Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 60-84, April 2015

Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds

*Pamela J. Edwards[1], Jon E. Schoonover[2], and Karl W. J. Williard[2]

[1]USDA Forest Service, Northern Research Station, Parsons, WV
[2]Southern Illinois University, Carbondale, IL
**Corresponding Author*

Abstract: Human actions must be well planned and include consideration of their potential influences on water and aquatic ecosystems – such consideration is the foundation of watershed management. Watersheds are the ideal land unit for managing and protecting water resources and aquatic health because watersheds integrate the physical, biological and chemical processes within their boundaries. Managed forested watersheds tend to have more natural watershed functions and better water quality than other land uses. Land uses with greater amounts of soil disturbance and permanent reductions in infiltration, such as in agricultural or urban/developed settings, usually have greater undesirable hydrologic alterations and poorer water quality. Nonpoint source pollutants resulting from many forestry, agricultural, and urban activities are controlled by techniques and tools known as best management practices (BMPs). Best management practices are applied by watershed managers to large-scale landscapes, but they also are applicable to the lives of ordinary citizens. Basic BMP principles, such as controlling the amounts and duration of soil disturbance during construction around the home, applying chemicals to lawns or gardens only at needed rates and during suitable times, and incorporating techniques to encourage infiltration of rooftop and driveway runoff are important actions that anyone can take to help protect watershed functions, water quality, and aquatic health.

Keywords: *land use, nonpoint source pollution, point source pollution, erosion and sedimentation, best management practices, watershed management, roads, water quality*

In "Fundamentals of Watershed Hydrology" (Edwards et al. 2015, this issue), the definition of a **watershed** (i.e., an area of land in which all of the incoming precipitation drains toward the same body of water as a result of its topography) was introduced from the perspective of understanding hydrologic principles and cycles. A watershed provides an ideal unit for managing lands because the hydrologic cycle within a watershed drives many of the physical, biological, and environmental processes in the catchment. Thus, the watershed integrates all of the interconnected physical, biological, and chemical environmental processes (both intended and unintended) that result from (and in spite of) all of the activities occurring in the watershed. Consequently, managing at the watershed scale can make more sense than managing at other scales, such as municipalities or counties that have arbitrary boundaries.

The science of **watershed management** implements actions that maintain and enhance watershed functions that are important to the sustainability of vegetative, animal, and human communities within the watershed boundaries. Examples of watershed characteristics and functions that are impacted by watershed management include water supply, water quality, storm runoff timing and volume, physical water body characteristics, aquatic habitats and aquatic health. Proposed actions in a watershed may be modified, require mitigation, or may be rejected entirely by watershed management agencies if the potential outcomes of the proposed actions present too great a risk to individual or integrated watershed functions.

Forested watersheds typically provide the greatest number of desirable watershed characteristics and functions, including slow and moderated releases of storm runoff, cool or cold water temperatures (from shading), quality habitat for aquatic species, low erosion rates, and high-quality water. When present, forested watersheds are often the preferred source for potable water for municipalities because the costs of water treatment are greatly reduced by the high quality of water delivered. For example, New York City saves billions of dollars by not having to filter water it receives from the Catskill and Delaware watersheds that are 90 percent forested (see http://ice.ucdavis.edu/node/133).

In this paper the discussion of watershed management begins with a focus on forested watersheds. This examination provides a baseline against which agricultural and urban land uses are described and compared. Readers who are unfamiliar with basic hydrologic concepts are encouraged to review the "Fundamentals of Watershed Hydrology" (Edwards et al. 2015, this issue) and "Soil Erosion in Humid Regions: A Review" (Holz et al. 2015, this issue) before reading this paper. Many of the concepts about the hydrologic cycle and the water budget equation, and erosion and sedimentation described in those papers, have direct application to watershed management.

Forest Management Influences on Hydrology

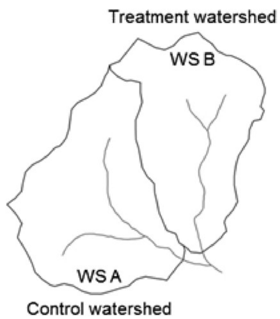
In the United States, much of what is currently known about hydrologic responses in forested watersheds and from forest management activities has been determined from small experimental watersheds operated by federal agencies (especially the U.S. Forest Service; e.g., Adams et al. 2004) or universities. **Experimental watersheds** have been important for understanding how forests affect the overall hydrologic cycle, especially for quantifying the effects of management on soil moisture and streamflow. In addition, the science of forest hydrology has augmented and accelerated the understanding of forest ecology since many important ecological processes are directly or indirectly dependent on moisture availability.

One of the primary techniques used to understand how forest management affects the hydrologic cycle has been the use of **paired watershed experiments** (Figure 1). The paired watershed approach compares hydrologic responses of two similar, and typically proximate watersheds, where one (the **treatment watershed**) receives a management activity (e.g., harvesting) and another (the **control** or **reference watershed**) remains undisturbed. Using data collected during several years prior to the application of the management activity, a mathematical relationship called a **calibration equation** is developed to predict the values of a hydrologic variable of interest (e.g., annual discharge, stormflow volumes, etc.) for the treatment watershed from the control watershed. Following this pretreatment period, the management activity is applied to the treatment watershed, and data are collected for several more years (i.e., the posttreatment period). Hydrologic responses for the treated watershed that would have resulted had the treatment not been implemented are predicted from the calibration equation using control watershed data during the posttreatment period. Posttreatment measured values from the treated watershed are compared to the predicted values, and the differences between observed and predicted values are attributable to the effects of the management applied to the watershed.

Every watershed is unique with respect to the combination and characteristics of the many variables that can influence hydrologic responses. However, even with the great variability and seemingly infinite combinations of topographic, geomorphic, climatic, soil, vegetative, and other factors that can influence hydrologic responses, some consistencies have been found for forested watersheds using the paired watershed approach:

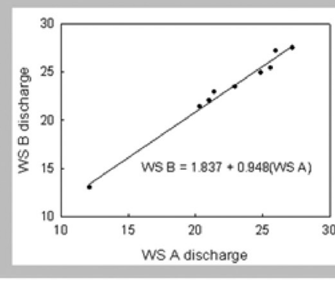
1) To induce a statistically measurable increase in annual streamflow in forested watersheds, the basal area in the watershed must be reduced (usually by harvesting) by a minimum of approximately 15 to 20 percent (Stednick 1996). **Basal area** is the cross sectional area of tree stems measured at 1.4 m above the ground, and it represents the ground area occupied by tree stems (e.g., square meters of tree stems per hectare). Basal area serves as a good surrogate for leaf area, and thus is strongly correlated with the magnitude of potential transpiration and interception loss by the forest.

2) Streamflow increases resulting from basal area reduction are primarily attributable to reductions



Annual discharge values for both catchments were collected for 10 years prior to clearcutting to develop a calibration equation predicting WS B from WS A

Year	WS A	WS B
1960	26.00	27.18
1961	24.87	24.92
1962	27.22	27.49
1963	25.61	25.44
1964	22.96	23.45
1965	12.14	13.01
1966	21.43	22.92
1967	21.05	22.01
1968	20.33	21.39

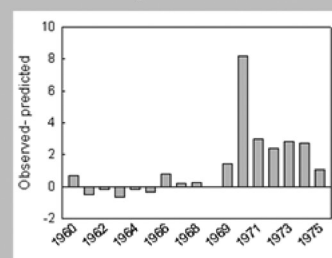


In summer of water year 1969, WS B was clearcut. WS A was not disturbed. Collection of annual discharge continued another 7 years.

Using the calibration equation, discharge for WS B was predicted using WS A data for the 7 years. The differences between observed and predicted discharges from WS B were calculated for the pretreatment and posttreatment periods.

Year	WS A Obs.	WS B Obs.	WS B Pred.	WS B Obs.-Pred.
1960	26.00	27.18	26.48	0.70
1961	24.87	24.92	25.41	-0.49
1962	27.22	27.49	27.64	-0.15
1963	25.61	25.44	26.11	-0.67
1964	22.96	23.45	23.60	-0.15
1965	12.14	13.01	13.34	-0.33
1966	21.43	22.92	22.15	0.77
1967	21.05	22.01	21.79	0.22
1968	20.33	21.39	21.11	0.28
1969	23.72	25.76	24.32	1.44
1970	21.62	30.49	22.33	8.16
1971	28.07	31.41	28.45	2.96
1972	33.41	35.91	33.51	2.40
1973	29.72	32.85	30.01	2.84
1974	30.55	33.51	30.80	2.71
1975	20.04	21.92	20.83	1.09

Plotting the differences, or deviations from predicted values, over time illustrates how much extra streamflow was yielded each year as a result of clearcutting WS B.



Additional statistical tests can be performed to determine whether the change each year was statistically significant.

