Lessons Learned in Watershed Management: A Retrospective View

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Abstract.— Forest watershed management research is mandated by over 100 years of legislation, from the Organic Act and Weeks Law enacted around the beginning of the 20th century, to a variety of environmental protection acts passed over the past several decades. Research results have come primarily from studies of a multitude of gaged watersheds selected to represent a variety of geographic locations, forest types, topography and climate. These studies have show the effects of forests and forest disturbances on water yield, peak and flood flows, snow accumulation and melt, soil erosion, and water quality including sedimentation and turbidity, chemicals and temperature. The resulting knowledge of hydrologic, nutrient and energy cycles and soil erosion has been incorporated into land and water management primarily through best management practices and an ever-increasing array of procedures including computer simulation models to help assess cumulative watershed effects. This paper reviews some important lessons learned from watershed management research across the nation and discusses management implications.

Introduction

Over the past century, knowledge of linkages between forests and streams has been gathered through watershed management and watershed ecosystem research. These studies, most often conducted on small, experimental watersheds, have shown how contributions of water, sediment, chemicals and heat from forests to streams change as forests undergo succession or experience natural and human-related disturbances. Our job is to summarize the lessons learned from these studies. This is a daunting task at best and requires some sideboards: 1) we will focus on forestry issues (convenient because that's what we know about) and mention other important watershed management activities including range, agriculture and urbanization effects only in passing; 2) although considerable, excellent work has been done elsewhere, we will confine our discussion to the U.S. and 3) we provide only a cursory overview of the subject matter (if we miss your pet interest, we apologize).

We start with a summary of the key legislation influencing the growth and direction of watershed management and a historical overview of watershed management research resulting therefrom. This will lead to a brief discussion of important lessons learned about watershed function followed by an overview on what we know about management implications.

Key Legislation

The Organic Act of 1897 defined water as one of the primary reasons for establishment of the national forests as follows: "No national forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States." This concern was reinforced by the 1911 Weeks Law that stated: "The Secretary of Agriculture is authorized and directed to examine, locate, and recommend for purchase such forest, cutover or denuded lands within the watersheds of navigable streams as in his judgment may be necessary to the regulation of the flow of navigable streams or for the production of timber." Although research has refined our understanding over the years, it is clear that early legislators recognized as a key issue the ties between forest cultural operations and streamflow.

A variety of subsequent legislation has been enacted to maintain and enhance the quality of soil and water resources on forest and other lands. Important acts for managing National Forest lands such as the Multiple Use-Sustained Yield Act, the Forest and Rangeland Renewable Resources Planning Act, and the National Forest Management Act all include protection of soil and water resources as a central theme. Additional legislation including the Watershed Protection and Flood Prevention Act, The Resource Conservation Act , the National Environmental Policy Act, the Federal Water Pollution Act, the Coastal Zone Management Act and the Clean Water Act all help to protect soil and water resources on all lands, not just forests. Last, but certainly not least, the Endangered Species Act promises to have profound effects on watershed management on all lands as well. In addition to the federal legislation, many states have adopted state forest practices acts and other laws directed at conserving soil and water resources.

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History of Forest Watershed Research

The first watershed experiment began in 1909 at Wagon Wheel Gap in Colorado. This was a comprehensive study utilizing a control and treatment watershed design to quantify the effects of deforestation on the volume and timing of streamflow, soil erosion and sediment loading (Bates, 1911). Since that time similar study designs, mostly on experimental small catchments less than 200 ha, have been conducted throughout the U.S. At their peak in 1960, there were a total of about 150 experimental watersheds scattered throughout the U.S. devoted to forest hydrology studies. This total has dwindled since that time due primarily to budget constraints and a lack of commitment to long-term watershed scale studies.

Watershed experiments are excellent for defining what happens at the catchment scale but it is often difficult to document exactly how and why. This prompted the development of studies designed to evaluate how individual hydrologic processes operate and respond to forest management activities. Process studies often involve field and/or laboratory plots designed to study basic hydrologic functions such as runoff (evapotranspiration, infiltration, subsurface and groundwater flow), erosion (surface and mass erosion) and sediment transport, nutrient cycling, function of riparian areas, etc.

