable in a less arid environment, where saturated soils are an assumed design condition. This cycle of rainfall, runoff, and mud slides was repeated in January 2011, and promises to occur frequently until land development planning better manages rainfall.

The current hydrologic cycle in southern California bears little resemblance to the natural system of a century ago, as so well described by D. Green in her book *Managing Water: Avoiding Crisis in California* [14]:

> In the 1920's, roughly 95% of the rainfall falling on Los Angeles either infiltrated into the ground or evaporated. Only 5% ran off to the sea. Today, with the extensive development and the paving over of our urban environment (as much as 80% of the land is now covered with roofs, roads, parking lots, patios, etc.) and the construction of the massive storm drain channel system, about 50% of stormwater runs off in the Los Angeles River drainage area, while 50% either infiltrates or evaporates. . . .

About 90% of the San Gabriel River's flow is captured for recharge into the groundwater supply. On average, only about 20% of the upper Los Angeles River native runoff is captured, due to a lack of sufficient spreading capacity and the prevalence of clay soils.

The state Water Board has developed models of the current reality of water balance in southern California, and these are a far cry from simplistic illustrations. Obviously, no single model adequately describes the existing cycle of water in all of the region's watersheds and the importance of stormwater in the cycle. Based on the current reality, LID must be integrated in the land development and redevelopment process to use the limited rainfall received most efficiently to sustain the daily water demand of 140 gallons per person, even as imported supplies diminish. At the same time, we must restore those elements of the natural system that remain or can be sustained. Even this statistic of per capita consumption must be reduced, and that reduction turns on ways to sustain our landscapes with less water, using stored rainfall until we can change the landscape paradigm to a more natural vegetative palette over the next decade.

1.4 THE ALTERED WATER BALANCE AND HYDROLOGIC IMPACTS

Imperviousness

How do our current development practices affect the hydrologic cycle? The most obvious alteration is the use of impervious materials to build our communities, which for virtually all of the past 10 millennia consisted only of the rooftops of our buildings, temples, and homes. Until the beginning of the twentieth century, the land surface surrounding building structures was always comprised of compacted soil or paving stones in one form or another (Figure 1-11), with only a few major cities utilizing pavement surfaces that could be considered impervious.

This building pattern was totally altered a century ago, when the battle was concluded over which energy system would be used to power the new horseless buggy. The internal combustion engine won out over the steam engine, and gasoline became the fuel to power the rapidly expanding demand for transportation vehicles. This production in the "cracking tower" of petroleum refining resulted in an accumulation of "tar" in the bottom of the tower, similar in property to natural occurring tar pits mined in a few locations around the world. It was soon discovered that this residue of gasoline manufacturing could be combined with the graduated stone roads of the previous century (macadam) to form Tarmac surfaces, well suited for paving of our urban streets and roadways (Figure 1-12). As the demand for gasoline skyrocketed, the availability of the newly defined "asphalt concrete" made the surfacing of roads affordable, and so began a cycle of increased imperviousness that characterized the land development process throughout the twentieth century.

Figure 1-11 The urban environment in the eighteenth century (1799). The road was pervious.

A popular tune of the 1970s declared our wish to "... *pave paradise and put up a parking lot* ..."—not an exaggeration but an accurate description of this transformation of the land surface (Figure 1-13). Recent studies of land development patterns in developing watersheds have distinguished the different types of impervious cover that form the current patterns of land cover, and these land cover analyses generally conclude that about 25% of the impervious cover found in a watershed is comprised of the building structures serving human activities, and 75% is comprised of impervious pavements, largely asphalt concrete, but also portland cement concrete, that serve for the transport and storage of our automotive vehicles. Other studies [15] have concluded that when a watershed approaches an impervious cover of 25%, the water resources have been so altered that water quality and quantity have been severely degraded.