Figure 1. Steps for performing paired watershed analyses and for calculating changes in streamflow due to a treatment applied to one of the watersheds. This example illustrates the annual increases measured following harvesting and during the first 7 years of natural regeneration of the forest.

in transpiration, decreases in interception losses, and changes in soil moisture storage resulting from these two variables. Increasing solar radiation to the ground may increase evaporation from the soil and offset some of the moisture increases.

3) Annual streamflow augmentation increases in proportion to the amount of basal area removed. The greatest streamflow increases occur from clearcutting and usually during the first or second year following the harvest, but the actual maximum increases vary with the physiographic and climatic conditions (Table 1). The pattern of management or disturbances within watersheds affects the degree and duration of hydrologic changes. Even when at least 20 percent of basal area is removed, if the harvesting targets individual trees spread throughout the watershed the hydrologic response will be less than harvesting the same amount of basal area in a single block. In the former situation the residual vegetation will grow into the small openings quickly, thereby using surplus soil moisture that resulted from reductions in transpiration. By contrast, large openings have less edge so much more time is required for trees around the edge and regeneration within the opening to utilize the increased soil moisture made available from the declines in interception losses and transpiration that result from harvesting.

Table 1. Examples of streamflow increases during the first two years after clearcutting watersheds throughout the U.S. In some instances additional treatments, such as site preparation, followed harvesting.

Location	Forest Type	Watershed Size (ha)	Years after Clearcutting	Annual Increase in Discharge (mm)	Reference
Hubbard Brook Experimental Forest, New Hampshire	Northern hardwood	22	1 2	152 47	Hornbeck et al. (1997)
Great Northern Paper Co., Maine	Spruce-fir	47	1 2	310 290	Pierce et al. (1993)
Leading Ridge, Pennsylvania	Mixed hardwood	45	1 2	137 39	Lynch and Corbett (1990)
Fernow Experimental Forest, West Virginia	Mixed hardwood	30	1 2	130 86	Lull and Reinhart (1967)
Coweeta Hydrologic Laboratory, North Carolina	Mixed hardwood	59	1 2	260 200	Swank et al. (1982)
Athens Plateau, Arkansas	Pine-oak-hickory	2-5 (3 replicates)	1 2	166 388	Beasley et al. (1986, 2000)
Wagon Wheel Gap, Colorado	Aspen-conifer	81	1 2	34 47	Bates and Henry (1928)
Coyote Creek, Oregon	Mixed conifer	50	1 2	360 292	Harr et al. (1979)
H. J. Andrews Experimental Forest, Oregon	Old-growth Douglas-fir	96	1 2	462 457	Rothacher (1970)

4) Basal area reductions that increase discharge can result from management activities or natural disturbances to vegetation. While harvesting is one of the most common, and certainly the most studied causes of basal area reductions in forested watersheds, other natural disturbances that alter evapotranspiration, such as wind events or insect defoliation, also can result in increases in annual discharge. In 1938, region-wide blowdown of forest vegetation affected 6 million hectares, or 15 percent of New England. The resulting reduction in evapotranspiration increased annual discharge by 127 mm in the Merrimack and Connecticut Rivers the first year after the hurricane (Patric 1974). Multiple examples of streamflow increases from insect defoliation have been reported (e.g., Love 1955; Bethlahmy 1975; Potts 1984). Given that only portions of a watershed tend to be affected by defoliation, the magnitude of streamflow increase caused by insect defoliation during any single year is typically more like that attributable to a partial harvest than to clearcutting. However, hydrologic effects from defoliation may extend over more years than harvesting because defoliation usually continues over multiple years.

5) Increases in annual streamflow attributable to basal area reductions are greatest in regions with warm temperatures and high precipitation, but their duration is shorter than in other climates (Bosch and Hewlett 1982; Stednick

1996; Brown et al. 2005) because regeneration can occur quickly due to the favorable growing conditions. Rapid re-growth by **coppicing**, which is regeneration by sprouts that grow from still-living stumps or roots of freshly harvested trees, also contributes to shortening the time during which streamflow is increased in any climate. Throughout the United States, annual streamflow generally returns to pre-harvest levels in less than three decades after clearcutting, and often much more quickly (Troendle et al. 2010). In the humid East, measurable increases to annual discharge typically last between 3 to 10 years. By contrast, recovery in cold, snow-dominated areas of the Rocky Mountain region can be longer than the three-decade generalization. Thirty years after strip clearcutting the Fool Creek watershed, significant increases in streamflow continued to be documented (Troendle and King 1985), with estimates of full hydrologic recovery several more decades in the future (Troendle et al. 2010). These extended responses are attributed to longer periods needed for forest regrowth and changes in snowpack accumulation that resulted from harvesting.

Species conversions from hardwoods to conifers (or vice versa) via management or natural succession can significantly change streamflow yields. This change occurs because conifers intercept more precipitation (especially snow), and they tend to transpire more year-round and during the growing season due to the continuous presence of leaves (i.e., needles) and greater leaf densities compared to hardwoods in the same climatic regions (Richardson and Rundel 1998). At Coweeta Hydrologic Laboratory in the mountains of western North Carolina, two hardwood watersheds (one north-facing and one south-facing) were clearcut and planted to eastern white pine (*Pinus strobus* L.) (Swank et al. 1988). Within the first 6 to 10 years following planting of the conifer seedlings, annual streamflow increases attributable to the clearcutting and presence of the young stand were similar to what would have been expected during hardwood regrowth in those watersheds. As the conifer stands further developed during the next five years, annual streamflow declined at a rate of 20 to 50 mm per year. When the conifers reached 15 years of age, annual discharge in both watersheds was about 20 percent below what would have occurred if the watershed had re-vegetated as hardwoods (Figure 2).

Because watershed management studies have illustrated the ability to augment annual water yields by clearcutting, forest removal is sometimes considered as a possible mechanism to alleviate water shortages during droughts or in dry climates. However, the relatively short duration of those increases make supplementation of water yield by clearcutting alone impractical.

All of the hydrologic changes from forest vegetation management described so far have focused on total annual streamflow. However, understanding how stormflow changes as a result of management or natural ecosystem changes also is useful because this information includes the timing and energy of streamflow, which can impact many watershed functions.

Stormflow is generated in forested watersheds in different ways than it is in watersheds or portions of watersheds that support other types of land uses. In addition to small amounts of precipitation that fall directly into channels, water primarily reaches streams in forests through soil water and groundwater contributions. This is because forest soils generally have high soil infiltration rates due to the presence of leaf litter and the low incidence of soil compaction. Overland flow outside of channels rarely occurs in forests, except where soil has become compacted sufficiently to reduce infiltration rates substantially. Consequently, watershed management guidelines for forests and other land uses often emphasize employing management practices or implementing techniques that limit changes to soil compaction or that enhance infiltration.

Across the United States, a primary focus of hydrograph analyses has been the examination of changes to instantaneous peakflows and total stormflow, with particular attention to the impacts of forest removal on the extent or frequency of flood flows (see Edwards et al. "Fundamentals of Watershed Hydrology", this issue for a discussion of hydrographs, peakflows, and stormflow). Statistically significant increases in peakflow and stormflow volumes have been reported for some small forested watersheds following clearcutting

