

Chapter 2

The Urban Water Budget

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2.1 Basic Concepts

In this chapter our goal is to highlight some of the many ways that urbanization affects the water budget and water cycle. A *water budget* describes the stores or volumes of water in the surface, subsurface and atmospheric compartments of the environment over a chosen increment of time. The *water cycle* has to do with characterizing the flow paths and flow rates of water from one store to another. Understanding how urbanization affects the water budget and water cycle first requires an appreciation of how conditions work in a natural system.

The sun drives the hydrologic cycle, whereby water is evaporated by solar radiation from oceans, inland water bodies and soil, condenses and falls on land as precipitation, and returns to receiving water bodies by either surface runoff or groundwater discharge (Fig. 2.1). There are many critical sub cycles within the overall hydrologic cycle. For example, a portion of precipitation is returned to the atmosphere by evaporation before it reaches the ground. A portion of precipitation that is stored on vegetation (interception storage), on the land surface in puddles (depression storage), or in shallow soil pores, also evaporates rather than moving downward to groundwater or running off to surface water channels. Precipitation infiltrating the soil that is not lost to evaporation can flow downward to *recharge* groundwater, contributing to a rise in the *water table*, or flow shallowly in a lateral direction and discharge to streams. Flow in streams that is not due to surface or shallow subsurface runoff from the land is termed *base flow*; base flow in natural systems arises from deep and shallow groundwater discharging to streams during both storm and non-storm periods.

A water budget or water mass balance can be calculated for any time increment for a chosen *control volume*, where

$$\text{Inflows} - \text{Outflows} = \Delta \text{Storage} \quad (2.1)$$

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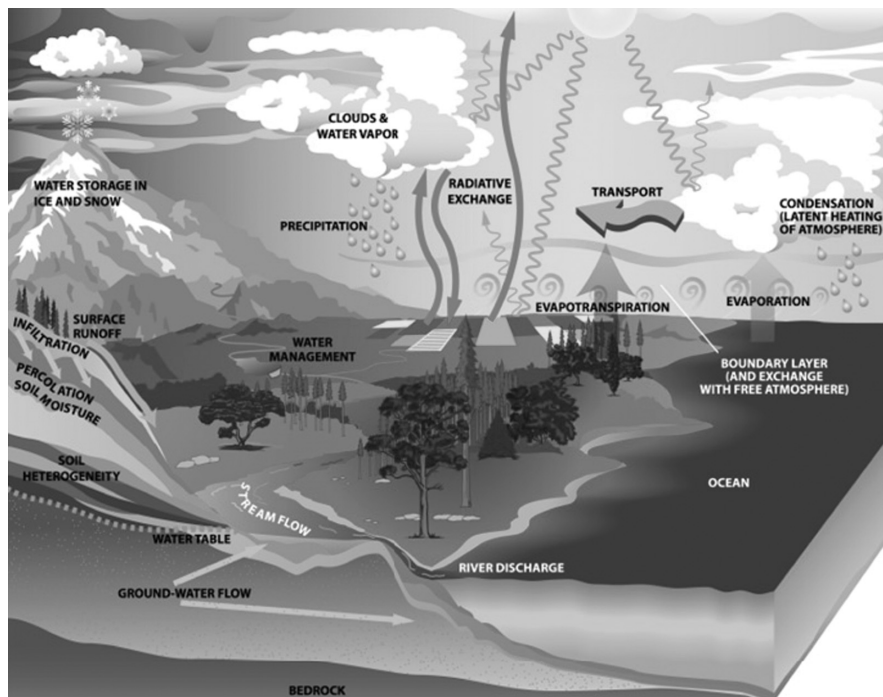


Fig. 2.1 The hydrologic cycle.

