Table 9-8. Water Sources That Are Appropriate for Specific Uses of Water

Water Use	Water Source					
	Surface Water (Untreated)	Surface Water (Treated)	Groundwater[a]	Rainwater (First Flush)	Rainwater (After First Flush)	Greywater
Drinking	X	A	A	X	A	X
Cooking	X	A	A	X	A	X
Bathing, hand washing, anal ablution	A[b]	U	A	A	A	X
Irrigation	A	U	A	A	A	A
Latrine flushing	A	U	A	A	A	A

Note: A = Appropriate, U = Unnecessary expense, and X = Inappropriate.

[a]Care must be taken in areas where arsenic, fluoride, or microbial contamination of groundwater is a concern. Sanitary surveys should be used to determine the risk of microbial contamination.

[b]In areas where schistosomiasis is endemic, people's skin should not come into contact with untreated surface water. Infected snails release a larval form of the parasite that can burrow through skin.

and hygiene, whereas community members might be more interested in water for productive activities, such as gardening. This misunderstanding can lead to different decisions regarding which water source to use, as well as an underestimation of potential demand. Both women and men, who may have contrasting ideas about which water-using activities are most important, must take part in the prioritization of a community's water needs.

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10

Watersheds: Hydrology and Drainage

10.1 Ecological Capital

The many benefits of natural and well-managed watersheds include water supply, drainage, flood protection, erosion control, wastewater treatment, wildlife habitat, and other biodiversity functions. In developing countries, and especially in rural areas, watershed conditions tend to affect human health and livelihood more directly than in urban areas or industrialized countries. This situation occurs because of the absence of infrastructure for freshwater, wastewater, and storm water conveyance and treatment—in these locales, the watershed itself must provide conveyance and treatment functions, essentially serving as ecological capital. Ecological capital is recognized to provide a "fundamental stepping stone in the economic empowerment of the rural poor" (WRI 2005). When watershed degradation occurs, beneficial functions are impaired or lost, and the ecological capital on which low-income communities depend is depleted.

Watershed degradation can occur for many reasons, some of which are illustrated in Fig. 10-1. Most notably, human activities can change land cover and lead to increased surface runoff and soil erosion, decreased spring output, and degraded water quality. It is also common for natural wetlands to be drained to increase arable land. Grazing activities affect vegetation cover and soil compaction, leading to reduction in evapotranspiration and infiltration rates and increased runoff. Animal wastes may also affect water quality. Deforestation due to agriculture, grazing, or firewood collection will also affect evapotranspiration and infiltration, but the magnitude of these effects depends on soil properties and subsequent land use. Any consumptive use of water, whether for domestic, industrial, or irrigation purposes, will affect the water budget as well (e.g., manifested in reduced stream flows or lower water tables) and could affect water quality through the resulting wastewater discharge.

Hydraulic structures (e.g., dams, culverts) or other stream channel modifications will affect the volume and timing of stream flows. Any construction activity can potentially lead to increased runoff and soil erosion. Construction over or along stream channels, such as roads and bridges, may also affect stream flow hydraulics.

Finally, regional climate change, whether because of natural cycles or anthropogenic effects, may affect watershed functions as vegetation and stream channels adjust to

This chapter was written by David W. Watkins, Jr.

