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Impacts of Forest Management on Water Quality

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Introduction

In forested catchments the hydrologic cycle, involving precipitation, interception, evapotranspiration, overland flow, subsurface flow, groundwater flow, and stream flow (**Figure 1**) is closely linked to water quality in that water movement through the forest ecosystem also transports sediment, and dissolved nutrients, as well as fertilizers, and pesticides if they are present. Understanding relationships between forested ecosystems and quality of surface and subsurface water associated with these systems is a key component of sustainable forest management because changes in water quality may result from forest management practices. These changes can reflect either positive or negative outcomes of forest practices. For example, logging road construction and harvesting of timber with improper consideration for erosion control can cause increased sedimentation of stream water and a degradation of water quality. In contrast, conversion from agricultural crop production to forestland can improve water quality by decreasing erosion rates and creating long-term storage pools (e.g., forest floor, woody biomass) for carbon and nutrient retention. This article provides a synthesis of our current thinking regarding (1) the concept of water quality, (2) the role of forested watersheds in providing water of relatively high quality, and (3) commonly evaluated water quality parameters and potential effects of forest practices on these parameters. The primary focus is on the relationship between water quality characteristics of streams draining forested watersheds and forestry practices. Where information is available, effects of forestry practices on groundwater quality are also addressed.

Water Quality: The Concept

The concept of water quality is largely based on value judgments developed in relation to the beneficial or intended use of the water resource of interest. For example, water quality standards – comprising selected physical, chemical, and biological characteristics of water (**Table 1**) – developed for domestic use are likely to be different from water quality standards developed for other beneficial uses such as recreation, habitat for aquatic biota, or irrigation. As such, water quality standards are relative values that are dependent on the intended use of the water. The key to assessing whether or not change in a water quality parameter is a pollutant concern depends on its impact on beneficial uses.

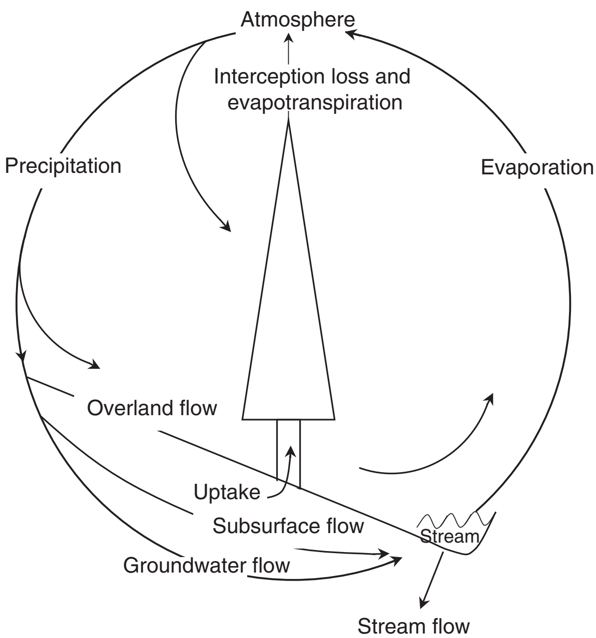

Figure 1 The hydrologic cycle for a forest. Adapted with permission from Brown GW (1988) *Forest and Water Quality*, Corvallis, OR: Oregon State University.

In cases where water quality is diminished because of anthropogenic influences, then pollution of the water resource has occurred. However, water quality can also be degraded by natural phenomena such as wildfire, volcanic eruptions, earthquakes, hurricanes, floods, and landslides. It is therefore important to consider anthropogenic influences on water quality in the context of the natural variation that is characteristic of water quality parameters. At times, changes in water quality resulting from natural causes can overwhelm effects of land use practices. Examples of this natural variation are provided by landslides, which often dramatically increase sediment loads in streams or by severe wildfires, which can also increase sediment loads as well as nutrient concentrations in stream water.

Importance of Forests for Water Quality

Water draining from undisturbed forested watersheds is generally of the highest quality, particularly with regard to beneficial uses including drinking water, aquatic habitat for native species, and contact recreation. A survey of the literature shows consistent patterns of relatively high water quality draining forested catchments in comparison to other land uses such as agriculture or urbanization (**Figure 2**). Recognition of the relative role of forests for providing water supplies of the highest quality has

