Chapter 4

Watershed-Based Systems

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Agricultural and other human activities have the potential to impact the quantity and quality of water resources used by communities of various sizes. Successful development and protection of water resources require a technical understanding of watershed processes as well as development of a management plan for coordinating the actions of diverse people and organizations. This chapter defines watersheds, outlines basic hydrologic and erosion processes, and provides practical guidance for applying the adaptive management planning process to watershed-scale systems. The discussion concludes with outlining needs for further research.

This chapter cites case studies selected from focus regions of the United States Agency for International Development. The authors also draw from their own experiences in watershed management. While the principles governing runoff and erosion are the same around the world, empirical models designed for use in developed countries may need to be modified to address, for example, the severe slopes of Latin America or the monsoonal climate of Southeast Asia. Similarly, assumptions regarding how the "social catchment" (Ellis-Jones et al. 2001) should operate may have to be modified. For example, insidious waterborne diseases and HIV-AIDS take their toll in parts of Zimbabwe, making it difficult to hold regular planning meetings (Ellis-Jones 2004). Political unrest, organizational corruption, lack of established agencies, and economic crisis can also complicate data collection and coordination of efforts (Voinov et al. 1994).

The purpose of this chapter is to provide guidance in solving problems at the watershed scale, with the focus on quality and quantity of water supplies in developing countries. The chapter discusses both the technical and organizational aspects of solving water resources problems. It builds on the previous chapters because it is the strategic application of field and farm practices that ultimately affects downstream water supplies. This chapter sets the stage for the chapters that follow because policies and technology transfer methods influence how a water supply is used as well as the effective adoption of desirable practices for protecting or improving that water supply. Finally, this chapter provides a foundation for discussion of ecosystem-based management, for the same hydrologic and problem solving processes are applicable to larger scale systems.

Watershed System Processes

The fundamental unit of study in water resource management is the watershed or catchment, defined as the land that drains to a particular point of interest (figure 1). That point is the watershed outlet and may be the site of volumetric interest (how much water passes or collects here),

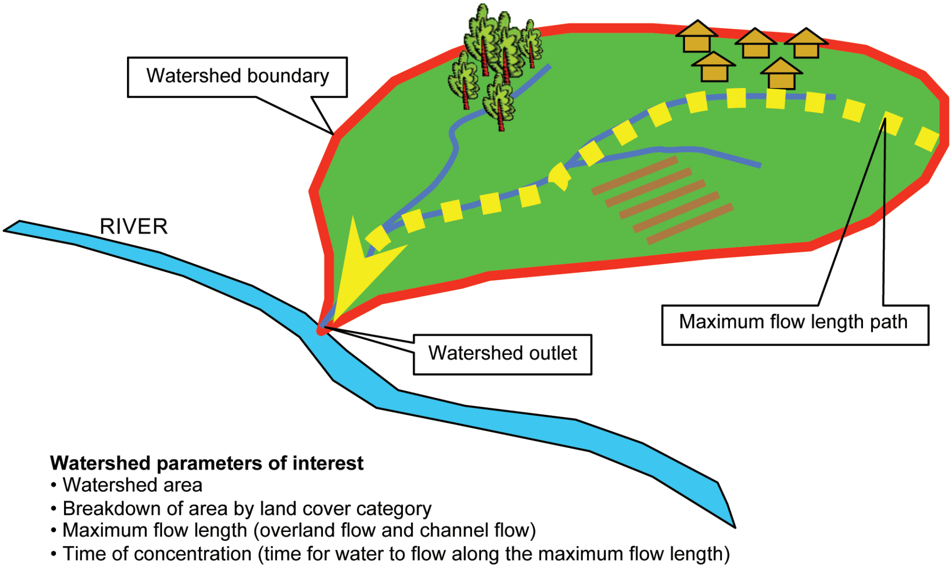

Figure 1. Parts of a watershed.

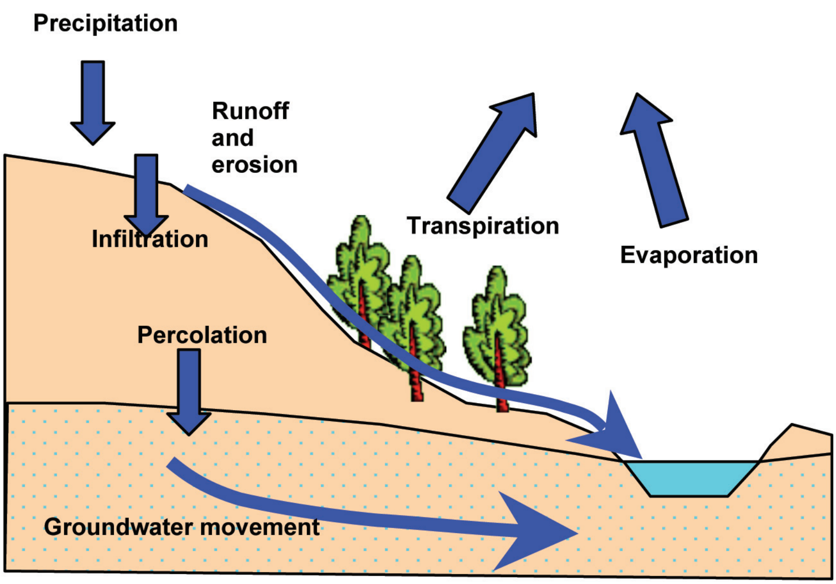

Figure 2. Basic watershed processes (adapted from Schwab et al. 1992).