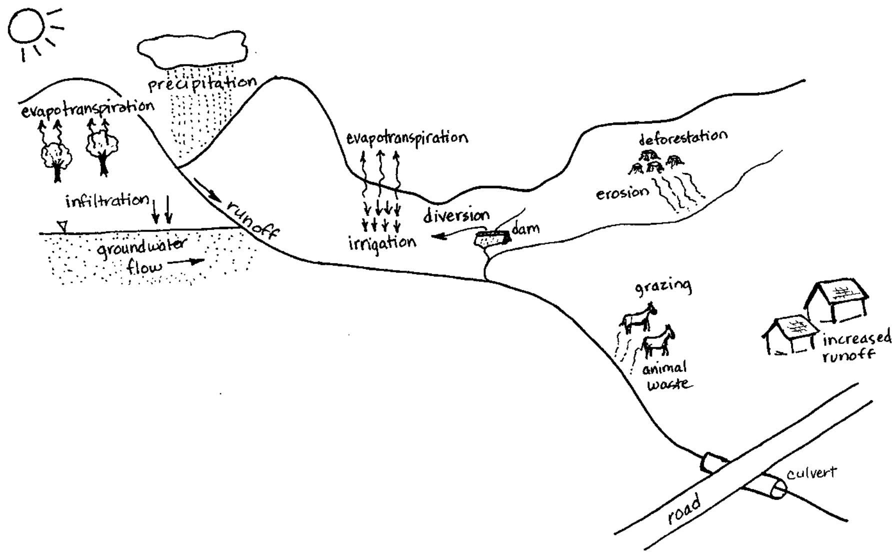


Figure 10-1. Examples of Human Activities Affecting the Hydrologic Cycle and Water Quality.

changing seasonal patterns of precipitation, temperature, and humidity. These effects can adversely affect human health through diminished access to water supplies or through the introduction of pathogens to water supplies. Environmental systems can be adversely affected through any changes to the natural hydrologic cycle.

Efforts to maintain beneficial watershed functions and protect human and environmental health can be made at a range of spatial and temporal scales. Ideally, sustainable development would entail long-term, holistic, consensus-based planning at the watershed scale (as well as other pertinent socioeconomic, political, and ecosystem scales). In practice, engineers find themselves arriving on the scene of a watershed in transition, often observing unintended or incompletely understood consequences of past and present activities, and with a limited budget with which to correct problems. Thus, practical, small-scale, and sometimes temporary solutions must be found, but these solutions should take into account larger space and time scales to the extent possible.

10.2 Watershed Management Principles

A *watershed* is defined as the land area that drains to a particular water body or, in the case of a river or stream, to a particular location along the channel. To delineate a watershed manually, a topographic map (showing elevation contours) is used to locate high points around the water body or outlet point. These points are then connected with lines sketched approximately perpendicular to the contours (Fig. 10-2).

Many organizations around the world have access to geographic information systems (GIS) software, such as ArcGIS. Watershed delineation is easily performed using GIS

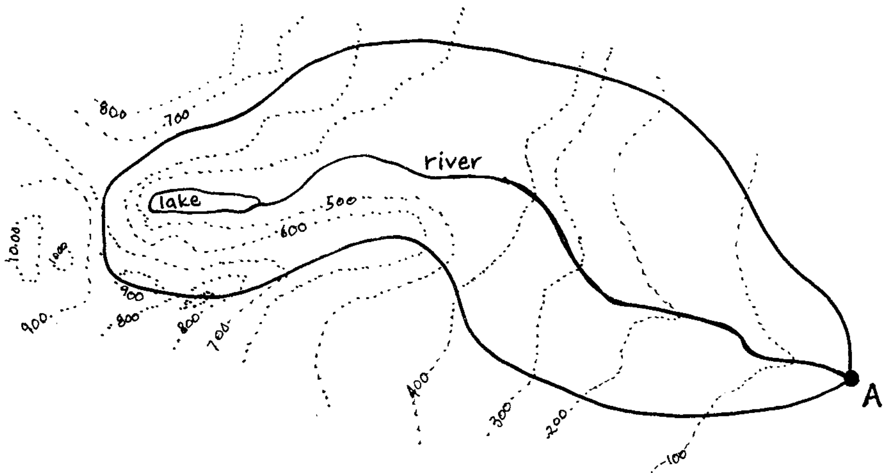


Figure 10-2. Watershed Delineation Overlaid on a Topographic Map. The Area Outlined Drains to Point A.

elevation data, such as a digital elevation model or elevation contour data. Free GIS data from various organizations are available online for many parts of the world. Online help is available for ArcGIS software, with instructions for watershed delineation at www.esri.com. Chang (2006) provides an introduction to GIS topics, such as coordinate systems, data models, data analysis, spatial interpolation, watershed analysis, and other useful topics for working with spatial data.

For many practical purposes, the watershed provides a physically meaningful boundary within which to carry out water resources assessment and planning activities. However, groundwater levels do not necessarily follow land surface elevations.