Early attempts to understand and extrapolate hydrologic information led to the development of empirically based, statistical models. More recently, information gained from process and watershed scale studies coupled with the development of computers, remote sensing and geographical information systems has made it possible to create computer simulation models for watershed function and response.

Lessons Learned

Streamflow

Annual Water Yield

Questions about the role of forests in regulating water yield have been prevalent for the past century. The Wagon Wheel Gap watershed study initiated in 1909 (Bates 1911) was the first North American study to address such questions. However, it was not until the late 1930s and the introduction of statistically designed, paired watershed studies at Coweeta and San Dimas that the scope of information regarding relationships between forests and water really began to broaden. Since then, a multitude of gaged watershed studies have been conducted, spanning a variety of geographic locations, forest types, topography, climate, and forest disturbances.

The watershed studies have provided careful, long-term measurements of precipitation and streamflow, and estimates of how much water forests return to the atmosphere as evapotranspiration (ET). Studies of throughfall have allowed separation of the canopy interception component within ET. Process studies have helped to identify source areas for streamflow, and to understand how water moves through forest ecosystems. Using this background knowledge for undisturbed forests as a basis, treatments on experimental watersheds have shown how hydrologic relationships and processes are changed by disturbances such as cutting, fire, and species conversion.

Hibbert (1967) summarized the results from 39 such experiments involving treated watersheds and developed three generalizations.

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

The magnitude of the increases alluded to in the first generalization was highly variable. First-year responses to complete forest reduction ranged from 34 mm to >450 mm of increased streamflow, thus giving rise to Hibbert's third generalization.

Bosch and Hewlett (1982) updated Hibbert's (1967) review with an additional 55 studies conducted on gaged watersheds. Their findings reinforced Hibbert's first and second generalizations. However, Bosch and Hewlett (1982) felt that knowledge and explanations for the increases had reached a point where responses to forest treatments were no longer unpredictable, as expressed in Hewlett's third generalization. Bosch and Hewlett (1982) based their arguments in part on the premise that the increases could be modeled with computer simulators, and were thus to some degree understood and predictable.

Most watershed studies indicate that responses of water yield to forest treatment are dependent on amount of precipitation. Yield changes are greater under higher precipitation regimes, reinforcing Hewlett's (1967) axiom about forest increases and water yield: "It takes water to fetch water." Under similar precipitation regimes, increases in water yield are roughly proportional to percentage reduction in stand basal area, with at least a 20-30%

reduction being necessary to generate detectable increases in annual water yield (Douglass and Swank 1972, Bosch and Hewlett 1982, Hornbeck et al 1997). Coniferous forests have greater influences on water yield than deciduous forests, and species conversions from softwoods to hardwoods or grass will usually increase water yields. A number of studies have shown that water yield increases following partial cuttings are related to the configuration and / or location of the cuttings in relation to source areas for streamflow (Hornbeck et al 1993; Troendle 1983).

The duration of water yield increases is again related strongly to amount of precipitation. Increases are prolonged in drier areas because disturbed sites are slow to revegetate. In more well-watered areas, rapid revegetation often limits meaningful water yield increases to the first 3 to 5 years after treatment (Hornbeck et al 1993). Deeper soils of the southeastern U.S. seem to help sustain water yield increases (Swank et al. 1988).

Water yield studies have found widespread application in northeastern US where forested watersheds serve as sources of water for more than 1,000 municipalities ranging from small, rural communities to large urban centers such as Boston and New York (Hornbeck et al. 1993, O'Connor et al. 1995). Elsewhere in the U.S., especially in the western states, water yield continues to be an issue (Harr, 1983; Troendle, 1983) but given the increasing emphasis on environmental issues, forest management for water yield alone is not a realistic forest management goal.

There are still lessons to be learned regarding water yield from forests. In particular, there are concerns about how global climate change and continually rising levels of atmospheric CO_2 may affect species composition, transpiration rates, and water yield. Paired watershed studies which have several decades of continuous hydrologic data are proving to be valuable for addressing these questions (Hornbeck et al. 1993, Amthor and Hornbeck 1999).