such as a stream crossing, dam for a farm pond or local reservoir, or major hydroelectric facility. The outlet could also be a point of environmental interest, such as an entrance to a lake or estuary where impacts of upstream activity on water quality may be of concern. Topography governs the physical extent of the area that is included in the watershed draining to the chosen outlet. Weather, watershed size, land use, soil types, and other factors determine the quantity and quality of the water that is “shed” to the outlet. A watershed can be any size, but for water supply projects, watersheds will be typically on the order of 100 to 100,000 hectares. Time scales of interest for studying watershed processes can range from minutes to many years, depending on watershed size and the types of activities involved. Effects of human activities can be noticeable within a few hours, such as in the case of an accidental manure slurry release; or may take several years, as is frequently the case with conservation measures. Ellis-Jones et al. (2001) suggest that 10 to 20 years may pass between conservation implementation and reduction in sedimentation rates for reservoirs in Zimbabwe. Unfortunately, projects are rarely funded long enough for such results to be documented.

Physical processes essential to the understanding of watershed systems are identified in figure 2 and include precipitation, infiltration, percolation, runoff, evaporation, transpiration, and erosion. Many of these processes are discussed in chapter 2 in relation to the field scale landscape (see for example figures 1 and 2). At the watershed scale, we are concerned with the cumulative effects of these processes on water quantity and/or quality at the outlet of interest. Mathematical description of these cumulative processes is crucial to answering the “how big” questions of project design.

Some of the processes illustrated in figure 2 are briefly described below. The reader is directed to Morgan (2005) and Schwab et al. (1992) for more in-depth discussion and presentation of equations used to quantify the magnitude of these processes.

Precipitation

Precipitation in all forms contributes to the quantity of water available for infiltration and runoff. Also, precipitation can play a significant role in erosion and pollutant transport. Rainfall can cause unprotected soil particles to be dislodged from the surface, the first step in the erosion process (Schwab et al. 1992).

Rainfall can also transport airborne pollutants. Watersheds in the Black Triangle region of the Czech Republic are undergoing restoration from damage caused by acid rain resulting from upwind lignite coal-burning operations (Krecek and Horicka 2001). Deposition of sulfate by rainfall in the Jizera Mountains led to defoliation of spruce trees and low pH in reservoirs. Low pH, increased sedimentation, and increased levels of aluminum killed fish and other aquatic life. With decreased coal power production in central Europe, improved forestry methods, and liming of reservoirs, water quality has been improving since the late 1980s (Krecek and Horicka 2001).

Precipitation depth and duration of a storm event are important parameters for estimating the volume of water draining to the watershed outlet. Water depth divided by the time over which that depth fell is the intensity of the rainfall. A hyetograph is a plot of rainfall depth or intensity over time. A hypothetical storm is represented in figure 3. The block-like shape of the plot is due to the fact that rainfall is typically recorded at regular time intervals (such as hours) rather than as a continuous function.

In some developing areas, planners must consider the impact of long periods of drought, as in the West African Sahel, or very high intensity (large depth over a short duration) monsoonal storms, as in Bangladesh. Ideally, an agency will collect rainfall records over a long period so that regional statistics can be generated to estimate frequency of a given storm depth and duration. A

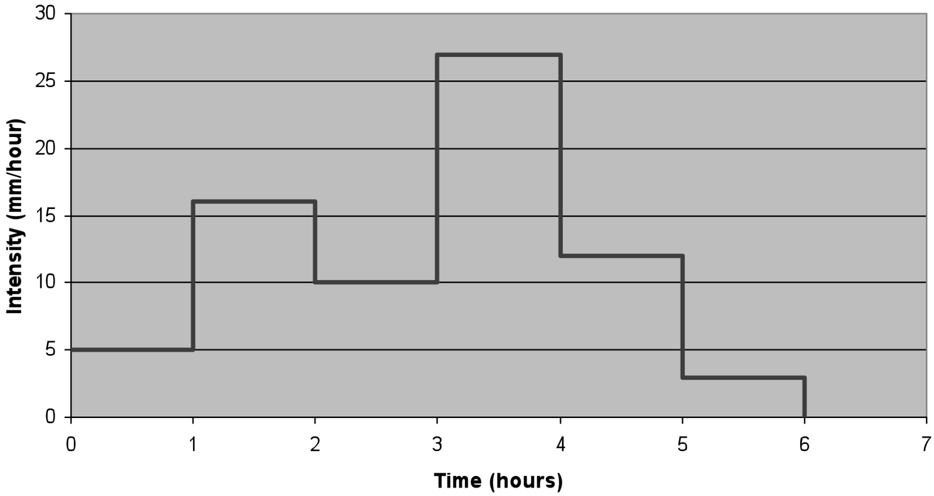

Figure 3. Hyetograph for a hypothetical six-hour storm.

Storm statistics
Total duration = 6 hours
Total storm depth = area under plot = 73 mm
Average storm intensity = depth/duration = 12 mm/hr
Maximum intensity = 27 mm/hr

storm that produces 75 mm of rain in one hour may only happen once every 10 years in a particular location. However, the same amount falling over a 24-hour period may be a more common event, perhaps happening once every two years. This statistical return period (for example, 10 years or two years) is one way of expressing storm frequency. Numerically, return period is the inverse of frequency (10 versus 0.1).

How much, how fast, and how often are key questions in determining the answer to the "how big" question in project design. Is it desirable to build a reservoir that can contain runoff from the largest conceivable storms (return period of 100 years or more)? Perhaps it is better to design for a storm occurring, for example, on average every 25 years, so that scant resources can be used to address other problems as well. The consequences of failure and its impact upstream and downstream of the project must be balanced against available resources. If local rainfall statistics are not available, statistics from another area having a similar climate combined with local memory of extreme events can provide a starting point for design. Perhaps a longtime resident can remember floodwaters reaching the base of particular landmark two times during the past 20 years and covering a second, lower landmark about every other year. Such information provides insight into the magnitude of the 10-year and two-year runoff events.