Source: US Global Change Research Program, <http://www.usgcrp.gov/usgcrp/ProgramElements/water.htm>

For natural systems, a control volume is often defined laterally by watershed boundaries (topographic highs) and vertically from the top of vegetation to the bottom extent of water-bearing subsurface sediments or fractured rock. Inflows are precipitation and groundwater flowing into the control volume; outflows are evaporation from surface water, vegetation, and soils, transpiration from plants (together called *evapotranspiration*), streamflow (runoff) and groundwater flow exiting the domain. A mass balance for a watershed-based control volume can therefore be expressed as

$$\text{Precipitation} - \text{Runoff} - \text{Net Groundwater Outflow} - \text{Evapotranspiration} = \Delta \text{Storage} \quad (2.2)$$

where the net groundwater outflow is groundwater inflow minus outflow, and all terms are measured in volumes over the time period of interest. The change in storage includes changes in both the amount of water stored in groundwater (or *aquifer storage*) as well as in surface reservoirs. Measurement records of precipitation, streamflow, groundwater levels, and surface reservoir levels are available from governmental agencies; evapotranspiration can be calculated because it is the only

unknown. A word of caution should accompany this kind of calculation: Although records are widely available, there are sampling and measurement errors associated with the data, and therefore evapotranspiration approximated this way reflects these uncertainties.

The urban water budget can be significantly affected by infrastructure moving water across natural flow boundaries. Piped water to and from a watershed (potable water supply, stormwater, and wastewater) can be an important part of the water balance. For urban areas, the water budget for a watershed-based control volume therefore may be altered to reflect these additional considerations and expressed as

$$\begin{aligned} & \text{Precipitation} - \text{Runoff} - \text{Net Groundwater Outflow} + \text{Net Potable Water Imported} \\ & + \text{Net Wastewater Imported} + \text{Net Stormwater Imported} - \text{Evapotranspiration} \\ & = \Delta \text{Storage} \end{aligned} \quad (2.3)$$

where net water imported is water imported minus exported by piped systems (potable water, wastewater, stormwater). A developed watershed may have any combination of water, wastewater, and stormwater imports and exports, which can lead to a net loss or gain to the system compared to the natural system. For example, water supply may be imported, and a portion may be used for lawn watering and disposal to a septic system, which would result in a net gain. Other portions of imported water may be disposed to a wastewater collection system transporting water out of the watershed, which would offset the gain in a partial loss. Box 2.1 shows calculations of a water budget for Valley Creek watershed in suburban Philadelphia, Pennsylvania where groundwater withdrawals from wells are a significant export. Calculation of a water budget for any urbanized area requires site-specific understanding in terms of the sources and disposition of all water budget components.

Box 2.1 Example Water Budget Calculation

This example illustrates calculation of the 1985 annual water budget for Valley Creek watershed, an urbanizing area in suburban Philadelphia, Pennsylvania. The area of interest is 20.8 mi² draining past a USGS gage recording the streamflow. (See http://waterdata.usgs.gov/pa/nwis/uv?site_no=01473169). The example is based on the work of Sloto (1990).

The relevant annual water budget for this case is given as:

$$\begin{aligned} & \text{Precipitation} - \text{Runoff} - \text{Groundwater Withdrawals} - \text{Evapotranspiration} \\ & = \Delta \text{Storage} \end{aligned}$$

where groundwater withdrawals are the amount pumped from wells and exported from the basin for water use elsewhere. In this case the net natural

groundwater outflow from across the basin divides is considered to be zero. It is also assumed that all wastewater generated within the basin is treated/disposed within the basin and therefore there is no net flow of wastewater across watershed divides to account for.

For 1985, the total precipitation measured at a raingage in the region was 42.71 inches, the average annual streamflow as measured at the USGS streamgage was reported as 23.83 ft³/sec, groundwater withdrawal from wells, obtained from utility records, was 1.89 mgd (million gallons per day), and the change in groundwater storage was estimated as 0.10 inches (change in depth of water in a representative well from one year to the next multiplied by specific yield.) (Specific yield is an aquifer characteristic of the volume of water that is released by drainage from a unit volume of aquifer material.) The unknown in this water balance is therefore evapotranspiration:

$$\text{Evapotranspiration} = \text{Precipitation} - \text{Runoff} - \text{Groundwater Withdrawals} - \Delta \text{Storage}$$