Flow Distribution

Given the widely documented increases in annual water yield from forest cutting, it is clear that streamflow increases following timber harvest; the question remains as to how the flow changes are distributed.

In this discussion, we differentiate between peak flows and flood flows. Peak flows are the maximum flows resulting from a runoff event. Flood flows are those peak flows that exceed channel capacity as defined by bankfull levels. Much of the early concern was based on the assumption that forests are necessary "...to prevent destructive floods and corresponding periods of low water" (Pinchot 1947). The issue of forest cutting and floods has diminished but continues to this day. Lull and Reinhart (1972) developed a comprehensive literature review of the effects of forests on floods in the eastern U.S. They conclude that (compared to cropland, pasture and urban – suburban land) "The forest is the best of all possible natural cover for minimizing overland flow, runoff and erosion. The flood-reduction potential of the forest can be realized through continued fire protection and careful logging ¼". In this context, careful logging is defined as any silvicultural method that generates minimal compaction with a carefully designed and located road system.

Harr (1979) reviewed the results of watershed studies to evaluate the effects of forest practices on peakflows at 11 different locations along the Pacific slope. The most common cause of increased flows was wetter, more hydrologically responsive soils in the fall caused by decreased evapotranspiration losses after timber cutting. Less rainfall is needed to recharge soils under such conditions resulting in relatively large peak flow increases. Generally, storms are small during this time of year so the large flow increases are limited to the smaller flow events. Later in the fall as soil moisture differences become less important, the magnitude of peak flow differences become smaller or non-existent. It is during this time of year that large, flood producing runoff events occur so that flood flows are not likely to increase. Other possible causes of peak flow increases from forest practices were identified including soil compaction, forest road construction and differences in snow accumulation and melt rates. In general, effects tend to decrease over time as forest stands regrow. Summarizing the results of the reported studies, Harr (1979) concludes: "Taken collectively, results of watershed studies indicate that size of peak flows may be increased, decreased, or remain unchanged after logging. Whether or not a change occurs depends on what part of the hydrologic system is altered, to what degree, and how permanent the alteration is." Subsequent studies on both small watersheds (Harr 1986; Wright et al. 1990; Thomas and Megahan 1998) and larger river basins (Duncan 1986; Storck et al. 1998) suggest that Harr's 1979 conclusions for Pacific Slope basins still apply.

Troendle et al. (1998) studied effects of timber harvest on the Coon Creek watershed in the snow zone of Wyoming. They found that the highest flows in this 1.7 km^2 basin were not significantly increased although the duration of the higher, near bankfull discharges was extended. The authors report that findings at Coon Creek support and are comparable with documented observations on smaller, experimental watershed studies elsewhere in the snow zone.

Natural disturbances, especially wildfire, may affect peak flows. Light forest burning has no effect on flood flows in the eastern U.S. (Lull and Reinhart 1972) but intense wildfire can increase flood flows by up to two orders of magnitude, especially on steep forest lands in the western U.S. (Bolton and Ward, 1987). Increased soil water repellency resulting from the intense burning is suggested as an important factor leading to the increased flood flows.

Even if flood flows were to increase on small watersheds, for example as a result of intense wildfire, the chances of detecting the effects in large river basins diminishes because of increased channel storage along larger streams. Chow (1964) states: "A distinct characteristic of small basins is that the effect of overland flow rather than the effect of channel flow is a dominating factor affecting the peak runoff. Also, small basins are very sensitive both to high-intensity rainfalls of short duration and to land use. On large basins, the effect of channel storage is so pronounced that such sensitivities are greatly suppressed."

If flood flows aren't likely to increase following timber harvest, then lower flows must if water yields are to increase. Most increases in water yield occur at low flow levels, or as augmented baseflow or delayed flow. Furthermore, the yield increases tend to occur primarily in the growing season when they are most beneficial for aquatic biota, recreational activities, and water supplies. This is because the difference in soil water storage at this time of year is the greatest due to reduced evapotranspiration demands. (Hornbeck et al. 1997). Although flood flows do not tend to increase, several researchers point out that increases in the duration of flows near bankfull may lead to bank and bed erosion problems in channels that are susceptible (Troendle et al. 1998; Van Haveren 1988).