Infiltration and Percolation

Infiltration is the process by which precipitation enters the soil. The process may be limited by surface compaction, crusting, sealing, or by an impervious layer (such as bedrock or clay) beneath the surface. Soil properties, surface cover, rainfall intensity, and the degree to which the soil is already saturated influence how much rainfall enters the soil in a given period. Tillage influences the ability of the soil to absorb precipitation, both in terms of the spaces between soil aggregates and disruption of macropores formed by earthworms, insects, or roots. Conservation agriculture methods increase infiltration through minimal soil disturbance and maintenance of soil cover (see chapter 2 for discussion). Percolation is the downward movement of water to the aquifer. Water-soluble pollutants such as nitrate and some pesticides may be transported from the surface to the groundwater through percolation. More information on infiltration can be found in texts such as Schwab et al. (1992).

Evaporation and Transpiration

Liquid water returns to the atmosphere as vapor by means of evaporation from soil, water, or other surfaces or by transpiration from plant tissue. The two processes are often combined as evapotranspiration (ET) and can account for a large portion of the water cycling through the system. Estimates of ET are particularly important for designing irrigation systems and for crop growth models. Temperature, relative humidity, wind, vegetation type, soil cover, and other factors influence ET. A lysimeter—a device for measuring soil moisture—can be used to estimate ET losses in the field. Such measurements can be used to develop empirical relations with climatological data for use in predicting ET in other areas. See Schwab et al. (1992) or other texts for a discussion of the Blaney-Criddle and other empirical methods for predicting ET.

Runoff

Rainfall will initially infiltrate into the soil. When the rate of rainfall exceeds the rate at which water infiltrates into the soil, there may be some ponding and filling of surface depressions, then runoff will occur. Runoff rate plotted against time is called a hydrograph. A hypothetical hydrograph is shown in figure 4. Runoff volume (the area under a hydrograph curve) and peak runoff rate are two important parameters for the design of water resources management structures. Runoff volume is necessary for sizing storage structures such as reservoirs, as well as for estimating runoff-borne contaminant loads such as sediment. Runoff rate information is needed to size channels or pipes for conveying flow.

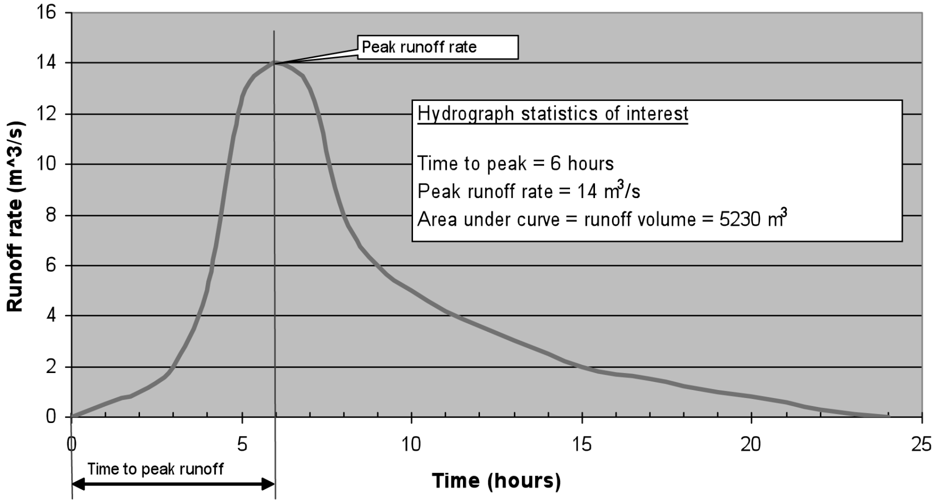

Figure 4. Hypothetical hydrograph.

Generally, it is neither practical nor necessary to measure the hydrograph for a particular watershed outlet resulting from a particular storm. Hydrologists devote much effort to the study of relationships between hyetographs (rainfall rate plotted against time) and hydrographs (runoff rate plotted against time) and the effects of land cover, soils, slope, degree of soil saturation at the time of the storm, watershed size and shape, and other factors. Simplified hydrograph shapes (triangles or curves) have been mathematically defined. Equations have been developed relating a watershed's time of concentration (time for water to travel from the most remote point of the watershed to the outlet) to the time to peak runoff and to the total time of runoff flow (base of the hydrograph) (Schwab et al. 1992). Other equations estimate total storm runoff volume and peak rate. Thus, a hydrograph can be constructed for design purposes for a storm of given depth and duration corresponding to the desired return period.