Countless small stream systems, especially in the headwaters of larger river basins, have been developed, filled, built upon, piped, and paved over during the past century. A good example is a small (440-acre) stream called Meeting of the Waters Creek in Chapel Hill, North Carolina, a tributary of the much larger Flint River basin, which drains to the coastal Atlantic estuary. Present conditions reflect expansion of the University of North Carolina over the past five decades. The present land cover is 77% impervious and still increasing (Figure 1-14A), with

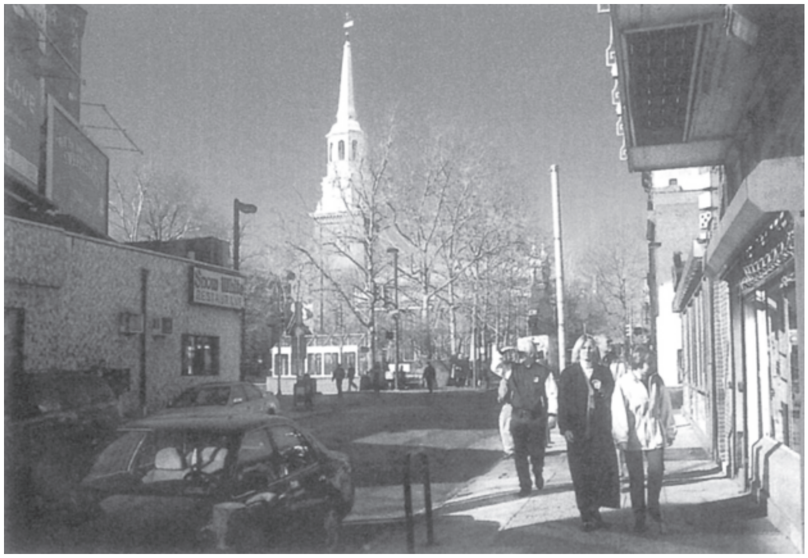

Figure 1-12 The urban environment 200 years later (1990), with impervious pavements.

Figure 1-13 A typical commercial site, with the building surrounded by a sea of impervious pavement.

(A)

(B)

Figure 1-14 (A) The University of North Carolina campus in Chapel Hill was over 70% impervious by 2001. (B) Meeting of the Waters Creek underlies the campus and emerges from sewers below.

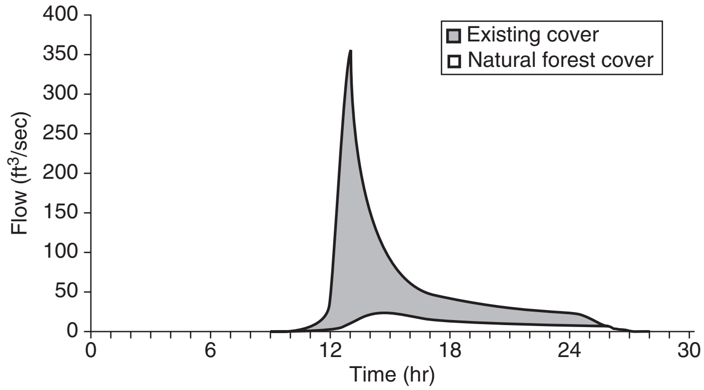

Figure 1-15 Hydrograph of Meeting of the Waters Creek, as affected by impervious surfaces.

the original stream system replaced by a network of sewer pipes that discharge to the remnant stream channel (Figure 1-14B).

The increase in runoff volume produced by this increase in impervious cover is dramatic (Figure 1-15), as illustrated during the 2-year-frequency rainfall. The increase in runoff volume (the area under the hydrograph) affects the downstream riparian corridor, eroding stream banks and conveying the pollutant load from the impervious surfaces as well as the channel to the large Lake Jordan, a future water supply reservoir, several miles downstream [16].

Impervious surfaces, be they rooftops, pavements, or streets, turn every drop of rainfall into direct and immediate runoff. In addition, the recharge of groundwater aquifers is effectively reduced or prevented altogether. Finally, the energy of runoff scours every pollutant that is dripped, dropped, spilled, or spread on the impervious (and pervious) land surfaces, and convey this **non-point source** pollution to surface waters. In all regions of the country, this impact can be understood by comparing the runoff volume increase from pre- to postdevelopment. For example, in the mid-Atlantic, where the annual rainfall reaches 45 in. and natural runoff is on the order of 8 inches, the net increase in runoff from impervious surfaces is 36 in. (3 ft) per year. One need only consider a typical parking lot surface as shown in Figure 1-13, and picture it covered with this depth of increased runoff, to fully understand the underlying cause of stormwater impacts from land development.