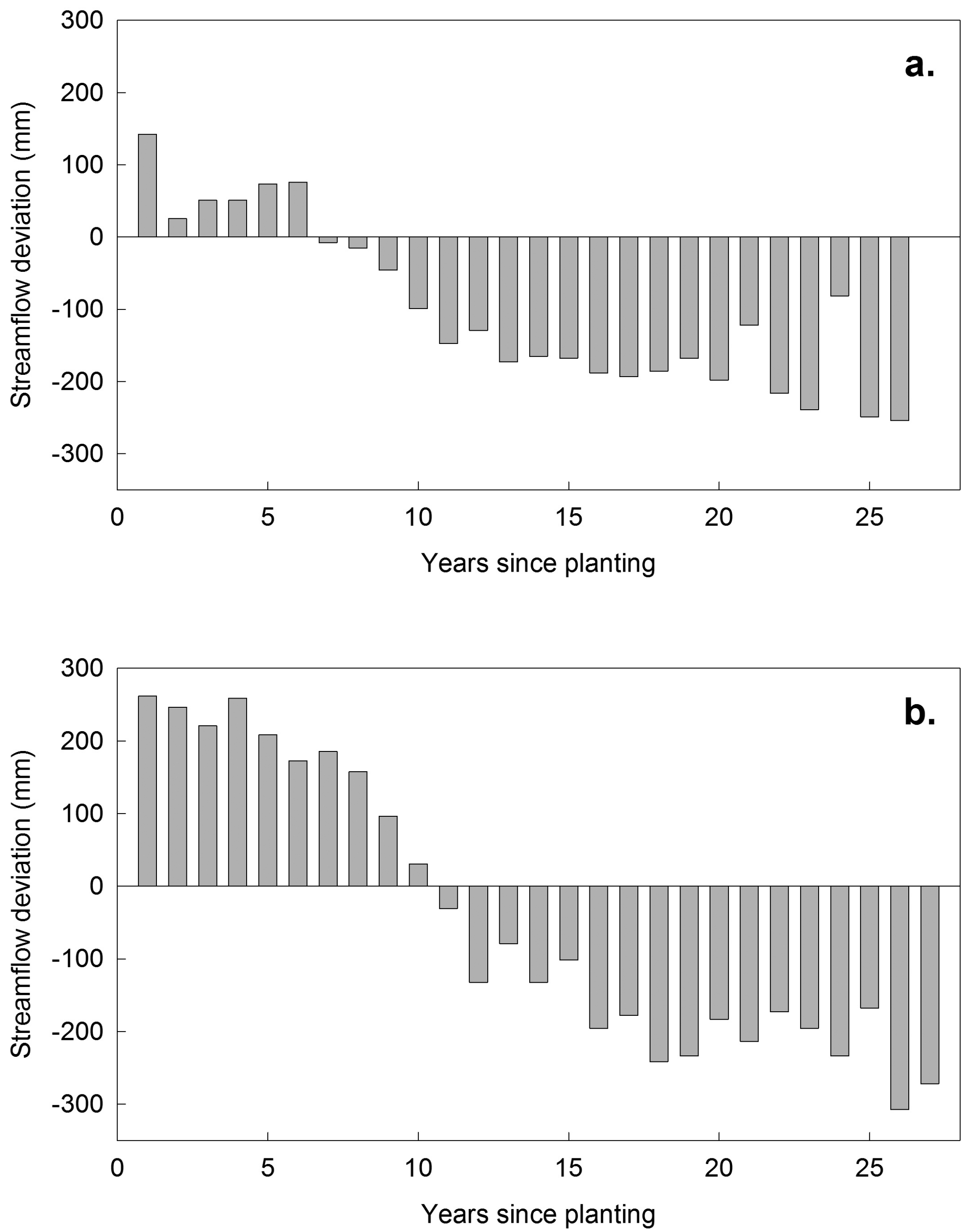


Figure 2. Paired watershed analysis was used to determine the effects of species conversion on annual stream discharge in a (a) south-facing and (b) north-facing watershed at the U.S. Forest Service's Coweeta Hydrologic Laboratory in western North Carolina. At time zero, both watersheds dominated by hardwood trees were harvested and then immediately planted to eastern white pine seedlings. Streamflow increased (as denoted by a positive streamflow deviation from predicted values) for a number of years, as typically occurs following forest harvesting due to the reduction in transpiration and interception losses. As the conifers became established on both watersheds, transpiration and interception losses eventually exceeded those levels of the original hardwood trees, and streamflow decreased below predicted levels (as denoted by negative streamflow deviations). Establishment of the conifers reduced annual discharge by at least 229 mm below what would have resulted from hardwood regrowth. Adapted from Swank et al. 1988.

(Hewlett and Helvey 1970; Hornbeck 1973; Swank et al. 2001; Troendle and King 1985), while other studies have found no measureable change in one or both of these variables (Hewlett and Hibbert 1967; Rothacher 1973; Settergren et al. 1980; Patric 1980). But even where changes have been reported, they generally have been relatively small increases and short-lived. Thus, the conventional thought in forest hydrology is that clearcutting does not change hydrology sufficiently to increase flooding. Where flooding has occurred in or downstream from watersheds subjected to intensive harvesting, stormflow increases from harvesting are considered negligible relative to the amount of precipitation received by the watershed during the storm event. However, a relatively new approach to peakflow and stormflow analyses for watersheds in the Pacific Northwest has challenged this conventional thought (Alila et al. 2009), and some new debate on this subject has emerged.

Soil As A Pollutant

Sediment, or mineral soil, is one of the most common water pollutants in the United States, and it is the most common pollutant associated with forest management. Sediment becomes a water pollutant when eroded soil is transported to waterbodies. Because it is so ubiquitous, sediment is the pollutant most commonly targeted for control during management of forested watersheds as well as other types of land management.

Erosion is a two-step process involving first soil particle detachment and then particle transport. Deposition of transported soil particles is known as **sedimentation**. Erosion and sedimentation are described in this paper only to a limited extent to support discussions herein; Holz et al. (2015, this issue) provides more in-depth coverage of erosion and sedimentation processes and the factors that control or contribute to them.

Erosion and sedimentation are natural and important processes for development of landforms as well as for maintenance of healthy channels (Leopold 1994, Swanson et al. 1988). Until the time that humans became capable of substantially changing the physical appearance of the landscape (especially with mechanized equipment), long-term erosion and sedimentation processes in combination with more catastrophic events (e.g., uplifting, volcanic activity, landslides, etc.) were predominantly responsible for controlling the morphology of natural landscapes, and the presence and locations of water bodies. Humans now have considerable influence on these variables and are responsible for elevating erosion and sediment levels above natural conditions in most water bodies throughout the world.

Concerns about sediment movement on land are tied primarily to the loss of fertile top soil at the location where the erosion occurred, but in-water deposition actually presents more numerous and important problems. Increased sediment delivery to water bodies and accelerated erosion of stream and river beds can have many negative consequences, including effects on potable water quality and treatment costs, aquatic organisms and aquatic habitats, and water body stability (Newcombe and MacDonald 1991; Wood and Armitage 1997). Toxic chemicals and organisms (e.g., parasites, bacteria, etc.) also can be bound to soil particles, and deposition of contaminated sediments in water bodies can result in a myriad of consequences for aquatic organisms and humans (U.S. Environmental Protection Agency 2004).

Fortunately, not all eroded sediment will reach a water body. Some may move very little because there is insufficient overland flow to transport the sediment, there is little slope to the ground surface so sediment movement is stalled, or the sediment becomes trapped by obstacles, known as **roughness features**, on the ground surface. Any element that can stop movement or slow the water transporting sediment can act as a roughness feature, including vegetation, leaf litter and woody material, rocks, and many types of human-placed (intentionally or by chance) features.

Once delivered to streams or rivers, only a small percentage of sediment is exported quickly through the entire channel network and lost from the watershed. This is because sediment also becomes trapped and stored in pools where water velocity slows, and behind and within in-stream roughness features, such as boulders, rocks, large logs, debris jams, etc. Sediment trapped in channels can be stored for long periods of time – storage lasting decades to hundreds of years has been reported (Madej 1987; Brakebill et al. 2010; Milius 1998).

The greatest percentages of sediment exported from watersheds result from only a few of the largest streamflow events each year (Edwards and Owens 1991; Kochenderfer et al. 1997); other events simply redistribute sediment within the channel network. Consequently, the adverse influences of elevated sediment levels in water bodies can be quite long.

Sediment storage and transport in stream and river systems that have received substantial human reconfiguration, such as straightened (aka **channelized**) and dredged channels or concrete-lined channels, is very different from that described above for more-natural channels. Streamflow velocities in channels with these types of extreme disturbances are higher due to increases in slope from straightening (Figure 3) and/or reductions in bed and bank roughness (Arcement and Schneider 1989). Higher velocities and decreased roughness will transport more sediment more quickly, thereby reducing the potential for in-channel deposition and sediment storage. Higher flow velocities and decreased roughness also result in more energy for stream bank and bed erosion. This increased energy and capacity for erosion explains why channel migration and realignment toward natural conditions continue to occur after channelization. Video illustrations of large river and small stream channel respectively, are available from the Missouri Department of Natural Resources (respectively, see http://serc.carleton.edu/details/files/19164.html and http://serc.carleton.edu/details/files/19084.html). The increased energy makes even concrete-lined or other artificially armored channels susceptible to failures (Figure 4). Substantially altered channels also provide poor habitat, feeding, and reproductive conditions for aquatic organisms, typically poor water quality, and high maintenance and repair costs, all of which argue for managing watersheds to maintain healthy, natural channel conditions.