Putting all terms into like units,

$$\text{Precipitation} = 42.71 \text{ in/yr}$$

$$\begin{aligned} \text{Runoff} &= [23.83 \text{ ft}^3/\text{sec} \times (12 \text{ in/ft}) \times 86,400 \text{ sec/d} \\ &\quad \times 365 \text{ d/yr}] / [20.8 \text{ mi}^2 \times (5280 \text{ ft/mi})^2] \\ &= 15.5 \text{ in/yr} \end{aligned}$$

$$\begin{aligned} \text{Groundwater withdrawals} &= 1.89 \times 10^6 \text{ gal/d} \times (365 \text{ d/yr}) \\ &\quad \times (12 \text{ in/ft}) / [7.48 \text{ gal/ft}^3 \\ &\quad \times [20.8 \text{ mi}^2 \times (5280 \text{ ft/mi})^2]] = 1.91 \text{ in/yr} \end{aligned}$$

$$\Delta \text{Storage} = \Delta \text{groundwater storage} = 0.42 \text{ in/yr (observed change in well water level} \times \text{specific yield)}$$

Note that in carrying out the calculations, the volume of runoff and the volume of well water withdrawn are spread over the area of the watershed to obtain equivalent depths, so that the units are comparable to those of precipitation.

Substituting for all terms in the water budget equation,

$$\text{Evapotranspiration} = (42.71 - 15.5 - 1.91 - 0.42) \text{ in/yr} = 24.8 \text{ in/yr}$$

This calculation shows that evapotranspiration is about 58% of the precipitation input.

In ultra-urban areas, the area drained by the dense underground system of pipes criss-crossing what remains of natural watershed boundaries may be so significantly different from the area drained by natural boundaries, that it may be desirable to delineate *sewersheds* drained by wastewater and stormwater pipes separately from the natural watershed, for purposes of water management (Mitchell et al., 2001). Delineation of sewersheds is carried out by spatial analysis of the system of pipe layouts to determine the area drained or serviced by the pipe system.

2.2 Impacts of Urbanization on the Water Cycle

Figure 2.2 is a map of an urbanized 14.3-km² watershed in Baltimore, Maryland, which shows how drastically the density and connectivity of the flow channels have been altered due to construction of buildings and roads. In some locations on this map it is difficult to discern the direction of surface water flow, owing to the high degree of landscape alteration. The vast network of pipes and utility conduits underlying urban areas can also significantly affect the cycling of water, although this effect is much more difficult to quantify because the systems are hidden.

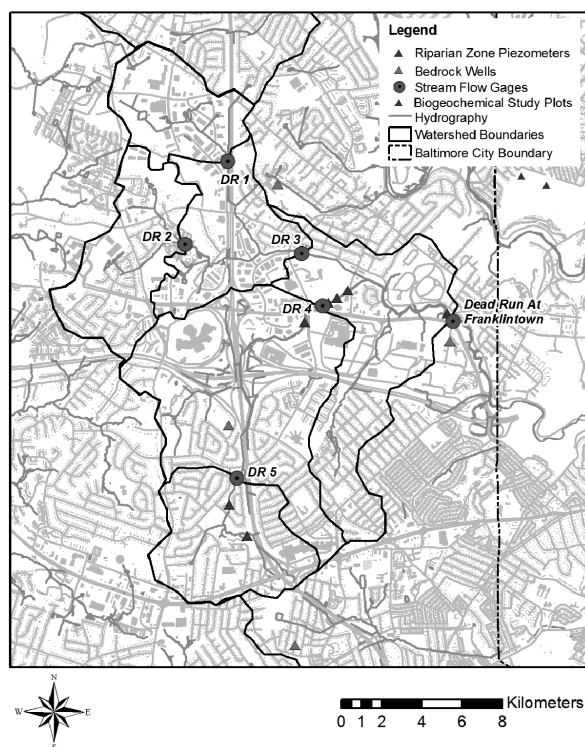


Fig. 2.2 Evidence of altered surface drainage in Dead Run watershed in the Baltimore, MD area. Pale blue lines are surface drainage; gray indicates impervious surfaces. (Courtesy of Michael P. McGuire, Geospatial Data Analysis Laboratory, Center for Urban Environmental Research and Education, UMBC)