As the above discussion suggests, we have learned many lessons over the years about the relationships between forests and water. New and interesting findings continue to crop up from gaged watershed studies, but the ample, existing knowledge is being widely used to incorporate streamflow considerations into management activities. This is being done by direct application of the appropriate literature, or by use of computer models of hydrologic cycles for forests such as BROOK90 (Federer 1995), OWLS (Chen and Beschta 1999) and DSHVM (Storck et al. 1998). Such models allow managers to simulate changes in streamflow resulting from different management and harvesting activities.

Erosion

Erosion is a normal geologic process that varies over time in response to changing climatic and site conditions. Erosion rates are usually minimal on undisturbed, forested watersheds. However, both surface and mass erosion can and does occur under such conditions. Forest disturbance, either natural (e.g., extreme storm events, wildfire) or human caused (e.g., timber harvest, road construction) can increase erosion rates, sometimes to extreme levels.

Surface Erosion

Surface erosion is the movement of individual soil particles by a force such as raindrop impact or overland flow and is described as interrill, rill or gully erosion depending on the degree of concentration of surface flow. Surface erosion is an issue on agricultural lands because of concerns about long term site productivity. In the past, site productivity has not been an issue on forest lands primarily because cutting rotations extend for many years. However, long term site productivity is becoming an issue on forest lands as forest practices intensify, particularly in the southeastern U.S.

Considerable effort has gone into the development of empirical studies to predict surface erosion over the years. Most notable was the development of the Universal Soil Loss Equation or USLE (Wischmeier and Smith 1978) and its iterations (Renard et al. 1991; Williams 1975) for application on agricultural and range lands. The USLE has been adapted for application on forest lands in the southeast U.S. (Dissmeyer and Foster 1985). Subsequent research has led to the development of additional empirical and process based models to predict surface erosion on forest land (Elliot et al 1996) and on forest roads (Tysdal et al. 1997; Cline et al. 1981, Ward 1985). Except for locations where intensive site preparation practices are used (presently confined to some sites in the southeastern U.S.) studies on forest land show that surface erosion following logging is confined to severely disturbed and compacted areas and thus is limited to skid trails, log landings and roads (Martin 1988; Megahan and Kidd 1972). A variety of Best Management Practices (BMP's) have been devised to cope with surface erosion from timber harvest activities (National Council of the paper industry for Air and Stream Improvement [NCASI] 1994; Martin and Hornbeck 1994).

Mass Erosion

Mass erosion is the movement of a group of soil particles en masse in response to gravitational force. Landslides are classified as either shallow (debris flows, avalanches and torrents) or deep seated (slumps and earthflows) depending on the nature of the slope failure process. Because of the strong influence of gravity, landslides occur most often on steep terrain, generally in excess of 30 degrees for the shallow types of slides. In such areas, mass erosion is usually the dominant erosion process for supplying sediment to streams.

Forest cutting has been shown to increase the risk of shallow landslides by reducing root strength and increasing soil water contents (Sidle et al. 1985). Most studies have relied on the use of aerial photos to identify slide activity on cut vs. uncut forest slopes. A recent study used a detailed field inventory to show that many of the earlier studies are biased because slides are often impossible to identify on aerial photos of uncut forest slopes (Robison et al. 1999). GIS based models to evaluate the topographic risk of shallow landslides provide a way to assess risks of timber cutting in landslide prone terrain (Montgomery and Dietrich 1994; Pack et al. In press).

Effect of Roads

Roads have been shown to be particularly problematic for erosion, especially in mountainous areas, because of exposure of erodible soil and subsoil by construction, reduced infiltration on the road surface, increased gradient on cut and fill slopes and concentration of overland flow from precipitation excess and interception of subsurface flow. Megahan and Kidd (1972) working on granitic soils in Idaho, showed that unit area rates of erosion were increased by an average of 1.6 times by cable logging. Road construction in the study watersheds increased unit area erosion rates by an average of 220 times as the result of surface erosion and an additional 550 times as the result of mass erosion over the 6 year study period. Numerous other studies have documented the potential severity of surface erosion (McCashion and Rice 1983; Swift 1984; Reid and Dunne 1984) and mass erosion (Megahan et al 1979; Robison et al. 1999; McClellend et al. 1996) on forest roads. A variety of BMP's have been developed to reduce surface erosion on road cut and fill slopes, on the road tread and in road ditches (Megahan 1977; Burroughs and King 1989). Mass erosion on forest roads can be reduced by avoiding high hazard areas and/or by careful road design, construction and maintenance.