Forest Management Influences on Water Quality

In undisturbed watersheds, hillsides and channel banks and beds provide the sources of erodible sediment. Hillside sources in undisturbed forests are limited primarily to small areas of soil that lack litter cover (e.g., small areas on steep slopes),

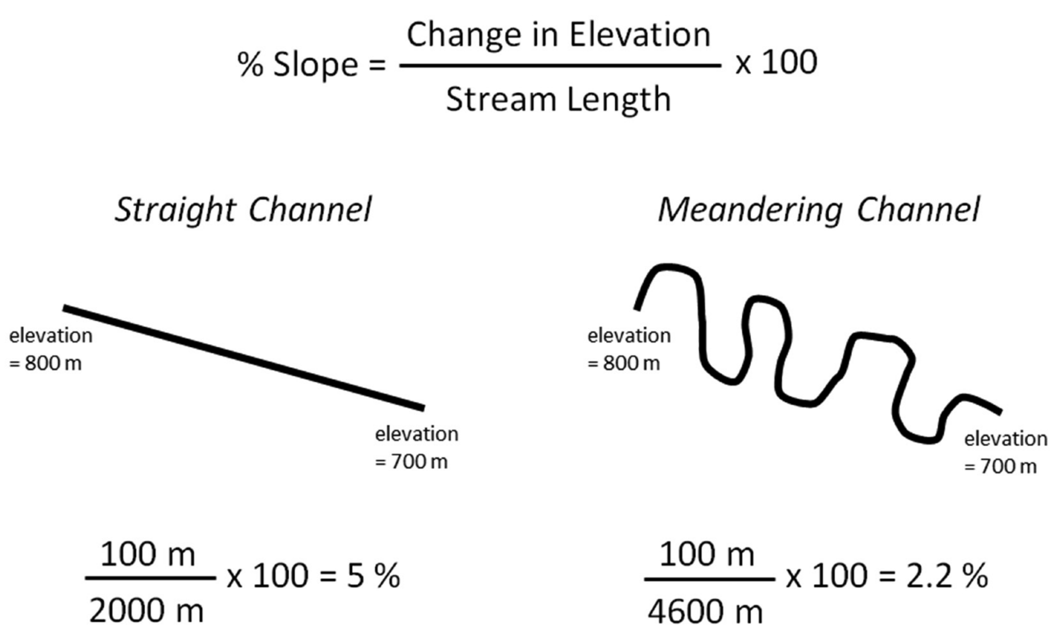


Figure 3. A stream or river's slope is calculated from the change in elevation between two points and the corresponding length of the stream channel. Consequently, when a meandering channel is straightened or channelized, the slope of the straightened channel will be greater. As a result, streamflow in the straightened channel will have a higher velocity and more energy for erosion.

animal trails, and root wads exposed by tree falls (Hamons 2007). Channel beds and banks are sediment sources because streamflow, particularly during stormflow events, provides energy to displace and transport exposed soil from the bed and banks.

Human-caused soil disturbances increase the availability of sediment sources, and thus, the potential for soil erosion in all types of land uses. Watersheds dominated by managed forest lands tend to have lower rates of erosion and sediment delivery than watersheds dominated by other land uses because there is less soil disturbance in managed forests, and soil exposure that does occur tends to be much less intense and short-term.

Roads are generally the most problematic feature relative to sediment pollution in forested watersheds. Roads contribute to soil erosion due to: soil disturbance and exposure during construction; soil that remains exposed and susceptible to erosion after construction; road slope or location; and compacted driving surfaces and drainage features and the concentrated runoff resulting from them. Roads and road effects are described in detail here because they are so ubiquitous in all land uses.

Water body crossings tend to be the most important features of road systems in terms of erosion and sedimentation. Because they occupy the area immediately adjacent to and over water bodies, they present the greatest potential to affect water quality. Historically, the focus of water body crossings in watershed management was on passing high flows, so designs considered only the size of the crossing (e.g., installing sufficiently large stream crossing culverts). Since the mid to late twentieth century, additional attention has been given to reducing sediment impacts on water quality at crossings by removing the connection between ditchlines (or ditches) and streams. Contemporary applications of the **Clean Water Act** to water body crossing designs now also include several other factors in crossing structure designs, such as improving aquatic organism passage during all ranges of flows and large wood passage during flood flows. Consequently, there are many physical and biological factors that must be considered to achieve properly functioning and safe water body crossings.

While a variety of techniques exist for building forest roads, **cut-and-fill construction** is one

Figure 4. Straightened channels often are hardened or armored with materials such as concrete to protect against channel migration back to a meandering or sinuous condition. However, the increased energy of streamflow that results from straightening, and the loss of roughness in these channels often will exceed the strength of these materials so that they eventually fail. From Ponce et al. (2004), used with permission.

of the most common types of road construction in hilly terrain or sloping landscapes (Figure 5). Cut-and-fill roads involve removing soil from the hillside from what will become most of the driving surface width, and placing the excavated material downslope of the excavated area. This side cast material is used to create the rest of the driving surface as well as the **fillslope**. If the hillside is steeply sloped, some side cast material will tend to "roll" fairly far downslope during fillslope construction. A **cutbank** on the upslope side of the road is created when hillside material is removed during excavation. **Ditchlines** also are commonly constructed along the inside edge of the road at the base of the cutbank to facilitate road drainage through pipe culverts (called **relief culverts** or **cross-drain culverts**) or similar structures constructed in or under the road and located along the road's length (Figure 5). The spacing of relief culverts generally is dependent upon the slope, or grade, of the road surface.

Once road construction is completed, erosion from the compacted driving surface can result from either raindrop impact or concentrated overland flow (see Holz et al. 2015, this issue). Erosion can be controlled in large part by paving or applying several centimeters of good quality gravel (e.g., resistant to particle breakdown by traffic). Neither covering reverses road-surface compaction, but they protect the soil surface from raindrop impact. By creating a more complex, or tortuous, path of travel and by providing roughness, gravel also reduces the slope that the water travels (analogous to how channel sinuosity influences slope in Figure 3), provides friction to slow the water, and ultimately reduces the energy for erosion of road surface overland flow. By controlling the energy of raindrop impact and overland flow, graveled roads have been reported to have 5.8 to 8.3 times less sediment losses than roads that received no surfacing with coarse fragments (Kochenderfer and Helvey 1987; Swift 1984). Paving effectively

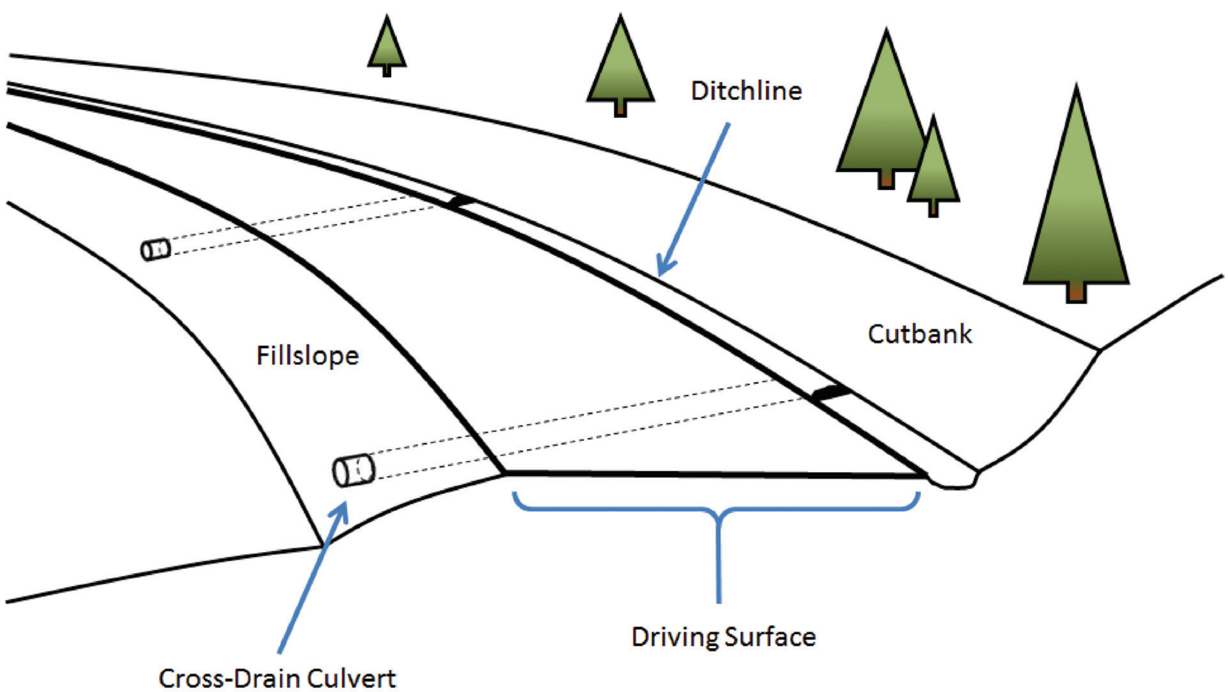


Figure 5. The major parts of a cut-and-fill road. About one-half of the inside portion of the driving surface is excavated with heavy equipment. The excavated soil is sidecast downslope creating the outer half of the driving surface and the fillslope. Road excavation also creates a cutbank. At the base of the cutbank and inside edge of the driving surface, a ditchline typically is constructed to capture water from at least part of the road surface and subsurface flow exposed by the cutbank. This runoff is carried in the ditchline until some type of cross-drain feature is encountered – in this drawing they are pipe culverts. Note that the fillslopes and cutbanks are necessarily steeper than the original hillside slope in which they were constructed. Drawing by Robin L. Quinlivan.

eliminates erosion on the road surface (Reid and Dunne 1984), but it does not slow road runoff.

Constructed cutbanks and fillslopes are steeper than the original hillsides, so in addition to being susceptible to erosion from water, they are also prone to erosion by gravitational forces. Increasing soil cover and soil stabilization on these features is critical to controlling water- and gravity-driven erosion. Typically, cover and stabilization are achieved through seeding with grass and herbaceous species and/or mulching the soil surface, and soil amendments, such as lime or fertilizers, may be applied to help hasten the rate of vegetation establishment. Natural re-vegetation might occur even without seeding, but in most climates the time required for full soil cover and stabilization is usually longer than with seeding. For major roads or particularly problematic areas around low-volume roads, organic mats (Grace 2000) or synthetic geotextiles (Theisen 1992) may be affixed to the soil surface temporarily until vegetation becomes established, or permanently if vegetation alone is not expected to be capable of providing sufficient soil stabilization.