Within any watershed, it is important to recognize the social, ecological, and economic value of the landscape and its water resources. Although certain economic uses of the watershed (agriculture, grazing, timber, roads) may be easily observed, and human health benefits from clean and plentiful water supplies are apparent, many environmental functions may not be widely recognized. Denny (1997) lists a number of environmental functions of watersheds (Box 10-1).

The stewardship of watershed lands is often neglected. Water supplies and other environmental functions may deteriorate rapidly if contributing areas are not protected from point and nonpoint source pollution or from damaging hydrologic effects of land use changes or structural modifications. Furthermore, because land use change is usually gradual, the effects of pollution may be delayed, and these effects are often distant from the point of water delivery, there may be a "psychological disconnect" in which residents fail to recognize the effects of their land use, water use, and waste disposal decisions (Lee 2000).

Among the most serious of these impacts are the public health effects of poor drainage and standing water, which can promote transmission of a host of water-borne and mosquito-borne diseases, including bacterial, viral, and parasitic infections. Of primary

Box 10-1. Environmental Functions of Watersheds

Climatic effects
- Carbon fixation and CO_2 balance
- Rainfall and humidity improvement
- Microclimate influences

Water quality functions
- Particulate filtration and settling
- Nutrient stripping
- Biodegradation of toxic chemicals
- Pathogen reduction
- Heavy metal sequestration
- Wastewater treatment

Biodiversity and habitat functions
- Landscape and ecosystem diversity
- Ecosystems transition zones
- Water supply
- Wildlife habitat
- Genetic biodiversity

Hydrologic and hydraulic functions
- Drainage
- Erosion protection
- Flood mitigation
- Water supply
- Groundwater recharge

From: Denny 1997.

importance are water-borne diseases (including cholera, typhoid, and many common diarrheal diseases), which are spread through fecal contamination of water supplies. This contamination may infect peoples' hands, utensils, food, or drinking water. There are also water-related diseases, such as schistosomiasis, which are acquired though skin contact with contaminated water. Finally, mosquito breeding in standing water can promote the spread of parasitic infections, such as malaria and filariasis, as well as viruses, such as those that cause yellow fever and dengue fever.

To the extent possible, the water supply, health, and environmental functions of watersheds must be valued explicitly, and a community-based watershed plan should be developed to evaluate trade-offs and promote watershed stewardship. Eight basic steps to developing a community-based watershed plan are illustrated in Fig. 10-3. These steps range from involving the community and gaining an understanding of the watershed and its functions, to identifying problems, establishing goals, identifying alternatives, and evaluating performance. As indicated in Fig. 10-3, sustainable watershed planning should be an ongoing process—as populations, technology, economics, and climate conditions change—rather than a linear process with an end point.

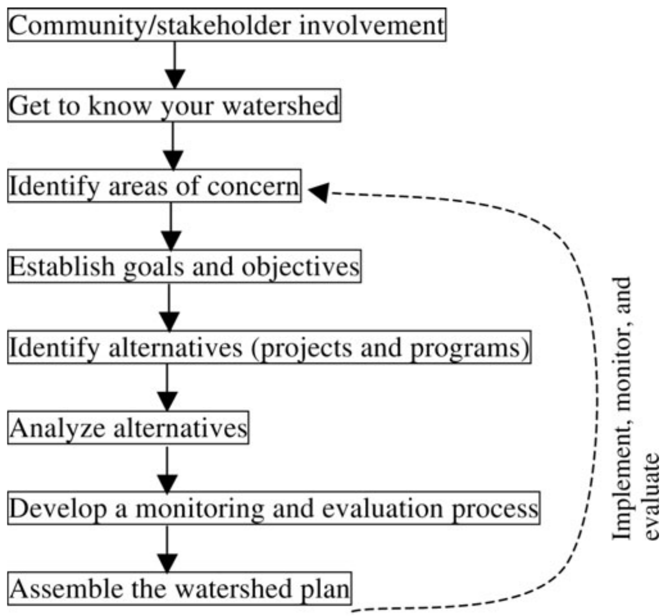


Figure 10-3. Steps in Developing a Community-Based Watershed Plan.