Increased Volume of Runoff

Figure 1-16 represents the same unit area as that shown in Figure 1-2, and illustrates the net impact of land development and impervious surfaces on the hydrologic cycle. To describe the process in simple terms, any impervious surface results in direct rainfall being converted into immediate and almost total runoff. Our building programs have always tried to transport this runoff away from the

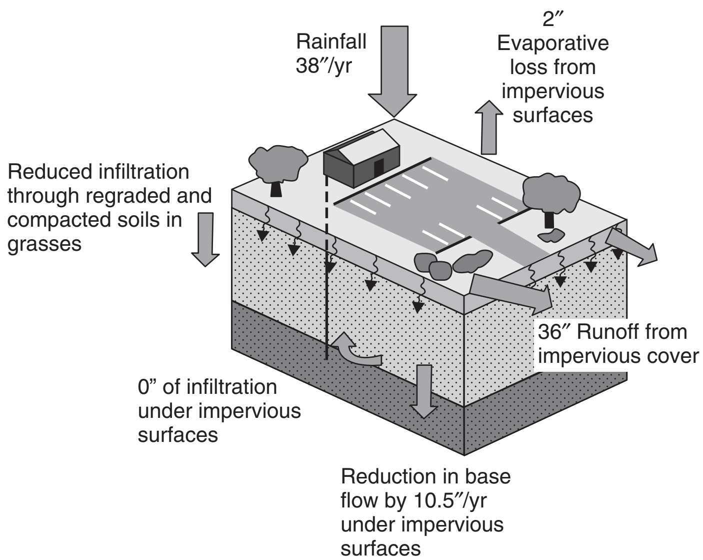

Figure 1-16 The impact of land development on the hydrologic cycle.

built environment to the remnant surface flow pathways and streams as quickly and directly as possible and to assure that both buildings and roadways can be utilized in the most severe rainfalls. Although this makes a great deal of sense from the building and transportation perspective, the net result was and is a dramatic and rapid increase in the rate and volume of runoff from a developed landscape. Observing this effect from a position downstream of the developed land, Figure 1-17 illustrates the rise in stream flow produced by a sudden increase in runoff from the upland drainage. This *hydrograph* of flow rate versus time defines a volume of runoff produced within a river basin, watershed, or catchment as the area contained within the figure, and is the most important aspect of the hydrograph measure.

Regardless of where land development occurs, the increases in imperviousness, the changes in vegetation, and the soil compaction associated with that development result in significant increases in runoff volume. The relative increase in runoff volume varies with event magnitude (return period). For example, the 2-year rainfall of 3.27 in. each 24 hours in southeastern Pennsylvania will result in an increase in runoff volume of 2.6 in. from every square foot of impervious surface placed on well-drained HSG B soil in woodland cover (Figure 1-18). For larger events, as the total rainfall increases, the net runoff also increases, but less than proportionately. For example, total rainfall for the 100-year storm is twice the rainfall for the 2-year storm (7.5 in. vs. 3.27 in.); however, the increase in runoff is only 1.7 in. (4.3 – 2.6 in.). This pattern holds true throughout the United States.

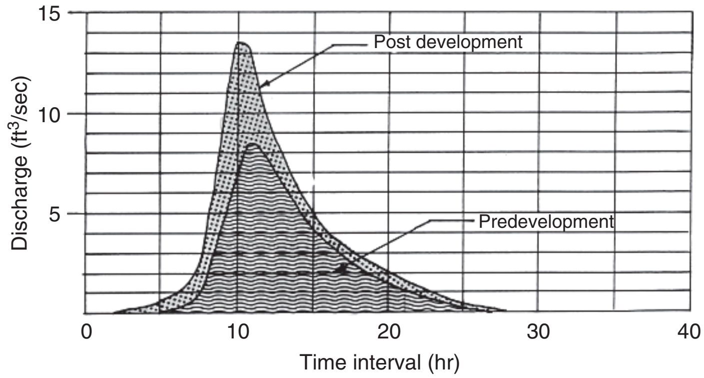

Figure 1-17 Hydrograph of increase downstream of development.