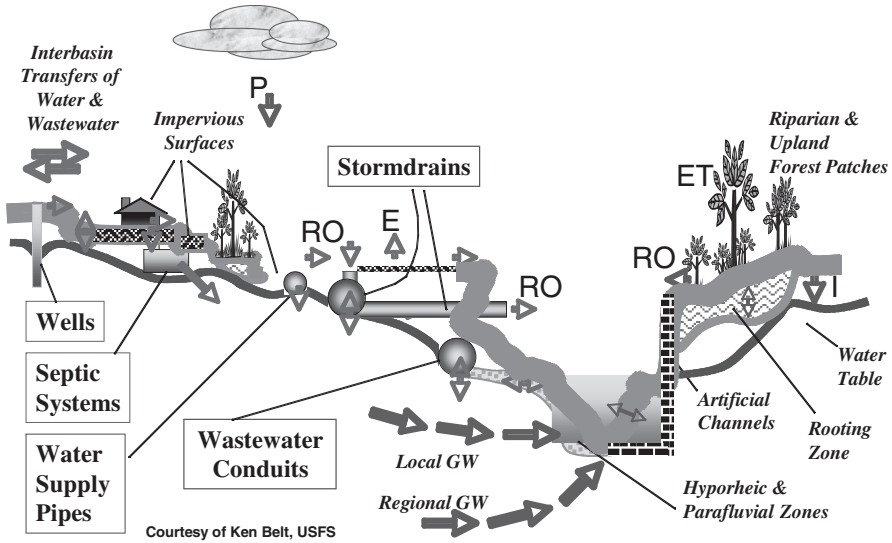


Fig. 2.3 The urban water cycle (Courtesy of Kenneth Belt, USDA Forest Service, Baltimore, Maryland)

Figure 2.3 is a conceptual cross-section through the surface and subsurface, where blue arrows depict a portion of the natural system flow paths, and red arrows show how the built environment alters the route that water takes. The effects of urbanization on the water cycle can include short-circuiting or path-lengthening compared to the natural system. Leaking pressurized water distribution systems can contribute to groundwater recharge. Cracks in parking lots and other sealed surfaces can act as focused recharge points to the subsurface (Sharp et al., 2006). Joints and cracks in sanitary and storm sewers can serve as drains for groundwater; conversely these pipes can also leak to groundwater, causing water quality impairment. Utility conduits and tunnels themselves can act as preferential flow channels for groundwater (Sharp et al., 2003), drastically altering the effective permeability of the subsurface. Treated wastewater discharged into a stream supplements base flow and in some cases accounts for the greatest portion of streamflow.

As pointed out in the introductory chapter, humans enhance the conditions for flood production in cities by hardening the land surface. The urbanized watershed of Fig. 2.2 shows impervious areas (parking lots, roads, sidewalks, roofs) in pale gray. In this particular watershed, impervious surfaces constitute 41% of the watershed area. Impervious area and compacted soils cause stormwater to run off instead of seeping into the ground; the highly engineered storm drain system carries water quickly away from properties.

Figure 2.4 depicts quantitatively the modeled effect of urbanization on storm runoff. This graph shows storm runoff from application of a 6-hour duration storm with a *return period* of 2 years to a 6-acre site in Valley Creek watershed, PA under conditions of (1) predevelopment, (2) post-development with no controls, and (3)

post-development with stormwater detention (Emerson, 2003). (Plots of flow rate versus time are termed *hydrographs*.) The peak flow rate of the post-development hydrograph (with no detention) is more than three times greater than the hydrograph of the pre-development case; and the first arrival of surface runoff of the post-development case with no detention is within several minutes as compared to a delay of about 90 min for runoff from the pre-development case. Clearly the area under the curve, the total stormwater volume, is much greater for the post-development case with no detention control compared to the pre-development case.