Natural Events

Natural events, such as large storms, earthquakes, and especially wildfire, can have a profound effect on both surface and mass erosion. By increasing soil saturation at slope locations that are normally unsaturated, large storms can trigger shallow landslides and accelerate the movement of deep seated landslides even on undisturbed forest lands (Robison et al. 1999). Normally, surface erosion is not increased by large storm events except on disturbed areas where mineral soil is exposed. Wildfire can greatly increase risks for both surface and mass erosion depending on the intensity of the fire (Connaughton 1935; Benda and Dunne 1997a). Very intense wildfires greatly increase surface erosion potentials by consuming organic materials that protect the soil surface and retard runoff and by creating soil water repellency that leads to overland flow. Increases in annual sediment yields of 2 to 3 orders of magnitude can occur from a single storm following severe wildfire on steep forest lands in the western US (Schultz et al. 1992; Moody and Martin 1999). Severe wildfire also increases landslide activity. A recent study by Benda and Dunne (1997a) shows that severe wildfires were a major cause of landslides on prehistoric landscapes in the coast range of Oregon.

Sedimentation

Sedimentation is the complementary natural process to erosion. It includes the transfer of eroded materials downslope to streams and downstream through the drainage system. Because of storage en route, on-site surface erosion does not equate to downstream sediment yield. Differences between watershed erosion and sediment yields, often quantified using a delivery ratio, account for the effects of long term sediment storage at different points in the watershed.

Increased sedimentation can cause a variety of environmental problems. The Environmental Protection Agency (US EPA 1992) found that sedimentation impairs a greater length of streams than any other type of pollutant including nutrients, pathogens, pesticides and organic enrichment and dissolved oxygen. On forested watersheds, concern for sedimentation is often keyed to fishery values. At high concentrations, suspended sediments can damage the gills of aquatic insects and fish. Bedload sediments can be of particular concern because of the potential for interference with both fish spawning and rearing success. In addition, fine organic sediments and clay sized lithic sediments may act as vectors for downstream transport of adsorbed pollutants such as pesticides, organic chemicals, radio nuclides, or heavy metals.

Sediment Delivery from Surface Erosion

Much of the sediment resulting from surface erosion on harvest areas and roads does not reach the stream channel network because of deposition on the slope below. Sediment from diffuse sources, such as a timber cutting unit or a road fill, moves very short distances if there are no concentrated sources of runoff. Megahan and Ketcheson (1996) found that sediment travel distance averaged about 6 meters for road fills where runoff originated only from the road fill. Sediment from concentrated runoff sources such as road cross drain culverts traveled much further, averaging about 53 meters. Sediment travel distance below road cross drains has been shown to vary with a number of site characteristics such as obstructions on the slope below the road, amount of road runoff, volume of erosion, and gradient of the slope below the road (Packer 1967; Swift 1986; Megahan and Ketcheson 1996). The volume of sediment deposition decreases exponentially downslope so that most of the sediment is stored nearest the source. Ketcheson et al. (1999) found that only about 4 percent of the material removed by surface erosion on forest roads in Idaho was delivered to streams over a 4 year period following construction. Surface erosion is selective to the smaller soil particles so sediment produced therefrom consists of silts and clays and some sands.