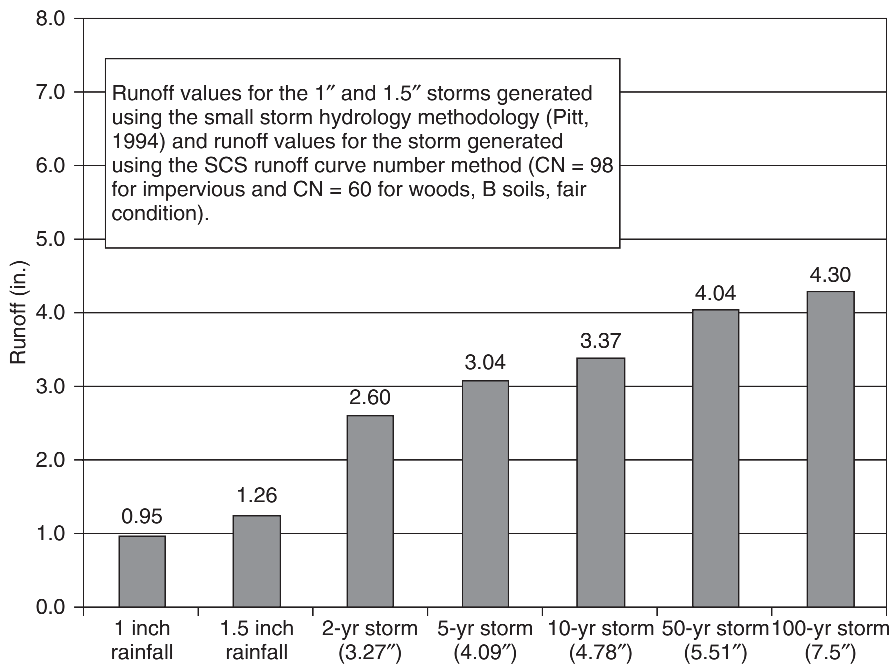

Figure 1-18 Runoff volume increase from impervious cover on HSG B soil.

For a specific site, the net increase in runoff volume during a given storm depends on both the predevelopment permeability of the natural soil and the vegetative cover. Poorly drained soils result in a smaller increase of runoff volume because the volume of predevelopment runoff is already high. Therefore, the amount of runoff resulting from development does not represent as large a net increase. Using the same rainfall values, Figure 1-19 illustrates that the 2-year rainfall of 3.27 in. in 24 hours produces an increase of only 2.01 in. on a HSG C

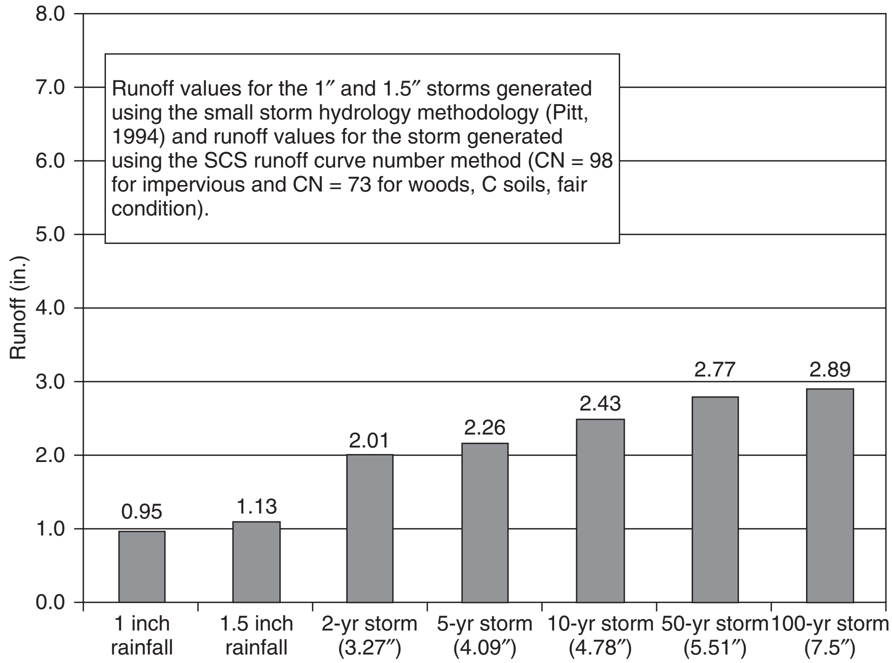

Figure 1-19 Runoff volume increase from impervious cover on HSG C soil.

soil, while the better-drained (B) soil produces a 2.60-in. runoff volume increase. Thus, a volume control guideline must be based on the net change in runoff volume for a given frequency rainfall, in order to be equitable throughout the country on any given development site.