A simple relationship known as the Rational Method can be used to demonstrate some basic hydrologic principles. McCuen (1989) cites literature that traces the use of the method to the late 1800s. Suppose a small watershed is completely impervious—a metal roof, for example—and suppose that water flows from the roof to a gutter to collect in a cistern. When it first starts raining, nothing flows into the cistern because it takes a short time for water to flow down the roof and along the gutter. That time will be influenced by the slope of the roof and gutter and the roughness of those surfaces. Flow into the gutter starts out small, reaches a peak, then tapers off. According to the Rational Method, the maximum flow rate (peak runoff) will be observed when all parts of the roof are contributing flow. That is, peak flow will be observed once sufficient time has elapsed for raindrops from the most remote corner of the roof to flow down the roof and down the full length of the gutter—or time to peak = time of concentration. The magnitude of the peak flow rate is the rainfall intensity (depth/time) times the area of the roof. The method assumes a constant rainfall intensity and a storm duration equal to the time of concentration. If these assumptions are true, the hydrograph can be represented by an isosceles triangle such as shown in figure 5, which

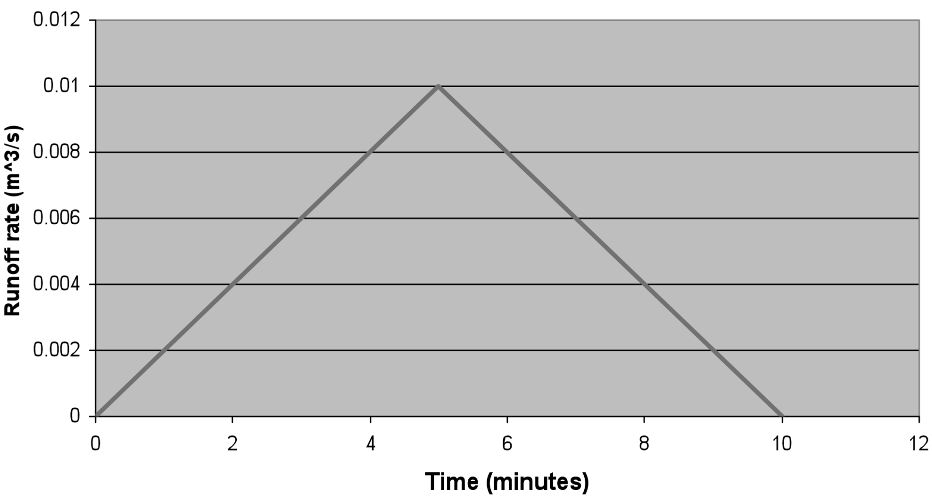

Figure 5. Hydrograph for Rational Method example.

Hydrograph statistics
Time to peak = 5 minutes
Peak runoff = 0.01 m^3/s
Runoff volume = area of triangle = 3 m^3

assumes a roof area, A, of 100 m^2, a time of concentration of 5 minutes, and a rainstorm lasting 5 minutes with intensity, I, of 360 mm/h (or 0.0001 m/s). Thus, peak runoff rate, $Q = IA = 0.01$ m^3/s, and the volume of water collected in the cistern is the area under the triangle or 3 m^3. If we analyze a design storm (depth and duration for a desired return period), the peak rate could be used to determine the size of a filtering device at the end of the gutter, and the runoff volume could be used to size a cistern to hold the water from the desired number of such storms.

Carrying the roof example a little further, suppose that instead of metal, the roof is made of vegetative material that absorbs some of the rainfall. We can still use the basic Rational Method to compute peak runoff rate and volume, but we need to add a "fudge factor" or runoff coefficient, C, to account for the fact that not all of the rainfall will reach the watershed outlet (cistern). Thus the Rational equation for peak runoff rate, Q, is often written as follows:

$$Q = CIA ,$$

where Q = peak runoff rate (volume/time), C = runoff coefficient that accounts for the degree of imperviousness of the watershed surface, I = rainfall intensity (depth/time), and A = area of watershed.

Units can be English or metric. If metric units are used, one either has to be consistent in expressing time and length, or apply a conversion factor. If English units are used (cfs, in/hr, and acres), the units happen to work out so that no unit conversion is needed. An impervious surface has a runoff coefficient (C) of 1; a fully absorbent surface has a coefficient of 0. Coefficients have been developed through field experiments for a variety of land cover conditions, and these are often tabulated in texts on hydrology such as McCuen (1989).

Watersheds on the natural landscape and their hydrographs get more complicated than the roof example. Additional equations for predicting peak flow, runoff volume, and hydrograph dimensions can be found in texts such as McCuen (1989), Schwab et al. (1992), and Morgan (2005). Equations that simplify complicated natural processes typically rely on empirical relationships with coefficients developed through extensive field tests. Caution should be exercised in using those formulas in areas where conditions (such as extreme terrain and high-intensity storms) may be outside the range of those originally tested.

Erosion

Movement of soil by water or by wind is of concern because it affects soil fertility, decreases downstream reservoir storage capacity, and can expose structural supports. Raindrops can start the erosion process by dislodging soil particles. Runoff then carries the dislodged particles and associated pollutants downhill and can dislodge more soil in the process.

Soil properties such as structure, texture, and organic matter affect a soil's vulnerability to erosion. As mentioned in the "Infiltration" section, maintaining a surface cover and practicing conservation tillage methods can help to reduce erosion. Slope severity and slope length influence the transport of eroded soil. Thus vegetated field borders, terraces, contour farming, and similar practices that interrupt the runoff flow path can help to reduce erosion.

All of these factors affecting erosion rate are captured in the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). The equation is written as follows:

$$A = RKLSCP ,$$

where A = average annual soil loss per unit area, R = rainfall and runoff erosivity, K = soil erodibility factor, LS = length-slope or topographic factor, C = cropping-management factor (includes crop cover, rotation, tillage), and P = conservation practice factor.

The equation is presented here without units for simplicity in order to communicate the general concept of the method. Use of the equation involves in-depth considerations best left to the referenced texts for explanation. Empirical relationships for the factors were developed using data from the United States. Nevertheless, the tool has been used successfully in many parts of the world. Onyando et al. (2005) discuss USLE parameter determination for a watershed in Kenya. Stolpe (2005) discusses application of USLE and other erosion models to volcanic soils in Chile. Similar to the USLE is the Soil Loss Estimator for Southern Africa, developed using data from Zimbabwe (Morgan 2005).