Sediment Delivery from Mass Erosion

Sediment delivery to streams from mass erosion tends to be higher than that from surface erosion. Debris-avalanche types of slides are usually located in areas of water concentration at the heads of steep drainages and follow the drainage path down into the lower channel system. Megahan et al. (1979) reported an average of 23 percent of the sediment volume from 629 landslides was delivered to streams over a three year period on the Clearwater National Forest in Idaho. More recent studies in the same area reported an average of about 50 percent delivery from a total of 905 landslides as the result of large storms in 1995 and 1996 (McClelland et al. 1997). Work by Benda and Cundy (1990) and Ward (1994) show that slope gradient below the slide, tributary junction angle, distance from stream, and landslide length all influence landslide delivery to streams. Unlike the fine materials supplied to channels from surface erosion, the particle size distribution of sediment delivered to streams can range from clay to boulders. Landslide activity is not necessarily detrimental. Benda and Dunne (1997b) show that sediments supplied from landslides following wildfires in the coast range of Oregon are essential to the long term maintenance of aquatic habitat in the channels.

Sediment Transport in Streams

Small sediments less than about 0.06 mm (silt) size tend to move relatively rapidly through the channel system as wash load. These fine sediments are a major factor influencing turbidity. Larger sediments move as bed material load and can have short to long residence times in the channel system depending on particle size. Bunte' and MacDonald (1998) made a comprehensive review of the literature dealing with sediment transport distance as a function of particle size. Travel distance for suspended load (wash load plus some sands) ranges from 2 to 20 km / year whereas bedload consisting of pebbles and cobbles travel only 0.02 to 0.5 km / yr. For low gradient channels such as those found in portions of the Lake states and the southeastern US, residence times for sands can range from 50 to 100 years (Dissmeyer 1976; Trimble 1981; Phillips 1993) Studies in the western U.S. show sediment storage times within the active stream channel ranging from 5 to 100's of years depending on particle size and the type of sediment deposit (Megahan et al. 1980; Madej and Ozaki 1996; Ziemer et al. 1991).

Sedimentation Cumulative Watershed Effects

The issue of cumulative watershed effects was first defined in the National Environmental Policy Act in 1969. Considerable debate ensued regarding the definition of cumulative effects. A definition by Reid (1993) summarizes the common elements of several definitions: "¼ a cumulative effect is any environmental change influenced by a combination of land-use activities." Given this definition, sedimentation cumulative effects are a distinct possibility, for example because of the potential for long residence time of bedload sediments.

The South Fork of the Salmon River in Idaho provides an excellent example of sedimentation cumulative effects. Logging in the 1950s and early 1960s was done on steep, granitic soils with little knowledge of the potential for accelerated erosion that existed in the area. Sediments began to accumulate in tributary channels as timber harvest spread to more areas. Large storm events in 1964 and 1965 flushed new and accumulated sediments into the river channel causing severe sediment deposition on valuable salmon spawning and rearing habitats. In this case, sediment deposits were almost entirely surface sands most of which was flushed out of the system within 5 years after the cessation of continued soil disturbance and a road rehabilitation program (Megahan et al. 1980). Longer duration sedimentation cumulative effects were found on Redwood Creek in California. Madej and Ozaki (1996) measured channel changes following extensive sediment deposition as the result of widespread timber harvest and road construction combined with a series of large floods. Their studies documented the occurrence of a large sediment wave in the lower 26 km of the gravel bedded river that is moving downstream at a rate of 800-1600 m / yr.

The sedimentation cumulative watershed effects (CWE) cited above are extreme examples that would be easily recognized by even the casual observer. Unfortunately, most sedimentation CWE are much more difficult to detect. Bunte' and MacDonald (1999) provide a comprehensive review of the literature of factors affecting the detectability of sedimentary CWE. Considering the effects of spatial and temporal scale and the problems of measuring sediment transport, they conclude *"Taken together, these factors suggest that we should not expect to detect less than a twofold change in sediment transport rates or sediment yields. Changes in measurement techniques, calculation procedures, or the period of comparison can create the appearance of a sedimentary CWE when none actually exists. The inherent spatial and temporal variability suggests that at least 5-10 years of both pre- and post-monitoring are likely to be necessary to reliably detect a sedimentary CWE."*

In lieu of measuring sediment transport or sediment yields, MacDonald et al. (1991) describe a series of channel response indicators that can be used to help assess sedimentary CWE. Sediment budgeting also provides a means to avoid many of the problems described by Bunte' and MacDonald (1999). A sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin. Techniques have been developed to conduct sediment budgets for purposes of evaluating sedimentary CWE (Reid and Dunne 1996).