Ditchlines themselves can be sources of sediment because they carry concentrated overland flow that can have substantial erosive energy. Ditchlines may become re-vegetated intentionally or naturally with grasses, but shallow-rooted plants can be scoured from ditchlines. Ditch cleaning or "dragging" with heavy equipment is also a common maintenance practice used to keep materials from building up and potentially clogging relief culverts, but it exacerbates ditch erosion. This practice tears vegetation from ditchlines and re-initiates elevated levels of ditch erosion. Ditch erosion can be dramatically reduced by lining ditches with moderate- to large-size quarried rock that has sufficient mass to withstand movement from the energy of the captured water. Rock-lining exploits the same erosion control mechanisms that apply to graveling road surfaces.

Even if all of the soil disturbed during road construction is successfully covered by gravel or paving, vegetation, or other materials, continued erosion from roads often remains problematic due to road drainage. **Road drainage** comes from two primary sources – overland flow from precipitation falling on the road that cannot infiltrate the driving surface, and water that becomes concentrated due to drainage features.

Overall, the key to controlling road drainage and associated erosion is dispersing water from the road in small quantities, since this will control the energy available to erode soil. Many drainage techniques have been developed toward this end, but each has its own difficulties in terms of operation and maintenance. However, most road drainage techniques result in the concentration of road runoff, through either surface features, such as **broad-based dips** used on low-volume woods roads (Figure 6a) or relief culverts under the road surface (Figures 5 and 6b). Sometimes water is drained from roads at natural breaks in the road slope, but these breaks also may discharge concentrated flow. Forest litter cover and planted grasses frequently are depended upon to provide protection against erosion by road drainage, but they provide little protection against concentrated discharge (Edwards and Evans 2004), so gully formation below the outlets of drainage features is common and can be chronic (Figure 7). Fillslopes are especially susceptible to gully formation because fillslope soil is unconsolidated. Once gullies form, further erosion and continued extension is difficult to stop without substantial effort and cost.

The volume of water that will be contributed to ditchlines is sometimes greater than anticipated due to **subsurface flow** contributions from the cutbank. During cutbank construction, large **macropores** that transport significant amounts of subsurface flow can be intersected, causing the water to emerge (Figure 8a) and be captured by the ditchline, thereby adding to road discharge (see Schoonover and Crim 2015, this issue and Edwards et al. 2015, this issue for more discussion on macropores and soil pores). The potential for exposing such macropores increases substantially if the cutbank removes the entire soil mantle (which is not uncommon in shallow soils), since subsurface flow often is concentrated above the underlying bedrock.

Landscape position can have a large influence on the likelihood that subsurface flow paths will be encountered. **Coves** in particular, and **swales** to a lesser extent, are sites of natural subsurface water accumulation and flow path development a.

b.

Figure 6. Two types of common cross-drain features that are used on forest roads are shown. A broad-based dip (a) is simply a constructed outsloping depression in the road surface into which water drains from the adjacent road length. The 2 to 3 percent outslope of the dip sheds water off the road, ideally in sufficiently small quantities that will allow it to infiltrate into the soil. The pipe culvert (b) is installed under the road and it discharges water that collects in the contributing ditchline (also see Figure 5).

Figure 7. When water is cast off a road from a road cross-drain feature where only grasses and herbaceous vegetation are available to reduce its energy and encourage infiltration, large gullies can develop, like the one shown here at the outlet of a broad-based dip.

a.

b.

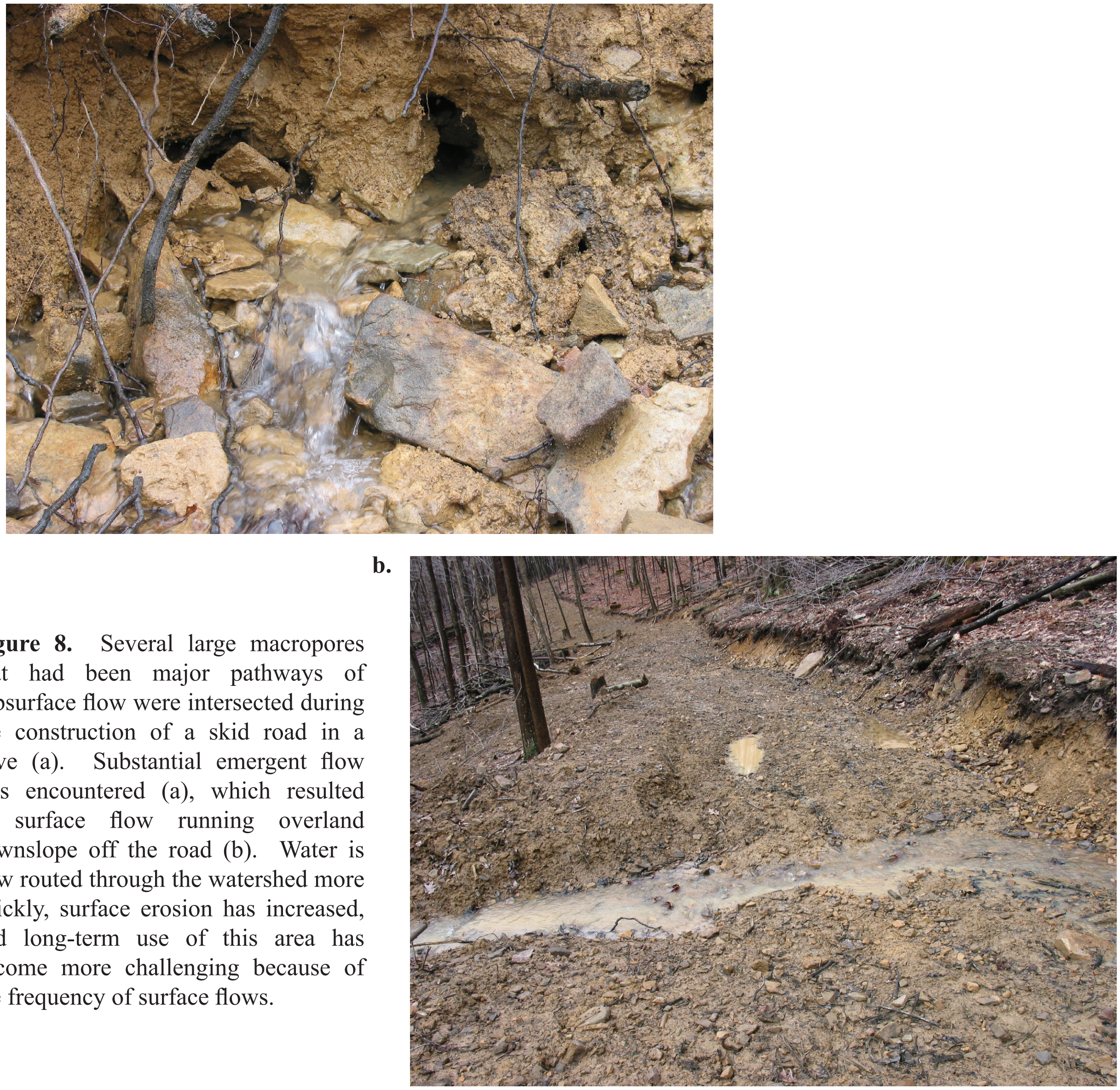


Figure 8. Several large macropores that had been major pathways of subsurface flow were intersected during the construction of a skid road in a cove (a). Substantial emergent flow was encountered (a), which resulted in surface flow running overland downslope off the road (b). Water is now routed through the watershed more quickly, surface erosion has increased, and long-term use of this area has become more challenging because of the frequency of surface flows.

because they exist in definable low elevations on the landscape (Keppeler et al. 1994, Gucinski et al. 2001). In many ways these areas behave much like subsurface stream channels in that subsurface flow can become concentrated and can result in high discharge volumes when they are intersected during road construction (Figure 8). Furthermore, coves often are source areas for surface stream channels that begin further downslope. Once subsurface flows become emergent, their volumes and velocities can be great enough to cause **head cutting**, which is the gradual migration of the top of the established channel to the source of emergent flow that occurs as the result of surface erosion. If the emergent flow and head cutting are substantial, segments of road that exist downslope between the original head of the channel and the new head can be washed out. Consequently, in many regions, road construction through coves should be avoided if possible to limit the degree to which subsurface flows are altered.

Best Management Practices

Water pollutants are classified as either nonpoint or point source based upon their origin. **Point source** pollutants are defined in Section 502 of the Clean Water Act as originating from "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture." Consequently, point source pollutants are associated with discharges from industrial and sewage treatment operations directly or indirectly into water bodies or groundwater. By contrast, **nonpoint source** pollution originates from diffuse sources, and it is transported by runoff and eventually deposited into water bodies, including groundwater. Sediment from forestry and agricultural operations, excess fertilizers from croplands, nutrients from livestock, oil and grease from urban runoff, lawn chemicals from residential areas, and acid mine drainage from abandoned mines are just a few examples of the many types of nonpoint source pollutants that exist.