Stormwater management regulations often require reduction of peak flow rates by routing flows to a *detention basin* designed for this purpose; a photograph of a detention basin is provided in Fig. 2.5. A detention basin or pond is the most commonly used *best management practice* (BMP) used to control runoff and nonpoint source pollution. Figure 2.4 shows that routing runoff through a detention pond reduces the hydrograph peak to a rate below that of pre-development flow rate, and delays the first arrival time of runoff compared to the post-development flow without detention. However, the area under the curve, which represents the runoff volume, remains much greater for the post-development case with detention compared to the pre-development case. In addition, the post-development case with detention control still has an earlier first arrival of flow initiation than pre-development flow in the example shown.

Storm detention systems designed to reduce higher flows typically pass lower flows through unattenuated; these flows plus volumes of larger detained flows all discharging into a watershed main channel in an additive fashion can result in

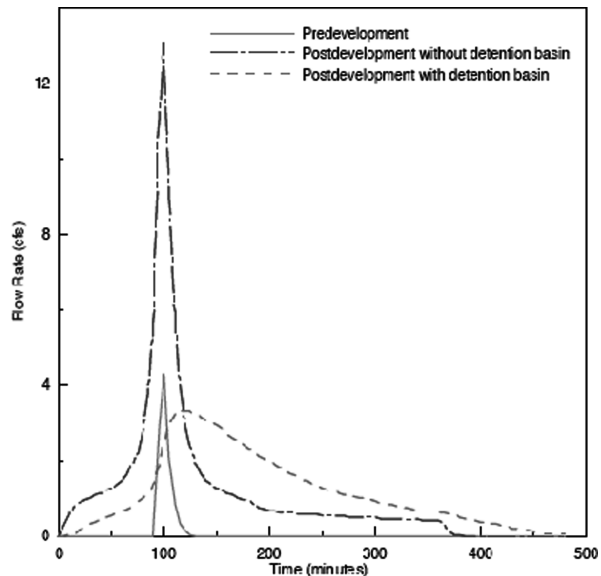


Fig. 2.4 Model results for pre-development surface water flow (solid line), post-development flow (dash-dot line), and post-development flow with detention (dashed line), for a storm having a duration of 6 hours and a return period of 2 years, applied to a 6-acre site from Valley Creek watershed, Pennsylvania (© Emerson, 2003; reprinted with permission)



Fig. 2.5 Stormwater detention basin in suburban Baltimore, MD. Photo by Claire Welty

exacerbated flooding in downstream areas (Emerson et al., 2005). A net result is that storm flow in downstream area has a greater flow rate and total volume than storm flow in downstream area before urbanization as a result of decreased travel time and increased water volume being directed toward the stream. Resolving this problem is one of the most challenging issues in stormwater management of the present day. In addition to actually posing life-threatening situations with high water velocities, greater streamflows contribute to increased bank erosion, often resulting in streams becoming wider and shallower in urban areas. This topic is discussed in further detail in Chapter 6. Down cutting of stream beds due to erosion can suppress water table elevations and reduce soil moisture available to *riparian zones* (Groffman et al., 2003).

A companion effect of increased runoff from impervious surfaces is reduced infiltration and groundwater recharge, which in turn can result in reduced groundwater discharge to streams and lower stream base flows. However, these reductions may partly offset by enhanced groundwater recharge in areas served by septic systems (Burns et al., 2005), as well as summertime irrigation in residential areas, especially during low base-flow months when such effects would be most pronounced (Meyer, 2005). Even in cases where groundwater is not used for water supply, groundwater in urban areas needs to be considered as a critical component of the hydrologic cycle owing to its important contribution to base flow and hence

maintenance of instream flows for aquatic life. A more detailed discussion on the importance of groundwater in urban systems is provided in Chapter 3.

Evapotranspiration is often assumed to be negligible in highly developed areas owing to lack of trees. While this may be true for downtown or industrial areas, suburban residential areas often have a higher density of trees than rural farmed areas, and can have significant evapotranspiration rates. Grimmond and Oke (1991) found that evapotranspiration was 40% of the annual and 80% of the summer water budget of Vancouver, British Columbia. Using eddy covariance equipment to measure water vapor flux and to calculate evapotranspiration rates, they also found that evapotranspiration was often sustained in residential areas in summer by use of the potable water supply for garden irrigation and that the evapotranspiration rate could actually exceed the precipitation rate (Grimmond and Oke, 1999).