Water Quality

Water quality has long been a part of gaged watershed studies. As suggested by the earlier discussion, sediment (or turbidity as an index of sediment) has usually been the water quality parameter of most interest, followed by temperature. In the 1960s it was recognized that gaged watersheds were also a good tool for studying nutrient cycling, impacts of introduced chemicals (e.g., atmospheric deposition, fertilizers, and pesticides) and water temperature.

Nutrient Cycling

Nutrient cycling studies on gaged watersheds began at Hubbard Brook Experimental Forest in 1963 and gradually became important additions to watershed studies at many other locations. This broad holistic approach to paired watershed studies led to the introduction of the term "watershed ecosystem analysis" (Hornbeck and Swank 1992).

The basic premise of watershed ecosystem analysis is that the many physical, chemical, and biological processes occurring within an ecosystem are interrelated. This approach attempts to understand these processes and to attach values to pools and fluxes of the chemical parameters in question. These pools and fluxes become the basis for assessing impacts of human-related or natural changes. Watershed ecosystem analysis can thus be used to evaluate how individual or combinations of uses might affect nutrient cycles and, in turn, the health and productivity of forest ecosystems, or the chemistry and biota of forest streams.

Nutrient leaching from forests to streams is affected by various factors including mineral weathering, soil and hydrologic characteristics, vegetation, climate, biological processes, and natural and human disturbances. Most studies have shown that forests free of recent disturbances have relatively "tight" nutrient cycles and that baseline concentrations of nutrients in forest streams are low. Thus nutrient concentrations are seldom an issue in terms of water quality, but they are an important consideration regarding stream biota and watershed nutrient capitals (Hornbeck et al. 1997).

One of the earliest applications of watershed ecosystem analysis was to help resolve the controversy caused by the increasing use of clearcutting during the late 1960s and early 1970s. There was widespread concern that clearcutting would increase nutrient concentrations in streams and deplete forest nutrient capitals (Horwitz 1974). A number of studies using watersheds showed that clearcutting would indeed increase both nutrient concentrations in streams and losses to leaching. Base cations and nitrate were the most susceptible. However, in all cases involving commercial harvests, the changes were short lived and of little significance to stream biota, water quality standards, or forest nutrient capitals (Hornbeck et al. 1987; Johnson et al. 1987; Saliman and Beschta 1991).

Watershed ecosystem analysis has played an important role in studies of atmospheric deposition. Studies in the eastern US have shown that acidic deposition can lower the pH of forest streams and mobilize inorganic aluminum to levels that are toxic to aquatic biota (Cronan and Schofield 1990). Strong mineral acids in precipitation can cause depletion of base cations in forest soils, and in certain situations may affect forest health and productivity (Cronan and Grigal 1995; Shortle and Smith 1988; Federer et al. 1989). Studies are in progress using acidifying chemicals applied to whole watersheds to mimic but hasten effects of acid precipitation on soils, streams, and plants (Adams et al. 1993; Rustad et al. 1996). These studies are intended to accelerate the development of strategies for controls and mitigation of atmospheric deposition, and thus protection of forest and aquatic ecosystems.

Due to temporal variations in weather and wet and dry deposition, watershed ecosystem analysis is inherently long term. Some parameters must be measured for decades to define variability. However, long-term data on nutrient concentrations of streams, some of which now spans 30 or more years, have proved of great value in studying trends related to forest succession and atmospheric deposition. For example, Driscoll et al. (1989) found that controls of sulfur emissions mandated in the 1970s have led to a gradual decline in sulfate concentrations of forest streams of the Northeast.

Introduced Chemicals

Norris et al. (1991) provided a thorough review of the extensive information regarding impacts of other introduced chemicals (including pesticides, fertilizers, and fire retardants) on water quality and aquatic ecosystems. The review points out that direct toxic effects of chemicals on aquatic organisms are major concerns, but that forest chemicals may also have indirect effects on aquatic ecosystems at concentrations much lower than those observed to cause mortality. The authors suggest that potential effects of forest chemicals must be evaluated on the basis of four factors: (1) changes in aquatic communities caused by forest chemicals, (2) subsequent changes in other communities of aquatic organisms, (3) alteration of terrestrial systems that influence aquatic ecosystems, and (4) effects on patterns of recovery in watersheds that have already been altered by logging or fire.