Both types of pollutants must be considered in the management of watersheds because each can have a substantial influence on water quality and the beneficial uses of water and water bodies. Point source pollutants are controlled and regulated through permits that identify the types and set the maximum loadings or concentrations of pollutants that can be discharged into water bodies. Because discrete origins of nonpoint source pollutants are not definable, their release is controlled by the use of **best management practices**, or **BMPs**, as specified by the Clean Water Act.

Best management practices are techniques and tools used to control nonpoint source pollution. It is important to note that BMPs do not eliminate nonpoint source pollution; instead they are designed to maintain nonpoint source pollution at levels acceptable to regulatory agencies and at an acceptable cost (Edwards 2003). The EPA requires states to have an approved set of BMPs that are recommended or required for the major land uses and industries that generate nonpoint source pollutants, such as agriculture, forestry, and mining. These typically are published in BMP manuals or stormwater control manuals and are easily located using internet searches involving key words that include the state name, the activity, and the term 'BMPs' (e.g., West Virginia forestry BMPs). BMP and stormwater control manuals are reviewed and updated regularly, and new scientific findings and methodologies are considered during the revision process.

Different types of BMPs are applicable to different types of land uses. Where commonalities in activities exist among land uses, such as site access (i.e., road construction and use) similar BMPs may be employed. In other situations, BMPs may exist for activities that are unique to a given land use, such as no-till farming for agriculture.

Best management practices for nearly all activities fall into categories with the following broad objectives: limiting the occurrence of concentrated overland flow; controlling the energy of overland flow; encouraging soil infiltration of precipitation and surface runoff; capturing or detaining pollutants; providing soil cover and soil stabilization; applying chemicals at rates and times that will not result in excess losses; promoting chemical uptake or chemical retention; and retaining shade around water bodies. Note that while some of these BMPs involve flow control, their ultimate purpose is to control detachment or transport of the associated pollutant – the focus on water exists simply because of the dependency of pollutant availability and migration on water movement and the direct relationships among overland flow volume, velocity and energy.

While often not identified explicitly in BMP manuals and stormwater control handbooks, **planning** is itself a BMP; indeed, many consider planning to be the most important BMP for controlling nonpoint source pollution (Phillips et al. 2000). Well-planned activities can allow managers to prevent problems that otherwise might require implementation of additional BMPs or avoid other mitigation measures after problems result. Costs associated with planning can be much less than costs associated with other BMP implementation and mitigation measures.

Forestry BMPs

The vast majority of BMPs applied in forest management are focused on the **road prism**, which includes the entire area disturbed for the construction of the road from the bottom of the fillslope to the top of the cutbank. Road BMPs rely on practices to control erosion using the broad approaches described previously: protecting the surface of the road; providing cover for other areas of disturbed soils (e.g., cutbanks, fillslopes, and log landings); controlling the energy and volumes of road drainage; and encouraging soil infiltration. Since the fundamentals of many of these were described previously they are not repeated here, but specific examples of these BMPs are given in Table 2.

Planning is the most important BMP for managing the effects of roads on watershed hydrology and water quality. Planning allows travel routes to be laid out away from sensitive areas (e.g., highly erodible soils, steep slopes, etc.) and allows planners to avoid or minimize the need for water body crossings.

When crossings are necessary, many construction BMPs come into play to reduce impacts to water bodies and water quality. These BMPs include crossing streams at right angles to reduce the length of the crossing and the amount of sediment that reaches the water body when fills and fillslopes are constructed in and around the crossing (Stedman 2008), eliminating connections between drainage ditches and crossings by diverting runoff onto the hillside before reaching a water body crossing, and properly installing the appropriate type of crossing to reduce undesirable changes to water body morphology (e.g., channel erosion, head cutting, etc.) or effects on aquatic organisms or habitats. While road and crossing BMPs comprise the majority of forestry BMPs, other common ones also exist. Some of these include implementing techniques that reduce land and water body disturbances by off-road equipment use and tree felling, maintain vegetation to promote infiltration of overland flow and trap sediment and other pollutants, and provide shade to protect against thermal pollution (Table 2). Each of these typically involves the establishment of strips of land along waterways in which either no disturbance is permitted or the breadth or intensity of activities is restricted to protect water quality and aquatic ecosystems from the disturbances. These areas go by a variety of names, including **filter strips**, **buffer strips**, **riparian buffers**, or **streamside management zones** (SMZs). The width of these strips and the allowable activities in them often depend upon the type of stream present in the area (perennial, intermittent, or ephemeral) or its habitat potential (e.g., trout stream). Other forestry BMPs are designed to reduce impacts from common soil-disturbing activities (e.g., site preparation, tree planting, etc.) or from activities that have a high potential to result in water pollution by chemicals (e.g., pesticide or fertilizer applications, or chemical storage)

The specific **prescriptions** (i.e., how to implement the BMP on the ground) for most forestry BMPs depend upon the physical characteristics of the landscape or feature. For example, relief-culvert spacing on roads is a function of the road grade – the steeper the road segment, the closer the spacing of relief culverts. Because each State is responsible for developing and regularly reviewing and revising its own forestry BMPs, forest managers and land owners should refer to their respective State's BMPs for the recommended or required prescriptions.

Agricultural Watersheds

To meet the food demands of a growing world population, it is anticipated that global crop production will need to double by 2050 (Tilman et al. 2011). This demand will likely be met by agricultural intensification in developed countries and increased land clearing for agriculture in developing countries. Part of the intensification process includes increasing drainage in fertile, poorly drained soils, such as Mollisols (see Schoonover and Crim 2015, this issue) of the Midwestern U.S., by installing drainage tiles. These extensive drainage networks have resulted in increased discharge from agricultural watersheds which flush excess nutrients, primarily nitrate, into streams or rivers (David et al. 2010). Elevated nutrient losses from the Mississippi River basin contribute to the hypoxic or "dead zone" in the Gulf of Mexico (Rabalais et al. 2001).

Intensive agriculture commonly results in surface water and groundwater quality impairment due to erosion of exposed mineral soil and export of nutrients not utilized by crops. Sediment and nutrient pollution from row-crop agricultural areas are considered nonpoint source pollutants and as such, are exempt from the permitting process under the Clean Water Act. Instead, voluntary BMPs,

Table 2. General categories of Best Management Practices (BMPs) and examples of each in different land uses.

General Type of BMP	Purpose of BMPs	Examples of BMPs
Protect existing soil cover or vegetation	To protect soils from erosion from raindrop impact; to maintain soil infiltration rates and avoid overland flow; to provide roughness when overland flow occurs	• Retain litter cover in forests by minimizing the area in haul roads, skid roads, and log landings • Conservation tillage or no-till in agriculture
	To protect soils from raindrop splash and soil particle detachment; to provide some roughness for overland flow	• Seed and mulch to promote grass and herbaceous plant establishment development • Geotextiles or riprap installed on highway cutbanks • Pave or apply gravel to road surfaces • Harden fillslopes at outlets of road drainage features (e.g., culvert outlets) • Cover crops
Sediment control barriers or roughness features	To capture and retain sediment	• Compost filter socks, straw wattles, silt fences, hay bales, etc. • Slash (aka windrows) from harvested tree tops installed at the base of and parallel to road fillslopes • Check dams installed in streams below crossings during construction; usually used in conjunction with pumping water around crossing area • Water and sediment control basins established in agricultural fields • Grassed waterways • Riparian buffers, filter strips, and streamside management zones along streams
Water control and drainage features	To handle and divert water in small quantities to reduce its potential for erosion and sediment transport	• Culverts, broad-based dips, or waterbars installed on roads • Road outsloping on noses of ridges to function as drainage features • Cross-drainage spacing defined by road segment grade • Water and sediment control basins established in agricultural fields • Grassed waterways
Control surface grades or provide slope breaks on roads	To manage the volume and velocity of overland flow	• Set maximum allowable grades on roads
Follow guidelines for chemical applications (herbicides, pesticides, etc.)	To reduce the potential for chemical runoff to surface waters or leaching to groundwater	• Apply chemicals when precipitation is not forecast • Apply only needed or recommended amounts of chemicals • Use chemicals away from water bodies, or adjust application method near water bodies
Provide protection zones between activities and water bodies; provide protection along water bodies	To provide a zone that will infiltrate overland flow carrying pollutants; to provide a zone between the activity and water body that can physically, chemically, or biologically keep pollutants from reaching the water body; to provide shade to water bodies; to provide sources of large wood to the water body to improve aquatic habitat; to provide woody vegetation for bank stabilization	• Retain riparian management zones, streamside management zones, forest buffers or filter strips between woods, roads, and streams, harvesting activity and streams, or agricultural fields and streams • Maintain at least a set minimum basal area or canopy cover requirement along streams for harvesting operations • Restrictions on heavy equipment use in riparian areas • In agricultural areas, periodic thinning in riparian buffers to remove nutrients stored in biomass and maintain actively growing stand for maximum nutrient uptake

such as riparian buffers, grassed waterways, and cover crops are established in agricultural watersheds to address pollution concerns (Table 2). By contrast, large animal feeding operations are a sector of agriculture that is considered a point source pollutant and is permitted by the U.S. Environmental Protection Agency. The primary challenges for large feeding operations are the handling, storage, and application of the animal manure. Manure can be land applied to row-crops and other areas as a fertilizer. However, large areas of land are needed to ensure that soils do not become saturated with nutrients that are then susceptible to leaching, which can result in surface and groundwater pollution.