When the balance of a developed site is cleared of existing vegetation, graded, and recompacted, it also produces an increase in runoff volume. Traditionally, if the original vegetation were replaced with "natural vegetation" such as a lawn, the runoff characteristics would be considered to be equivalent to the original natural vegetation, but the fact is that the disturbance and compaction destroy the permeability of the natural soil and increase soil density, which has a direct impact on permeability. *Lawnscapes* actually produce significant runoff during rainfall, laden with nutrients, pesticides, and herbicides.

Consideration of runoff volume control has focused on the frequent rainfalls that comprise a major portion of events in most parts of the country. Since the 2-year rainfall comprises some 95% of the total rainfall in most regions, control of the 2-year event becomes the recommended basis for stormwater management as a *control guideline*. It is considered unreasonable to design any stormwater volume LID measure for greater than a 2-year event. The increase in runoff volume from the 100-year rainfall after site development is so large that it is impractical to require management of this total increase in volume. During such extreme events, the cumulative impact of this volume from largely impervious parcels and in developed watersheds simply overwhelms the natural and human-made conveyance elements of pipes and stream channels. In practice, a best management practice sized for the increase in the 100-year runoff volume would be empty most of the time and would have a 1% probability of functioning at capacity in any one year. Of course, large storms still need to be managed in terms of flooding and peak rate control, to the extent possible. If the 2-year frequency runoff increase can effectively be removed from runoff during the 100-year event, the increase in the peak of the flow rate can be mitigated.

1.5 THE IMPACTS OF DEVELOPMENT ON THE HYDROLOGIC CYCLE

The impact of stormwater runoff from land development on surface water systems such as rivers, lakes, and coastal estuaries is direct and obvious, and the turbid storm flow observed in every small and large watershed that has experienced substantial development is commonplace across the country. What is not so obvious, however, is the impact of land development on the subsurface or underground elements of the hydrologic cycle, as illustrated in Figure 1-2. Most of the rainfall that occurs in any part of the country immediately soaks into the soil mantle under normal climate conditions and is subsequently utilized by surface vegetation in photosynthesis, returning almost half of the annual precipitation back to the atmosphere. The landscapes that are covered with established woodlands and forests are the most efficient in this process, and every tree can be considered a "water pump," drawing moisture from the soil mantle. Where surface vegetation is comprised of less efficient systems, such as grasses or even cultivated crops, the process still comprises a major fraction of the total rainfall. While the amount of evapotranspiration (ET) expected from different types of vegetative systems across the country and the fraction of annual rainfall that this ET represents vary by physiographic region and season, the hydrograph separation of stream flows [17] remains the best method to observe how the runoff process takes place in a watershed over a given year.

Reduced Groundwater Recharge

Under natural conditions, most rain soaks into the soil mantle most of the time. When we cover the soil surface with impervious material and compact the balance of a land development parcel, we effectively prevent the infiltration process from recharging the groundwater aquifer system. The rainfall that would have slowly percolated into the soil mantle and weathered bedrock can no longer reach the *water table*, or *zone of saturation*. This loss of recharge is difficult to quantify, because the only real measurement of this phase of the hydrologic cycle is the reduction in stream base flow as a watershed undergoes the transformation from woodland to cultivated land to suburban or urban land cover. Our records of continuous stream flow on urban tributaries over time can identify the change in flow regime with urbanization, with dramatic increases in storm runoff volume and rate followed by a base flow that frequently approaches zero, altering and frequently destroying the aquatic habitat.

Reduced Stream Base Flow

Because the mechanism of infiltration is not observable on the land surface, we can only measure it indirectly. The same observations of stream and river flow that we use to quantify the discharge in a surface channel serve to measure the groundwater as a part of this flow. When it has not rained in a watershed for several days, all of the water observed (and measured) flowing in the stream (Figure 1-20) or surface channel is coming from the subsurface storage system. During an extended period of stream flow measurement, the flow observed can be distinguished between that which occurs immediately following rainfall as direct surface runoff, and that discharge which comprises the stream flow during the balance of the year. This *base flow* usually represents the major portion of surface stream flow during most of the year, usually on the order of 60% of the annual volume and comprising stream flow about 90% of the year.