NCASI (1999) has summarized responses of stream water chemistry to forest fertilization. The results show that the most commonly occurring effect from fertilization is an increase in peak concentrations of nitrate in stream water. However, the increases remain within drinking water standards, and increases in average concentrations are much less than those in peak concentrations.

The processes by which chemicals reach streams include direct application, drift from nearby treatments, and mobilization of residues in ephemeral stream channels during the first storms after application (Norris et al. 1991). Margins of safety can be calculated for fish based on maximum acute and short-term chronic exposures likely to occur when applying forest chemicals (Norris et al. 1991). Streams are 5-10 times less likely to be affected when they are not in treated areas, when buffer strips are used along streams, and when full attention is given to preventing drift and direct application to streams.

Water Temperature

The temperature of aquatic systems greatly influences fish production, recreational use, and value for water and temperature changes can be detrimental or beneficial depending on local conditions. Early studies suggested that the principal source of heat for streams draining forests is solar energy striking directly on the surface of the stream (Brown 1980). Thus shade from overhanging vegetation is an important factor regulating the temperature of streams. In some situations other factors regulating stream temperature including groundwater inflow, evaporation and condensation and conduction from air and streambed are also important. Stream temperatures normally exhibit fairly predictable annual, seasonal and daily variations. Spatial variations also occur with a general tendency for temperature increase from headlands to lowlands even under mature forest conditions (Sullivan et al. 1990). Coniferous forests generally provide greater shade than deciduous forests and thus have lower stream temperatures. Elimination of stream shading by harvest or fire can increase maximum daily stream temperatures up to 10^0C (Lynch et al. 1975; Beschta et al. 1987). Streams from exposed areas cool when flowing through shaded areas primarily due to inflow from cool groundwater and cooling from ambient air temperature. Channel length required for the stream to return to its characteristic temperature signature can be as little as 150 meters depending on channel properties (Zwieniecki and Newton 1999).

In summary, considerable information exists about the relationships of forests and water quality. Much of this information has been synthesized and passed to managers in the form of BMPs and monitoring guidelines (MacDonald et al. 1991).

Management Implications

The bottom-line lesson is that nearly everything that happens on forested landscapes has some effect, ranging from very minor to very major, on the volume, quality, and timing of streamflow and the habitat characteristics of streams. As our discussion suggests, much is known about the various linkages between forests and streams. The challenge is to incorporate this knowledge into management practices. This will be easiest when pertinent site specific information is available about rates of the various contributions from forests to streams. But in the absence of or in combination with site-specific information, computer models are rapidly improving as a tool that can be used for indicating the effects of various management options.

It is important to consider the role of riparian areas. A properly designed and managed riparian area can provide a variety of amenities and still protect against stream temperature changes, assure a continuous supply of large woody debris and organic matter, absorb nutrients, sediment, and water from upslope, and maintain a diversity of species composition. However, the protective capabilities of riparian areas must be supported by careful management of forests both within and outside the riparian area.

In the case of harvesting disturbances, application of BMPs is essential. It has been shown time and again that BMPs can protect soil and water resources. Beyond BMPs it is helpful to think in terms of long-term cumulative effects. That is to answer the question — “Will the combined effects of multiple disturbances over space and time still result in acceptable watershed performance?”. In this case, watershed performance includes not only the more traditional goals of regulating streamflow quantity, timing and quality, but also the broader concepts of maintaining ecosystem and aquatic habitat integrity as well. Assessment and management of cumulative effects requires linking cause and effect in order to be effective. Establishing such linkages may be difficult and time consuming given natural spatial and temporal variability and the effects of major episodic events that can totally “reset” established watershed processes. There is no easy answer to cumulative effects issues; simple indicators such as acres of harvest areas or road density do not suffice as either assessment or management tools.

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