Over the years, the USLE has been modified and revised. The Modified USLE (MUSLE) is a method for estimating soil loss for a given storm event rather than as an average annual quantity (Williams 1975). The Revised Universal Soil Loss Equation (RUSLE and now RUSLE2) provides an improvement in the methods used for selecting values for the USLE input factors (Foster et al. 2000). Millward and Mersey (1999) discuss adapting RUSLE to accommodate the mountainous terrain and tropical precipitation in the Sierra de Manantlán Biosphere Reserve in southwestern Mexico.

Watershed Resource Management Planning Process

Chapter 1 introduced the concept of adaptive management. These are the basic steps, applicable to any system scale:

- Identify the problems and stakeholders involved.
- Collect and analyze relevant data.
- Determine what needs to change and how to change it.
- Implement the solutions.
- Monitor results and evaluate the solutions.
- Repeat steps 1–5, refining the solutions as needed.

At the field and farm scale, one landholder and possibly the family will work through these steps. The process need not be formal, written, or consciously labeled as "adaptive management." However, at the watershed scale,

- many people may be involved in creating both the problems and solutions, both upstream and downstream of the point of interest;
- the complexity of the problem(s) will likely be greater (for example, how to increase food production on upland fields and reduce siltation in the downstream reservoir);
- data collection, organization, and analysis needs will increase; *and*
- multiple stakeholders will need to coordinate their actions.

Because the number of people, problems, and data needs can increase exponentially at the watershed scale, it may be necessary to formalize the adaptive management process to diffuse conflicts, provide a means of organization, provide a method for breaking down seemingly overwhelming problems into solvable parts, and encourage commitment in adoption of solutions. Several agencies have outlined formal procedures to aid groups involved in natural resource management. The United States Department of Agriculture Natural Resources Conservation Service advocates use of a three-phase, nine-step planning process involving stakeholders and technical experts to develop strategies for addressing the wise use of watershed resources. Similar concepts can be found in documents produced by the Australian Land Care organization (Roberts 1992). Participatory planning steps are outlined by Ellis-Jones et al. (2001) with respect to small dam projects in Zimbabwe, and in Pezzullo (1982) with respect to planning of development projects in Latin America. Murwira et al. (2000) do an excellent job of documenting the process used in addressing food security in Zimbabwe. They describe how government agencies had developed and promoted various conservation strategies (such as tied ridges for conserving soil moisture) with little success. However, when farmers went through a participatory planning process in which they were responsible for identifying their problems, and investigating and modifying their own solutions, the result was very positive, with widespread adoption of tied ridges and other practices. In other words, the planning process was absolutely critical to allow those in a position to solve the problems to take ownership of the solutions.

The number and names of steps used in a planning process are unimportant, and any written description of the process is at best a crude representation of what actually takes place when people come together to solve a common problem. For the sake of simplicity, the rest of this section will discuss the basic steps of data collection, analysis and decision support, and project evaluation as they apply to watershed-scale planning. Forming effective coordinating groups to carry out these steps is essential to project success and is addressed in chapters 5 and 8.

Data Collection

The stakeholder committee or its technical assistance group should gather basic information about the watershed as well as facts pertinent to the concerns identified. Basic information should include the following:

- Watershed boundary
- Hydrologic data
- Outlet flow hydraulics
- Soils
- Land-use capacity and current land use
- Other information

Watershed boundary

The boundary is important for determining what areas are involved in contributing runoff, sediment, and pollutants. Delineating the boundary is necessary for estimating parameters for hydrologic analysis such as watershed size and the length of the flow path to the outlet. Also, the location of the watershed boundary with respect to institutional boundaries is essential for identifying project stakeholders and authorities.

Topographic maps are valuable tools for delineating watershed boundaries. The elevation contours are used to reveal the watershed boundary by starting at the outlet location on the map and tracing a line perpendicular to the contours. Eventually the traced line will end back at the outlet, forming an enclosed polygon. The goal is to identify where the terrain “breaks” such that rain falling on one side of the break (watershed boundary) flows toward the identified outlet, and rain falling on the other side flows somewhere else. In determining which way water will flow, bear in mind that water will take the most direct path downhill, that is, perpendicular to the contours. Figure 6 illustrates the procedure.

If a digital elevation model of the area exists, geographic information system (GIS) software can be used to delineate the watershed boundary. However, use of such automated methods should not take the place of understanding the process of watershed delineation. A computer-generated watershed boundary should be checked carefully because digital elevation models can be flawed or too coarse in resolution for the application.