Within a given physiographic region, where the annual rainfall is relatively uniform, the base flow can vary significantly. This variation is generally attributed to the surface vegetative system, which can utilize more or less of the infiltrating rainfall. For example, the water balance can vary greatly in different watersheds across the country. Climate also plays a major role, with longer summer seasons and higher average temperatures producing greater evapotranspiration.

Countless small (and large) perennial streams in urban portions of the country have undergone a slow transformation over the past century to a channel that is frequently dry or experiences a very low base flow most of the year, and then is flooded during relatively minor rainfalls as the rapid runoff from extensive

Figure 1-20 Base flow in a perennial stream occurs 90% of the time.

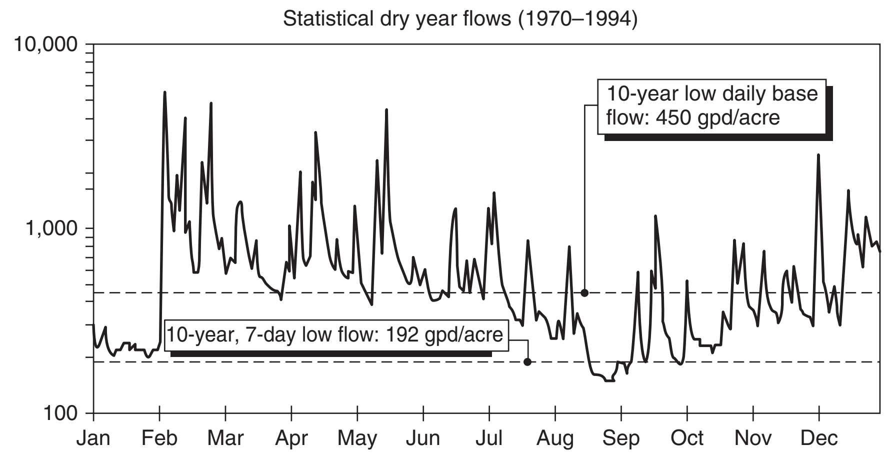

Figure 1-21 Base flow analysis of minimum low flow in a stream.

impervious surfaces pours into the stream. The reduction in base flow of any surface stream usually represents a significant loss of water quality and aquatic habitat, as countless studies have documented. In effect, when we reduce the base flow below the minimum required to sustain the aquatic habitat (Figure 1-21), the system dies or is transformed into something very different.

Altered Stream Channel Morphology

While the increased runoff volume produced and the pollutant load transported with stormwater are important, the impact of this flow in the network of natural stream channels through which it passes is of equal concern. Even where a detention system has been constructed in one or many development sites, the total increase in runoff volume results in a greater flow for longer periods, which affects the natural stream channel by altering the morphology of these channels. Since most surface streams have reached equilibrium with the flow variability under natural conditions, the shape, size, depth, and bank condition of the riparian section is long established prior to land development, although larger river systems that have formed a broad floodplain over millennia will move the channel within this floodplain as discharges vary [18]. On smaller streams that have no tributaries, referred to as *first-order streams*, the impact of the increased volume of runoff is significant, and erodes the channel banks to increase the non-point source pollutant load as the channel readjusts to convey this greater flow.

Water Supply Impacts

A modern water treatment plant is capable of removing virtually all of the sediment and associated pollutants that are attached to the soil particles from a water source. Trace pollutants that are soluble in the raw water are more difficult to remove. The disinfection processes that are a part of this treatment are also capable of removing or killing all of the disease-producing microorganisms found in rivers and lakes. Where only disinfection is included in the treatment process (such as the City of New York), the potential for infectious protozoans, such as *Cryptosporidium parvum* and *Giardia lamblia* to survive the disinfection treatment is very real and can pose a significant health threat, especially to a compromised population (e.g., HIV-infected citizens). The initial sources of these protozoans are wild and domesticated animals, but infected human wastes can also transmit them with runoff.