Agriculture BMPs

Many different BMPs have been designed to address nonpoint source pollution issues in agricultural watersheds. Best management practices in agriculture often are referred to as **conservation practices**, and they generally are established on private farm lands through cost-share programs administered by the USDA Natural Resources Conservation Service (NRCS). The NRCS maintains a database of accepted conservation practices that have been field tested through multiple research projects. The following sections review some of the most commonly applied in-field and edge-of-field practices to control agricultural pollution.

Nutrient Management Planning. Developing a whole-farm nutrient management plan is one of the first actions taken in conservation planning and may incorporate multiple conservation practices to meet nutrient management planning goals. In general, the plans focus on optimizing the timing and rates of applied fertilizers. The overall goal is to maximize crop yields while controlling nutrient losses to the environment. At the most basic level this is accomplished by meeting but not exceeding the nutrient demands of the growing crop. A recent program promoted by multiple fertilizer, soil, and crop associations summarized proper nutrient management as the 4 Rs: applying the right fertilizer source at the right rate at the right time and in the right place (Ehmke 2012).

No-till and Conservation Tillage. Reduced tillage has become a common conservation practice in the past two decades as a means to maintain more residues (i.e., cover) on the soil surface and reduce erosion rates. The lack of soil disturbance also helps foster a richer soil biological community, including earthworms, which can increase surface soil porosity (Hobbs et al. 2008). Increased porosity allows greater water infiltration rates, which reduce the potential for surface runoff and erosion. The aforementioned sequence of events generally takes multiple years to a decade to develop. In the short term (1 to 2 years), converting from **conventional tillage** (disturbing the majority of the soil surface) to **no-till** may temporarily reduce infiltration rates due to surface crusting and compaction. However, when the soil biological community becomes re-established, soil porosity and infiltration rates increase because of the reduced soil disturbance (Haines and Uren 1990). Under reduced agricultural tillage regimes, there is an increased reliance on herbicides for weed control, which creates the potential for water quality concerns.

Cover Crops. Over the past five years, the establishment of cover crops during the dormant season has become a popular conservation practice for increasing crop yields, building soil organic matter, providing an alternative source of nitrogen, and protecting water quality. Across the U.S., producers have realized 3 to 5 percent increases in corn and soybean yields the year following cover crops (Watts 2014). Multiple research projects have demonstrated long-term increases in soil organic matter and soil organic carbon stocks with the use of cover crops (Olson et al. 2014). These increases are due to root and above-ground biomass production in the late fall and early spring. **Nitrogen-fixing legumes** (which can change nitrogen gas into plant-useable forms of nitrogen), such as hairy vetch (*Vicia villosa* Roth) can provide significant amounts of nitrogen to subsequent crops, which may help reduce synthetic fertilizer application rates. The decomposition and mineralization of cover crop residue during the growing season can provide inorganic nitrogen to crops.

Cover crops can help protect water quality via multiple mechanisms. The ground cover provided during the dormant season helps reduce erosion rates, which are commonly elevated at that time of year. Non-legume cover crops, such as ryegrass (*Lolium perenne* L.) and cereal rye (*Secale cereale* L.) can scavenge nitrogen and phosphorus from the soil and help prevent nutrient leaching to groundwater and surface water (Dabney et al. 2001). Challenges associated with utilizing cover crops include additional costs to the producer, getting cover crops established early enough in the fall to ensure successful development, and successful termination of cover crop growth in the spring prior to crop planting.

Grassed Waterways. In humid regions of the U.S., grassed waterways have become an important conservation practice to address erosion issues associated with concentrated and channelized flow in agricultural fields. Surface runoff in agricultural fields may start as sheet flow (shallow, dispersed flow), but it generally quickly concentrates into channelized flow due to the microtopography of the soil surface. Channelized flow in fields can result in significant erosion during storm events. Wide grassed waterways can be established in channelized flow areas to reduce the energy of runoff and control soil erosion (Fiener and Auerswald 2003). Generally, grassed waterways need to be re-shaped or re-constructed after a decade because soil berms build up on their margins or channelized flow cuts around them, both of which reduce their effectiveness.

Riparian Buffers. Riparian buffers are the most common conservation practice established along the edges of fields to protect water quality. Riparian areas are transitional areas between water bodies and adjacent terrestrial areas. Riparian buffers provide many of the same benefits in agricultural systems that they do in forested systems (though the vegetation comprising the buffer may differ), including serving as wildlife habitat, providing thermal protection to cold and cool water streams, contributing woody material to streams that provide aquatic habitat, providing carbon to support aquatic food webs, and providing stream bank stabilization by the presence of extensive root networks.

Grasses, trees, or combinations of both have been planted in riparian areas to capture nutrients and sediment from adjacent agricultural fields. Riparian buffers are typically 15 or 30 meters wide. However, even narrow (9 m), remnant riparian buffers have been shown to effectively protect surface water quality (Schoonover and Williard 2003). Riparian buffers generally have high infiltration rates allowing incoming surface runoff to infiltrate and deposit sediment in the buffer. Vegetated riparian buffers also significantly reduce nitrate concentrations in groundwater, primarily through **denitrification** (conversion of nitrate to nitrogen gas in the soil and subsequent loss of the gas to the atmosphere), and plant uptake (Dosskey 2001). The greatest reductions in soil nitrate have been found in buffers where groundwater occurs at shallow depths – this is because near-surface soils are high in carbon which supports denitrification, and plant roots are able to take up nitrogen directly from groundwater (Hill 1996).

Urban Watersheds

Most U.S. citizens reside in or near cities or towns. In 2010, the U.S. population was just over 310 million and it is expected to reach nearly 440 million by 2050 (Ortman and Guarneri 2009). As the U.S. population continues to grow there will be increasing demand placed upon the country's water resources and increasing stresses placed on watershed hydrology and water quality due to the characteristics of urban environments.

The urban or developed environment is distinguished by the many types of land uses and characteristics that exist within it. For instance, some land classified as urban may be heavily commercialized, while other areas may be dominated by lower-intensity residential use or recreational use. Regardless of the specific land use, the most common indicator of urbanization is the amount of **impervious surface cover** within a watershed. The increase in impervious cover in urban areas typically exceeds the rate of population growth. For example, in Georgia a 17 percent increase in population translated to a 100 percent increase in impervious surfaces over the same time period (Ford et al. 2003).

Impervious surface cover is linked strongly to water quality, aquatic health, stream condition, and overall hydrology. Impervious cover generally is classified using one of two methods, either

Total Impervious Area (TIA) or **Effective Impervious Surfaces (EIS)**. As the name suggests, TIA includes all impervious surfaces within a watershed and is reported as a percentage of the total watershed area. Effective impervious surfaces involve only impervious surfaces that are hydrologically-connected to water bodies. For example, the area of a house roof with gutters that drains to a cistern or empties onto the surface of a lawn is considered as TIA. The area of a roof that has gutters connected to a tile network that drains directly into a ditch or stream would be considered as EIS. In the past, 10 percent TIA had been considered a threshold value at which stream ecosystems begin to degrade or show impacts from urban land use (Schueler 1994). More recent studies have shown that stream degradation begins at much lower levels of TIA, and degradation occurs progressively with increasing TIA rather than beginning once a specific threshold is reached (Schoonover et al. 2005).

Surface runoff is an important component of urban hydrology due to the large amount of impervious surfaces and their negative impact on water infiltration into the soil. As a result of reduced infiltration, there is much less groundwater recharge in urban areas compared to their rural counterparts. Overland flow delivers precipitation to streams quickly compared to the prolonged contributions of water to streams that occur from subsurface flow when soil infiltration dominates. The dominant sources of runoff into urban streams typically are roads, parking lots, rooftops, and driveways. Urban lawns often act similarly to impervious surfaces due to their high degree of compaction from mowing and other uses.