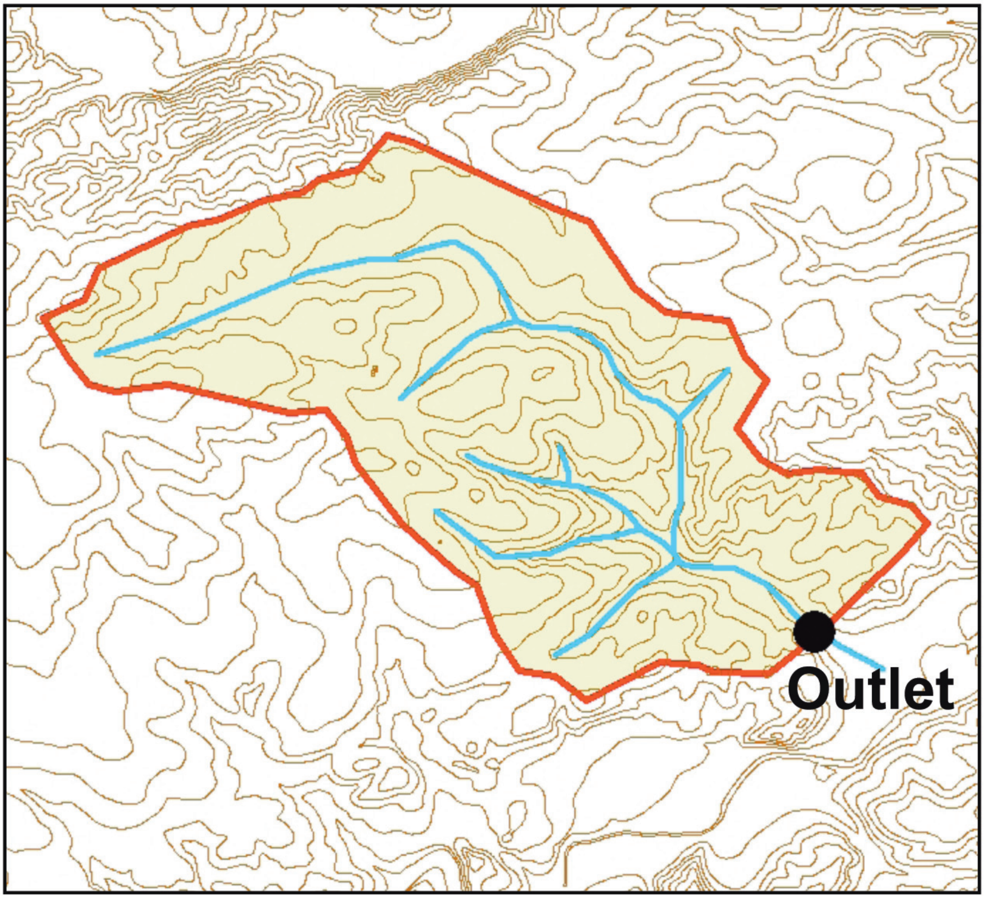

Figure 6. Watershed delineation process.

Dot = outlet.

Watershed delineation guidelines:

1. Identify watershed outlet.
2. Highlight stream channels and draws to get a general idea of the extent of the watershed. Remember that contour lines “point” upstream, hence toward the watershed boundary. The boundary will lie between where contours are pointing in different directions.
3. Start at the outlet and trace a line perpendicular to the contours.
4. Split ridge tops.
5. Continue to trace until the watershed boundary closes on itself at the outlet.
6. Check the boundary by choosing points on both sides and visualizing whether runoff from each point will flow towards or away from the outlet.

If topographic maps are not available, the area can be toured and the approximate boundary determined from observation of the terrain. Even if topographic maps are available, visual inspection of the area is useful for observing current watershed activities and land uses. Aerial photography can aid the visual inspection.

Hydrologic data

Rainfall statistics (depth, duration, frequency) will be needed for the locale to design structures to store or convey runoff from a particular size storm. Ideally, an agency or organization will have collected rainfall records over several decades at many locations across the country. The resulting statistics will be maintained in a database and conveniently tabulated or represented graphically on a map. Lacking such a record, estimates may need to be made using data from areas with similar climates and topography. A meteorologist may be able to assist in extrapolating the data to the location of interest. It may be a worthwhile investment to establish a rainfall recording station or network of stations in the watershed. Recording stations can range from very simple rain gauges with recording performed manually to complete weather stations with automatic data recording and wireless data transmittal. Rain gauges should be located in clear, level areas protected from wind. Equipment should also be secured against curious animals and humans.

Outlet flow hydraulics

In some applications, it may be desirable to relate water level at the watershed outlet to flow rate. Flow rate is equal to the velocity of the water times the cross-sectional area of the water flowing in the channel ($Q = VA$). Flow can be measured at bridge crossings to provide a convenient work platform. The cross-sectional area of the stream can be determined by measuring the distance to the bottom of the channel at different points along the bridge. Channel bottom elevations can also be determined with a surveyor's level and rod. The cross section can then be plotted and area computed based on geometry for different water levels. Depending on the precision needed, the channel cross-section can also be approximated as a triangle, trapezoid, or parabola.

Velocity can be measured with a current meter at various points along the cross-section as well as at different water depths. Velocities will tend to be slower close to the bottom and sides of the channel due to friction. Other means for estimating channel velocity include measuring the time it takes for visible, floatable objects such as oranges to travel a known distance downstream, and using Manning's equation (Schwab et al. 1992):

$$V = R^{2/3} S^{1/2}\, 1/n$$

where V = average flow velocity (m/s); R = hydraulic radius (m) cross-sectional area /wetted perimeter, where wetted perimeter is the bottom width plus the length of the channel side slopes that are wet (wetted perimeter can be approximated by the channel top width for most natural channels); S = channel slope (measured from riffle to riffle along the channel profile); and n = Manning's roughness coefficient, estimated from experience or the use of tables provided in many texts on channel hydraulics.

Once flow rate ($Q = VA$) has been determined for several water levels, flow rate can be plotted against water level, and a mathematical or graphical relationship can be derived to relate the two parameters. Such a graph is known as a stage-discharge curve. An example is shown in figure 7. Marked graduations can then be mounted against a bridge pier or other convenient place so that flow rate can be determined from observing water height (stage). Water stage can also be recorded continually using a float or pressure transducer system connected to a paper or digital recording unit.

Another way to measure flow is to install a weir or flume with known dimensions for which stage-discharge relationships have already been determined. These relationships can be found in hydraulics texts such as Brater et al. (1996). Water height is recorded as previously described.