10.3 Hydrologic Analysis and Design Methods

Historically, the ubiquitous lack of watershed data has led to the development of relatively simple, empirical methods for performing hydrologic analysis and design calculations. This section outlines a few standard methods that are widely used to assess hydrologic effects of land use change and to design solutions for drainage and flooding problems.

10.3.1 Water Budget Method

One simple analysis, in concept at least, is to develop a water budget for the watershed or subarea of the watershed to be analyzed. Considering the hydrologic processes shown in Fig. 10-1, a water budget may be represented as

$$\Delta S = P - I - ET - R \tag{10-1}$$

where ΔS is the change in surface storage (amount of ponded water), P is precipitation, I is infiltration, ET is evapotranspiration (which may also include "interception" of rainfall by plants), and R is runoff. While simple in concept, an accurate water budget over any given time period may be elusive in practice because of uncertainties in measuring each of the components.

Precipitation may be measured at one or possibly a few gauges throughout the watershed but can vary significantly even over short distances. Runoff may be estimated as the increase in stream flow volume (over some "base flow," which is the flow during

Box 10-2. Thornthwaite-Type Monthly Water Balance

A Thornthwaite-type monthly water balance model is a simple and relatively reliable method for simulating a steady-state climatic average or continuous water balance in a watershed. The method assumes that if potential evapotranspiration (PET) is less than or equal to water input, then evapotranspiration (ET) is equal to the potential evapotranspiration. Otherwise, ET is the sum of water input and an increment removed from soil storage. PET was defined by Penman (1956) as "the amount of water transpired . . . by a short green crop, completely shading the ground, of uniform height and never short of water." It is best estimated by the Hamon method, which is based only on temperature and day length.

A typical Thorntwhaite-type model requires the following input:

- Field capacity, θ_{fc} (moisture content of soil after excess water has drained away)
- Vertical extent of the root zone, Z_{rz} (cm)
- Total monthly precipitation, P_m (cm)
- Average monthly temperature, T_m (°C)

1. Calculate the maximum soil-water storage capacity:

$$\text{Soil}_{\max} = \theta_{fc} \times Z_{rz}$$

2. Calculate the monthly water input:

   a. Divide precipitation into rain and snow:

$$\text{Rain}_m = F_m \times P_m$$
$$\text{Snow}_m = (1 - F_m) \times P_m$$

   The melt factor, F_m, depends on temperature:

$$F_m = 0 \text{ for } T_m \leq 0\ °\text{C}$$
$$F_m = 0.167 \times T_m \text{ for } 0\ °\text{C} < T_m < 6\ °\text{C}$$
$$F_m = 1 \text{ for } T_m \geq 6\ °\text{C}$$

   b. Calculate monthly snowmelt.

   The monthly snowmelt depends on snowfall and snowpack. The monthly snowpack, Pack_m is calculated using the snowpack from the previous month:

$$\text{Pack}_m = (1 - F_m)^2 \times P_m + (1 - F_m) \times \text{Pack}_{m-1}$$

   Monthly snowmelt is then:

$$\text{Melt}_m = F_m \times (\text{Pack}_{m-1} + \text{Snow}_m)$$

   c. Calculate monthly water input, W_m:

$$W_m = \text{Rain}_m + \text{Melt}_m$$

3. Calculate the evapotranspiration and soil moisture:

   a. Calculate PET_m. PET has been estimated by Hammon (1963) as

$$PET = 29.8D\frac{e_a^*(T_a)}{T_a + 273.2}$$

Where PET is in mm/day, D is day length in hours, and $e_a^*(T_a)$ is the saturation vapor pressure at the mean daily temperature, T_a:

$$e_a^*(T_a) = 0.611 \exp\left(\frac{17.3T_a}{T_a + 237.3}\right)$$

b. If $W_m \geq \text{PET}_m$, then

$$\text{ET}_m = \text{PET}_m$$
$$\text{Soil}_m = \min\{[(W_m - \text{PET}_m) + \text{Soil}_{m-1}], \text{Soil}_{\max}\}$$

c. If $W_m < \text{PET}_m$, then

$$\text{ET}_m = W_m + \text{Soil}_{m-1} - \text{Soil}_m$$

where the decrease in soil moisture is found using:

$$SOIL_{m-1} - SOIL_m = SOIL_{m-1}\left[1 - \exp\left(-\frac{PET_m - W_m}{SOIL_{\max}}\right)\right]$$

This type of model can be used for either continuous monthly data or climatic monthly averages. If the model is used with climatic monthly averages, then at month $m = 1$, the previous month, m, is $m - 1 = 12$.