Perhaps the greatest impact of degraded streams on potable water supply sources is the subtle taste and odor impacts produced in a water supply, especially during warm summer months when raw water reservoirs may themselves be heavily laden with algae. Again, it is the phosphorus conveyed with stormwater runoff that creates the eutrophic environment in the raw water reservoir. In some developed watersheds, surface supply intakes are suspended during periods of heavy rain, but this is not always possible in many supply systems.

Although most modern water treatment plants are very efficient, they do not remove every pollutant conveyed in stormwater runoff, and an increasing number of pollutants are being found in our water supplies. The long-term solution, of course, is to prevent or eliminate their use in the environment, but many are decomposition or end products of common and widely used materials that have become a part of our living environment and cannot be eliminated easily.

1.6 THE HISTORIC APPROACH: DETENTION SYSTEM DESIGN

In the early 1970s, as we began to recognize the hydrologic impacts of land development, the immediate concern was the condition of natural drainage immediately downstream of the building development, and this impact was perceived as a flow-rate problem. We took the technology developed several decades previously for small earthen dams built in agricultural sites (the farm pond) and tailored it to serve as a rate reduction system for the increased runoff volume produced by new impervious surfaces and soil alteration. The detention basin quickly became the design standard, in both a technical and regulatory sense, for stormwater management at every new development site across the country, with significant site impacts (Figure 1-22).

The design criterion became *flow-rate control*, and the stated goal of every stormwater management system was to assure that the rate of stormwater runoff generated from a building site was no greater following development than occurred prior to development. Initially, detention structures were designed primarily to control the extreme runoff conditions of the most severe rainfalls, once again applying the river structure guideline of the 100-year-frequency storm to a small earthen basin built on the upland or in some small drainage swale. With experience, it was recognized that smaller rainfall events could also

Figure 1-22 Detention basin construction removes vegetation and compacts the soil, reducing infiltration and evapotranspiration.

produce erosion impacts downstream, so the detention basin outlet structures were modified to prevent any increase in rate for more frequent storms, such as the 2-year event. The size of any detention basin, however, was based on mitigating the peak rate of the 100-year-frequency rainfall.

As the regulatory programs and design guidelines evolved during the 1980s, it became apparent that a stormwater management system limited to flow-rate mitigation by detention was inadequate. The dramatic increase in runoff volume from developed landscapes was recognized as an important but largely unmitigated result of land development. While the standard detention basin might allow a limited amount of infiltration into the soil mantle at the bottom of the basin, compaction during construction virtually eliminates this possibility. Over time, some designs allowed vegetation to be established within the basin, and this could provide evapotranspiration during and following impoundment, but the actual reduction in runoff volume afforded by the standard detention basin was very little. For the most part, runoff detained in this type of structure simply passes through the basin in a matter of hours and adds to the increase in watershed runoff. Sedimentation of suspended solids does occur, with accumulation in the basin bottom, but the smallest particles (colloids) remain in suspension and pass downstream, transporting most of the phosphorus in the runoff as well as synthetic organics.

Figure 1-23 illustrates how a detention basin operates in terms of runoff volume produced from a development site. The increased runoff volume is held in the structure and subsequently released downstream with no significant mitigation of

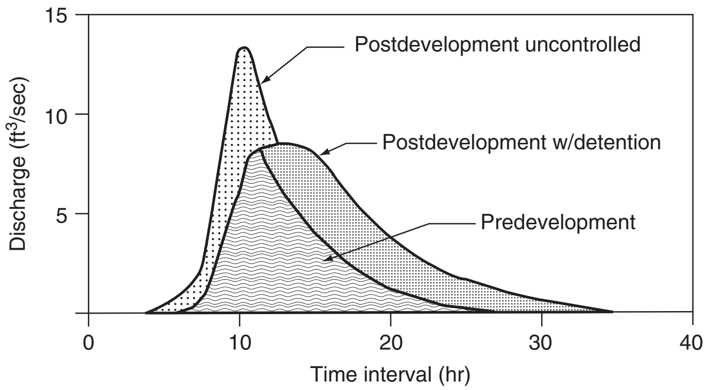

Figure 1-23 Detention basins hold the increased runoff but do not reduce the volume, which subsequently floods downstream.