Soils

Soil properties influence erodibility, how quickly water moves to the outlet, and the selection of management practices. In the absence of detailed soil maps, some general information can be

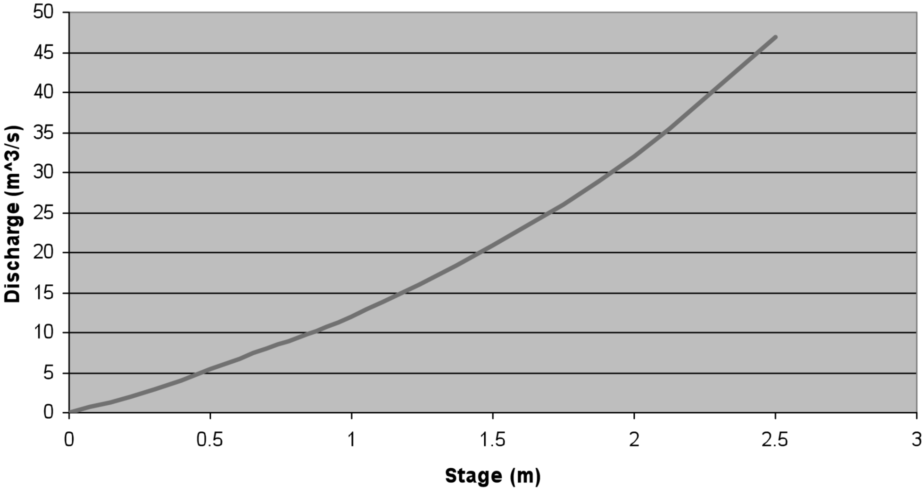

Figure 7. Stage-discharge curve for the outlet of a hypothetical watershed.

obtained from Web sites such as http://soils.usda.gov/use/worldsoils/index.html. Such information can then be coupled with local knowledge and sampling of soils from different parts of the landscape. Stocking and Murnaghan (2001) provide practical guidance for assessing local soil properties and identifying signs of soil erosion and degradation.

Of particular interest to watershed hydrology is the runoff potential of the soil. Sandy soils have a low runoff potential because they allow rain to infiltrate deeply into the soil profile. Clay soils, however, have a high runoff potential. Also, shallow soils on top of an impermeable layer would have a high runoff potential. Runoff potential influences selection of coefficients used in runoff estimations (see the "Runoff" section as well as McCuen [1989]). In the absence of soil maps and tabulated hydrologic soil groups, basic field knowledge of local soil texture can guide selection of coefficients.

Land-use capacity and current land use

Land-use capacity is closely tied to soil properties and indicates the most intense use a land unit can sustain without degradation from erosion and loss of fertility. For example, bottomland is generally more capable of supporting intense cropping than steeply sloping land. Steeply sloping land, however, may be capable of supporting grazing or some silvicultural practices. Morgan (2005) describes various classification systems. Perez and Tschinkel (2003) emphasize the importance of mapping this parameter before selecting practices. They state that it is important for local land users to determine their own criteria for identifying the most intensive use that a particular unit can handle. An example of a classification system from Guatemala includes seven categories ranging from annual cropland without limitations (most intense use) to forestland for protection (least intense use) (Perez and Tschinkel 2003).

Perez and Tschinkel (2003) conclude: "The bottom line is that projects should not promote practices that exceed the capacity of a site based on the local definition of land use potential. Where the land is already used beyond its capacity, projects should focus on the difficult task of promoting conversion to less intensive uses."

Thus, collecting data related to land-use capacity and current land use is essential to the planning process. Hand-sketched maps based on field visits and interviews with local residents can accomplish the purpose. In some cases, such an approach may be impractical. The use of satellites and aircraft can aid in collecting land-use and land degradation data in areas that are difficult to sample due to extreme terrain or human violence. Remote sensing can also reveal patterns from the bird's eye view that might not be detectable with ground-based mapping. Khawlie et al. (2005) discuss the use of remote sensing techniques for detecting human impacts on the environment for a watershed on the border of Lebanon and Syria. Ouattara et al. (2004) discuss the problems of interpreting satellite imagery of high relief areas in Bolivia as well as their solution of combining radar and optical data.

Other information

Demographics, cultural practices, water use statistics, wells, and native plants are examples of other types of data that may be worthy of inventory depending on the nature of the problem to be solved.

If computers are available, data can be organized into spreadsheets or GIS to facilitate analysis and presentation. Whether or not computers are available, the information described above should be compiled on hardcopy maps and graphs for use during discussions and on-site planning. Visually organized information will help in communicating with all involved in the planning process.

There will always be a desire for more data, no matter the location or the challenges to be overcome, thus the inventory steps are never fully complete. Nevertheless, the lack of data should not be allowed to prevent forward movement in the planning process. Varis and Lahtela (2002) express this theme in their discussion of the data-poor situation of the Senegal River basin. The authors used trends, rather than numerical data, in examining the interactions of 45 variables for assessing three approaches to water resource management. Motzafi-Haller (2005) laments "the urge to produce more and more data" as an excuse for not solving gender-related problems in rural development projects. Thus, the stakeholder committee and its technical assistance group must do what it can with the best available information and revise the strategy as experience cultivates the knowledgebase.

Analysis and Decision Support

Once data have been collected and organized, the planning group can analyze the information as well as alternative solutions. Perhaps it is desirable to estimate the combined effects of different upland erosion control practices on reservoir siltation. Or perhaps the best site for a reservoir must be chosen from six candidate sites. In some cases, the complexity of the data and alternatives involved will justify the use of computer-based tools. In other situations, simplifying assumptions and an intuitive understanding of the particular system will lead to the same management conclusions as results generated from a complicated model.