Source: Dingman 2002.

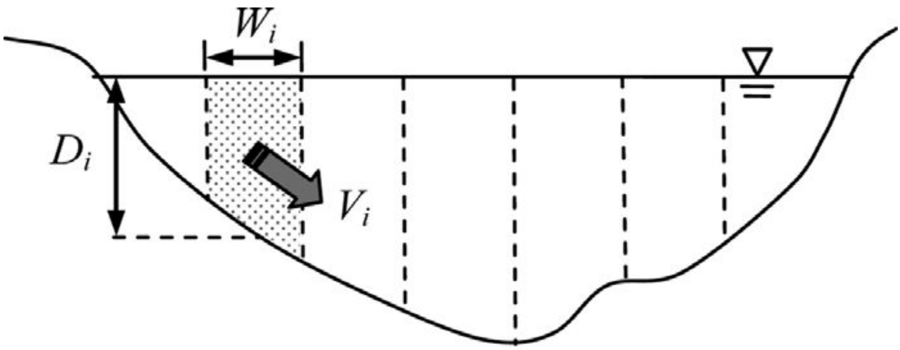
dry periods), with stream flow calculated as the cross-sectional area of the flow times the average velocity (see Fig. 10-4). Infiltration and evapotranspiration (ET) are difficult to measure directly, however. This problem prevents closure of the water budget. For even rough estimates of these components of the hydrologic cycle, simplified methods may be needed. One approach is to rely on tabulated "crop coefficients" to estimate ET. Another approach is to use simple equations, as in a Thornthwaite-type water balance model (Dingman 2002).

10.3.2 Analyzing Large Rainfall Events

In reality, the water budget of a watershed varies continuously in time, with significant changes throughout each day, even if no precipitation occurs, because of diurnal changes in solar radiation, temperature, wind, and humidity. Because of the difficulties of continuously tracking water as it moves throughout the watershed, a number of simplified methods (or models) have been developed specifically for analyzing large rainfall events that may lead to flooding or drainage problems. Two of these are the rational method and the Natural Resources Conservation Service (NRCS) runoff curve number method.

Rational Method

One common method for estimating peak runoff rates in urban settings or small watersheds (less than 200 acres) is the rational method. This method computes a peak runoff



$$Q = \sum_i V_i A_i = \sum_i V_i \times (W_i \times D_i)$$

Figure 10-4. Illustration of Flow Measurement Technique.

Note: The average velocity at each section may be roughly estimated by measuring the distance a small float, such as a leaf, travels in 10 s and multiplying this surface velocity by 0.85.

rate, Q (ft^3/s), from a storm based on a given rainfall intensity, i (in./h), the drainage area, A (acres), and a runoff coefficient, C, that depends on land use, terrain, and soil conditions. The equation is

$$Q = C \times i \times A \tag{10-2}$$

No unit conversions are required in Eq. 10-2 because 1 acre-in./h is approximately equal to 1.008 ft^3/s.

Infiltration rates are higher for sandy soil than for clay soil. Infiltration may be minimal for rocky or compacted ground and is essentially zero for impervious surfaces, such as rooftops and paved surfaces. Also, infiltration decreases on steep slopes because the water has less time to infiltrate than when it moves slowly or ponds over flat surfaces. Land use also affects infiltration rates because vegetation loosens the soil. Runoff coefficients, as shown in Table 10-1, are therefore higher in areas of clay soil or rock, on steep slopes, and in urbanized areas.

Two important concepts must be understood to select the proper rainfall intensity, i: the duration of the rainfall and the return period of the storm. The duration is important because rainfall intensity can vary significantly during a storm, with intense bursts for short periods but a much lower average intensity over the course of a long event.

The rational method assumes that the critical duration of a storm is equal to the time it takes for the entire watershed to be contributing runoff to the watershed outlet (design point), which is called the *time of concentration* of the watershed. Alternatively, the