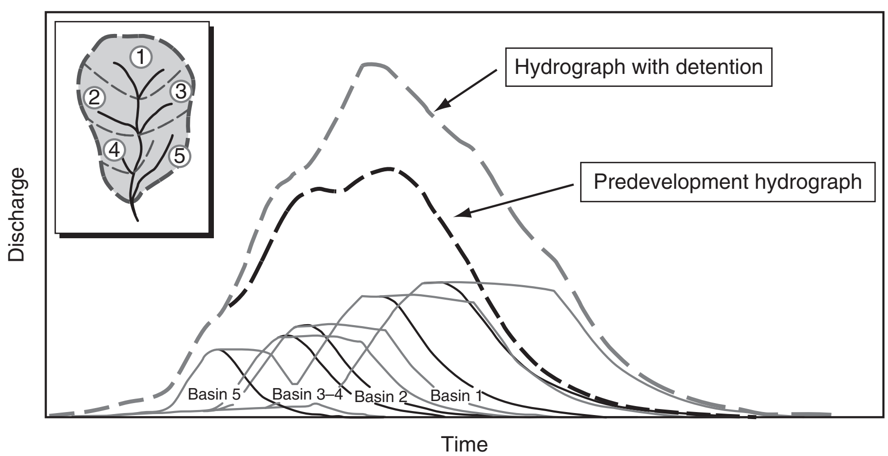

Figure 1-24 Multiple hydrographs in a watershed with detention basins. The compound hydrograph is actually greater than it was predevelopment.

volume. Figure 1-24 illustrates the effect of multiple detention structures within a common drainage basin, with the net result an actual increase in the flow rate downstream, because of the delayed timing in releases from multiple structures. It is obvious that detention-based designs will never be capable of controlling or mitigating the volume increase of rainfall runoff produced by land development. However, we now have countless thousands of these rate control structures situated across the suburban landscape. One of the current issues in stormwater management is how to modify these structures to improve their function beyond simple rate control, as discussed in a later chapter.

1.7 STORMWATER VOLUME METHODOLOGIES

The land development process results in significantly greater volumes of runoff and conveys land pollutants to surface waters, but the difficult issue remains as to how to prevent or reduce this impact. Before we consider how best to "manage" our runoff, we must decide how much of the net increase should or can be reduced or prevented. Since our measurements of the hydrologic cycle are limited to input (rainfall) and output (stream flow), understanding what happens in between in a watershed or catchment is the initial issue.

This is certainly not a new problem, and engineers and hydrologists have developed a number of analytical methods over the past several decades to estimate the amount of runoff produced in a watershed. These various methods are based on the land that comprises the drainage area, and attempt to replicate the complex process of how surface runoff is produced and the multiple pathways followed by each raindrop as it follows the energy gradient downhill. Whatever the algorithm formulated to describe the process, the end result is to estimate the form of the resulting hydrograph that occurs in the receiving stream following rainfall. Since this surface flow hydrograph is the end result of the process, all models "calibrate" or adjust input parameters to replicate this energy waveform.

Since most of this effort has been undertaken to allow the building of structures within the stream or river channel, in the form of culverts, bridges, dams, and other hydraulic structures, the key value measured (or estimated) by the hydrologic modeling analysis has been the *peak rate* of flow that will result during a given rainfall at a specific point in the drainage system. The current stormwater management strategy of reducing or mitigating runoff volume produces a very different perspective on these various modeling procedures, and begs the question: Which method best estimates the change in runoff *volume* resulting from land development?

Many methodologies have been developed to estimate the total runoff volume, the peak rate of runoff, and the stream hydrograph produced from land surfaces under a variety of conditions. In Chapter 6 we describe some of the methods that are most widely used throughout the country. It is certainly not a complete list of procedures, nor is it intended to discourage the use of new and better methods as they become available. There are a wide variety of both public- and private-domain computer models available for performing stormwater calculations, and these models use one or more calculation methodologies to estimate runoff characteristics, following procedures discussed in Chapter 6. To facilitate a consistent and organized presentation of information throughout the country, to assist design engineers in meeting the recommended control guidelines, and to help reviewers analyze project data, a series of worksheets are provided in Appendix A for design professionals to complete and submit with their development applications.

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