GIS allows multiple layers of spatial information such as satellite imagery, topography, soils, and land use to be viewed and analyzed. GIS is useful for visual presentation because maps of different scales and projections can be viewed simultaneously and, in some cases, in three dimensions. It is also useful as an analysis tool for selecting sites that meet multiple spatial criteria. GIS is often used in combination with erosion and runoff models for either generating model input values or displaying model results. Onyando et al. (2005) used GIS and satellite imagery in combination with the Universal Soil Loss Equation to identify priority areas for erosion control for the Perkerra River watershed in Kenya. Millward and Mersey (1999) conducted a similar erosion study in southwestern Mexico with the goal of modifying the RUSLE to take into account the rugged terrain and tropical precipitation pattern of the region. Luijten et al. (2001) used GIS with Landsat imagery and the CROPGRO irrigation model to study the effects of three development scenarios on water budget in the Cabuyal River watershed in Colombia.

Computer models can provide a useful structure for organizing resource inventory data and in some cases are useful for analyzing the complex interactions of alternative scenarios. Computer models become particularly useful in analyzing hydrology of large watersheds where hydrographs from subwatersheds must be combined and then routed to the outlet. Hydrograph routing uses an upstream hydrograph to predict a downstream hydrograph by considering the effects of water storage in the channel. The general result is that the hydrograph peak will decrease and the base will broaden as the hydrograph is routed downstream. A computer can alleviate the computational burden of channel routing. McCuen (1989) describes the mathematical methods involved.

Caution should be taken when considering use of a computer model, however. Much time can be wasted gathering input data to feed a computational monster created for research purposes and conditions inappropriate to the situation at hand. A computer model should be used to manage large amounts of data and to perform repetitive and intensive computations in cases where the model's underlying assumptions and equations match the modeler's understanding of the watershed system.

Project Evaluation

The resource management plan should include strategies for monitoring, evaluating, and refining the individual practices as well as for measuring the cumulative effects at the watershed outlet. Evaluation criteria should be determined by the stakeholder group. Murwira et al. (2000) emphasized this recommendation in their comparison of two evaluation systems for a sustainability project in the Chivi District of Zimbabwe. One system was designed by development staff, while the other was designed by project stakeholders. The first included 28 quantitative indicators of success. While useful to the project funding partners, these indicators were not meaningful to the community stakeholders who ultimately had to make decisions regarding project modification. Ellis-Jones et al. (2001) also expressed the importance of stakeholder-led evaluation as part of a resource management project in Masvingo, Zimbabwe. Very few case studies present the results of evaluating the overall effects of plan implementation on water quantity or quality at the watershed outlet. This is likely due to short-term funding cycles, participant turnover, and the time needed to see the effects of many conservation practices.

Depending on the chosen criteria, implementation of a watershed plan might be evaluated using before-and-after photographs of field or channel conditions, participation statistics (in terms of land area and number of people), and measurement of water quantity or quality at the watershed outlet (see Deutsch et al. 2001). Measurement of water quantity has already been discussed.

Water-quality parameters of interest may include bacteria, total suspended solids, pesticides, and nutrients (nitrate and phosphorus). These parameters should be monitored at the watershed outlet as well as at the outlets of subwatersheds, if of interest. Flow measurements will also be needed at these points to relate measured concentrations to pollutant loads (mass). Samples should be collected in containers free of contaminants that might interfere with the test. Samples can be collected by hand or with an automatic sampler. If a water quality laboratory is not available to process samples, field test kits can be purchased to measure some parameters. In Sustainable

Agriculture and Natural Resource Management Collaborative Research Support Program Phases I and II, water quality test kits for community monitoring were used in the Philippines and Ecuador (Deutsch et al. 2001; Ruiz-Córdova et al. 2005).

One simple test appropriate for reservoirs is Secchi depth. A disk, about 20 cm in diameter and painted with black and white markings, is lowered into the water with a rope. The depth at which the markings are just barely visible is the Secchi depth. This parameter is a measure of water clarity and is related to other parameters of interest such as total suspended solids, bacteria, and nutrients. Secchi depth should be measured each time by the same person and at the same time of day.

Whatever the means of evaluation, results should be documented and used to provide feedback for refining solutions as well as for providing encouragement among stakeholders. At the watershed scale, the large number of people involved can sometimes slow the planning and implementation process to the point that participants become discouraged. Documentation and communication of results can help maintain project interest.

Needs and Opportunities for Additional Study

The literature reviewed for this chapter reveals three main needs for future efforts:

- ***Development of a practical handbook of field measurement and estimation methods.*** Practical guidance on estimating hydrologic parameters, soil properties, and water quality parameters using inexpensive tools needs to be compiled for a large range of climatic and topographic conditions. Stocking and Murnaghan's *Handbook for the Field Assessment of Land Degradation* (2001) is an excellent start in meeting this need.
- ***Development and easy access of basic GIS layers suitable for analysis at 1:24,000 or better.*** Layers useful for most watershed resource applications include aerial photography, soils, land use, and topography. The United States Geological Survey and Cornell University are making progress in this area. Web sites of interest include http://www.agiweb.org/pubs/globalgis/ and http://atlas.geo.cornell.edu/ .
- ***Documentation of long-term results following implementation of watershed management plans.*** Few studies have been found reporting what happened to the water resource or to the planning committee after completing one full cycle of a formal adaptive management planning process. Murwira et al. (2000) do an excellent job of documenting a decade's worth of experience in promoting food security in Zimbabwe. Such a time span proved to be a rarity in the literature reviewed.

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