Storm hydrographs in urbanized channels typically rise and fall quickly due to the high volumes and transitory nature of surface runoff. The result is termed "**flashy**" streamflow. Much higher peak discharges occur in urban watersheds compared to watersheds with similar physical characteristics but less development. The rapid delivery of storm runoff to perennial streams results in a large percentage of the total annual flow being comprised by stormflow. In turn, baseflow in perennial streams can become reduced substantially – so much so that perennial streams can become intermittent in some instances (Korhnak and Vince 2005). Such a hydrologic shift greatly impacts stream health and characteristics. For example, many species of aquatic organisms found in perennial streams are not adapted to the temporary dry conditions that exist in intermittent streams. Even when such drastic changes in hydrology do not occur, lower baseflow levels can create challenging conditions for aquatic organisms because smaller discharges are susceptible to having or being associated with higher temperatures, lower oxygen levels, poorer habitat or less habitat variability, less food availability, and higher pollutant concentrations.

Both point and nonpoint sources of pollutants are common in urban environments (Table 3). Point source pollutants are commonly associated with discharges from commercial or industrial areas of a city. Nonpoint pollution is associated with most other forms of urban development, including residential development, and road and parking lot runoff.

Urban BMPs

Best management practices applicable to urban environments are designed to address chemical and biological nonpoint source pollutants. Many urban BMPs apply the same or similar concepts that are used in forestry and agriculture, particularly BMPs that encourage infiltration of surface runoff. Infiltration can contribute to improved water quality by reducing the erosive energy of overland flow and through biological, physical, or chemical retention or reactions that reduce pollutant transfer to water bodies.

Green Roofs. Green roofs have gained popularity over the past decade. A green roof is a rooftop that is partially or entirely covered by vegetation. They are common in both commercial and residential settings. Green roofs benefit both wildlife (habitat) and humans (aesthetics), save money through energy costs, mitigate the urban heat island effect, and play a key role in stormwater retention (Carter and Butler 2008). Green roofs can be either intensive or extensive. **Intensive** roofs typically are used on commercial buildings and can incorporate grasses, shrubs, trees, and even walking paths because the soil depth, or growth medium, usually exceeds 15 centimeters. **Extensive** roofs generally only have

Table 3. Common water quality impairments and sources associated with urbanization.

Water Quality Impairment	**Potential Sources**
Fecal coliform, *E. coli*, other pathogens and bacteria	Septic systems, sewage effluent, pet waste
Nutrients (e.g., nitrogen, phosphorus)	Sewage effluent, pet waste, lawn fertilizers, industrial pollution
Sediment	Channel erosion, surface runoff from developing sites
Polycyclic aromatic hydrocarbons, PCBs, pesticides	Combustion, industrial solvents, lawn runoff
Road salt	Salt/brine application for de-icing roads
Heavy metals	Automobile emissions, road runoff, old paint, corrosion, batteries, preservatives

5 to 15 centimeters of soil depth and are used in residential roofing projects where they are walked on only for maintenance. Both roofing systems provide stormwater runoff benefits by slowing the time it takes water to reach water bodies. Some roof designs have a plastic underlayment that retains some precipitation for subsequent plant growth on the roof.

Cisterns. Cisterns are regaining popularity and are being incorporated into new building designs. As in the past, cisterns are designed to collect water running off rooftops, removing some water from the stormflow hydrograph while retaining it for later use, typically for landscape watering (Jones and Hunt 2008). Although the practice might seem insignificant, a 232 m2 roof generates approximately 7,571 liters of water during a 25-mm rain event. However, there are some locations, particularly in dry climates, where cistern use or "water harvesting" requires a permit or license (Waskom and Kallenberger 2012).

Rain Gardens. Rain gardens are areas on the landscape where surface runoff naturally accumulates or areas where runoff accumulation has been incorporated into the landscape design (University of Wisconsin-Extension 2003). The drainage areas usually contain soils or growth media that drain quickly to avoid inundation, and in well-designed systems, most of the surface runoff infiltrates into the soil. Typically, rain gardens are planted with native vegetation that is adapted to alternating wet and dry conditions and that can tolerate nitrogen and phosphorus inputs, both of which can be high especially near fertilized lawns or golf courses. Like most other urban BMP designs, rain gardens interrupt and slow the travel time for surface runoff to reach surface waters.

Parking Lot BMPs. In developed areas, parking lots usually occupy the greatest amount of area, especially in commercial areas. Tremendous volumes of surface runoff are generated by parking areas, and they are a source of many types of pollutants that impact water chemistry. A 0.4-ha area of land with an impervious surface produces approximately 102,789 liters of water during a 25-mm rain event, which can quickly lead to local flooding. To lessen the impacts of impervious surfaces on stream hydrology and water quality, many parking lot BMPs have been designed and adopted across the U.S. Some of the BMPs used to reduce the negative impacts of parking lots on water quantity and quality include the use of pervious pavers, sand filters, bioswales and bioretention areas, and retention and detention ponds.

Pervious Pavers. Pervious pavers typically are designed in a grid or lattice pattern and can be constructed with cements, plastics, or even gravel mixed with a growth medium (Brattebo and Booth

2003). The holes in the pavers typically are filled with gravel, sand, or soil to allow water to quickly infiltrate. Pervious pavers are being adopted in "green" parking lots and are commonly used in spill-over lots, or those that are rarely used. They have also been adopted in residential driveways (Gilbert and Clausen 2006), fire lanes, golf cart/pedestrian paths, and other drivable green surfaces. Pervious pavers can significantly reduce runoff, but the maintenance costs and short longevity of pervious pavers can be cost-prohibitive. Pavers tend to clog easily, and their maintenance requires vacuum street sweeper use or high pressure washing.

Sand Filters. Sand filters are used to remove moderate to high loadings of pollutants, such as sediment, biochemical oxygen demand (BOD) and fecal coliform bacteria from parking lot runoff (U.S. Environmental Protection Agency 1999a). They consist of a storm grate at the parking lot surface over a sand or organic filter below the lot. They are installed during the construction of the parking lot and commonly extend along the outer perimeter of the lot. While they can be easily accessed for maintenance, the upper few centimeters of the filter material must be replaced frequently to prevent clogging.

Bioswales/Bioretention Areas. Bioswales utilize parking lot "islands" for the establishment of vegetation on soils or other materials that have high hydraulic conductivities (i.e., the soils drain quickly) (Xiao and McPherson 2011). These areas generally are designed to provide on-site treatment for the first 13 mm of stormwater runoff. Pollutants also are removed by biological, chemical, and physical mechanisms in the soil and by vegetative uptake. Bioswales are a desirable BMP because they typically take up only 5 to 10 percent of a parking lot's area and they are easily maintained.

Retention and Detention Ponds. Retention ponds, sometimes called stormwater wetlands, are areas that retain or hold a certain amount of water year-round (U.S. Environmental Protection Agency 1999b). They are designed to temporarily capture some urban runoff and release it slowly to streams. They typically have native aquatic vegetation included in their design to take up nutrients and other pollutants present in the runoff. Detention ponds also hold water during storm events and release it slowly, but they revert to dry basins during non-storm periods (Stanley 1996). Both retention and detention basins are commonly used in residential developments and adjacent to large parking lots.

Conclusion

A basic understanding of the impacts of land use/land cover on water quality and hydrology is critical for watershed planning and management. The watershed is the most appropriate level or scale for managing landscapes because it integrates the physical, chemical, and biological inputs to a given water body. Recognizing the various impacts that individual land uses can have on soils and water resources is central to controlling detrimental effects within the watershed as well as downstream.

The current era of watershed management is focused largely on nonpoint source pollutant management strategies. Unlike point source, "end-of-pipe" pollutants whose loadings are documented and quantified, nonpoint pollutant sources are much more ubiquitous and subtle, making their contributions to water quality impairment much more difficult to assess. Best management practice implementation, which begins with thorough project planning, is the primary strategy for controlling nonpoint source pollutants. While BMPs exist for major land management activities, such as forestry, agriculture, and urban development, they also are applicable in the day to day lives of all citizens. Basic BMP principles, such as controlling the amounts and duration of soil disturbance during construction around the home, applying chemicals to lawns or gardens only at needed rates and during suitable times, and incorporating techniques to encourage infiltration of rooftop and driveway runoff are important actions that contribute to protecting watershed functions, water quality, and aquatic health.

Author Bio and Contact Information

Pamela J. Edwards is a research hydrologist with the USDA Forest Service, Northern Research Station in Parsons, WV. Her current research focuses on the effects of forest management on water quality, streamflow and

stream stability, and the development and effectiveness of best management practices for protecting water, riparian and aquatic resources. She can be contacted at pjedwards@fs.fed.us or P.O. Box 404, Parsons, WV 26287.

Jon E. Schoonover is an Associate Professor of Forest Soils and Physical Hydrology at Southern Illinois University Carbondale. His current research interests focus on the influence of agricultural best management practices on soil and water quality. More specifically, his work focuses on riparian buffer vegetation, nutrient management strategies, and cover cropping systems. He is also interested in the propagation and restoration of giant cane in Southern Illinois riparian areas.

Karl W. J. Williard is a Professor of Forest Hydrology at Southern Illinois University Carbondale. His current research interests include agricultural land management impacts on soil and water quality, quantifying the water quality benefits of riparian buffers in agricultural watersheds, the impacts of forest management on hydrology, erosion, and sedimentation, and watershed management and planning.

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