2.3 Effects of New Approaches to Water Management on the Water Cycle

In recent years there has been an emphasis on so-called “low-impact” development (LID) technologies for managing stormwater, including use of green roofs, cisterns, rain gardens, and on-site infiltration ponds. These practices can have a significant impact on the urban water cycle by increasing on-site recharge and reducing runoff rates. In evaluating the hydrologic response to three types of landscapes – undeveloped, developed, and LID – Holman-Dodds et al. (2003) were able to show that LID was most effective for small, frequent storms and that further stormwater protection (e.g., detention basins) was needed for larger events. The optimal kinds of sites where stormwater infiltration can be promoted are in upland areas where the soils are better suited for infiltration. Williams and Wise (2006) reached a similar conclusion in modeling the hydrologic response to four types of land development patterns, concluding that land preservation and infiltration could be effective at reducing stormwater flows, although detention ponds were needed to control peak storm flows.

2.4 Future Directions

The basis for sound water management starts with reliable water budget calculations (Healy et al., 2007). In other words, one needs to understand the urban water system before making recommendations to modify it. Example types of sustainable water management scenarios that would be dependent on water budget calculations are listed in Table 2.1. The concept of “water use regime” has been recently advanced (Weiskel et al., 2007) as a system to quantify the sustainable use of water by humans compared to water cycling that would be expected in a natural system. Four bounding conditions are defined: Natural-flow-dominated (undeveloped), human-flow-dominated (“churned”), withdrawal-dominated (“depleted”), and

Table 2.1 Sustainable water management strategies in urban systems (after Eiswirth, 2002)

Component of the Urban Water System	Example of Sustainable Development
Wastewater drainage	Automated leak detection system Scheduled infrastructure replacement and repair
Wastewater treatment	Reuse of treated wastewater for irrigation or groundwater recharge Advanced wastewater treatment Direct wastewater to potable reuse
Stormwater drainage	Separate storm sewer system Promotion of infiltration where feasible Reuse of stormwater on-site Disconnection of impervious surfaces Management on a watershed scale Managing small, frequent storms differently than large, infrequent events
Water supply	Leak detection and leak reduction Scheduled infrastructure replacement and repair
All	Manage the water system as a single resource Set up data collection, management, and archiving system

return-flow-dominated (“surcharged”), against which alternative and historic scenarios can be compared. This classification system depends strongly on the availability of water budget information. There is currently also a desire to assess the impact of climate change on urban water systems. A recent study involving water balance calculations in Connecticut showed that climate change had a far more significant impact on the water budget than land cover change brought about by urbanization (Claessens et al., 2006).

There is a very real need for coordinated data collection of all components in the urban water budget, and sometimes at small time increments (as small as a day for some applications) and small watershed scales (on the order of square kilometers), to be able to calibrate numerical hydrologic models to current conditions or to make reliable predictions. A consistent methodology must be established for data collection, processing, and archiving, in a consistent set of units, such that the data can easily be assimilated into models. Such an approach has been promoted by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (<http://www.cuahsi.org>). In addition to the “natural” components of stream-flow, groundwater levels, precipitation, and evapotranspiration, it is of paramount importance to quantify imported and exported water to the basin of interest, so that highly managed systems can be accurately assessed. Once a coherent coordinated data collection system is in place, fully coupled water-cycle models can be calibrated, enabling predictions of various scenarios involving growth and climate change. There are many challenges in modeling of urban systems, especially how to represent the fine granularity of the landscape in a total water cycle approach. New approaches to modeling the effects of pipe infrastructure over large scales are

needed, as well as greater utilization of remote sensing (satellite, aircraft) data for variables such as land surface temperature and soil moisture.

Finally, holistic water management is likely to be thwarted unless management agencies (water supply, wastewater treatment, stormwater management) operate under either one umbrella or in a more coordinated fashion so that water is managed as a single resource. Institutional issues are discussed in Chapters 11 and 12.

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