Table 1 Commonly measured water quality parameters in forested watersheds

Parameter	*Influence on water quality*
pH	Influences chemical and biological reactions; toxic at extreme high or low values
Acidity	Capacity to neutralize base; affects chemical and biological reactions
Alkalinity	Capacity to neutralize acid; affects chemical and biological reactions
Conductivity	Estimate of total dissolved solids
Suspended sediment	Restricts sunlight and photosynthesis; smothers benthic communities; covers spawning gravels
Turbidity	Measure of water clarity; often surrogate measure for suspended sediment
Dissolved phosphorus	Essential nutrient; excess can cause eutrophication
Dissolved nitrogen	Essential nutrient; excess can cause eutrophication; forms can be toxic to stream biota and humans
Dissolved oxygen	Required for aerobic metabolic processes; affects chemical reactions
Temperature	Affects dissolved oxygen and metabolic processes
Biochemical oxygen demand	Measure of decomposable organic loading in water
Pathogenic bacteria and protozoa	Potential human health hazard
Pesticides	Forms can be toxic to stream biota

Figure 2 Undisturbed, forested watersheds generally produce outstanding water quality.

been one of the driving factors for establishment of forest reserves and for development of forest management practices designed to protect this high quality.

In some cases forest management activities such as road construction, harvesting, site preparation for regeneration of forest tree species, and fertilization of existing forests have been shown to alter water quality, primarily by causing changes in sediment loads, stream temperature, dissolved oxygen, and dissolved nutrients, particularly nitrogen. Fortunately, the wealth of literature addressing forest management impacts on water quality reports that, if impairment of water quality resulting from forestry practices is observed, it is relatively short-lived, diminishing rapidly as vegetation is re-established, and occurs at infrequent intervals because forest practices on a given site may only occur once or twice during a forest rotation (i.e., several years for intensively managed, fast-growing trees in the tropics to several centuries for unmanaged forests in areas of low productivity).

Effects of Forestry Practices on Water Quality

Suspended sediment, turbidity, stream water temperature, dissolved oxygen, and dissolved chemicals including nutrients and pesticides are the most studied characteristics of streamwater in relation to effects of forestry practices. Biological characteristics including pathogenic bacteria and protozoa in surface water have also received attention in forested watersheds because of their potential to impair human health and restrict water use. Other constituents that are commonly assessed for water quality characterization but have received less attention in relation to forestry practices to date include biochemical oxygen demand (an index of the oxygen-demanding properties of biodegradable material in water), pH, acidity, alkalinity, and conductivity (**Table 1**). The following subsections discuss (1) erosion and resultant sedimentation, (2) water temperature and dissolved oxygen, (3) dissolved nutrients in relation to nutrient cycling and fertilization, (4) application of pesticides, and (5) pathogenic microorganisms and their impacts on water quality in response to forestry practices.

Suspended Sediment

In general, forest lands produce very low sediment yield compared to other rural land uses (e.g., cropland). In many cases, much of the sediment observed in streams draining forested watersheds is the result of geologic weathering and erosion that are natural processes. Stream channels (including the stream banks) are also an important natural source of suspended sediment and are probably the dominant contributor of suspended sediment in undisturbed forested watersheds (unless in geologically unstable terrain prone to landsliding). For example, concentrations of suspended sediment measured during storm events may result from redistribution of sediment previously stored in the streambed or from the collapse of an unstable section of the stream bank. Nevertheless, excessive suspended sediment loads in streams are the major water quality concern for forest management because poorly planned forest management activities on hillslopes or in the vicinity of the stream channel that cause erosion can add to naturally derived levels of suspended sediment.

Increases in suspended sediment levels resulting from erosion and soil mass movement (i.e., landslides) can degrade drinking water quality, detract from recreational values, decrease stream depth, fill pools in the stream channel, increase stream width, and cause sedimentation of gravel beds which lowers their permeability and degrades their habitat quality for spawning fish (**Figure 3**). Furthermore, large accumulations of fine sediment can restrict sunlight and smother benthic communities thereby disrupting the aquatic food chain. Sediment also increases turbidity

Figure 3 Landslides and debris flows can cause downstream sedimentation.

Table 2 Factors commonly affecting rates of erosion in forested watersheds

Factor	*Characteristic*
Climate	Timing, intensity, duration, form of precipitation
Site	Forest floor composition, structure, depth
	Soil water content, infiltration capacity, texture, structure, depth
	Slope length and gradient
Vegetation	Composition, structure, age
	Rate of interception, evapotranspiration
Forestry practices	Road construction and maintenance
	Skid trail construction
	Mechanical site preparation
	Prescribed fire

and carries nutrients and anthropogenic chemicals (i.e., pesticides) that can degrade water quality.

Responses of suspended sediment concentrations are a function of the effects of climate, site characteristics, and forest practices on soil erosion (**Table 2**). More specifically, climate influences erosion rates through its effects on timing, quantity, intensity, and form of precipitation. Climate also affects erosion indirectly through its influence on soil properties and plant communities. The interaction between rainfall intensity and soil infiltration capacity plays a major role in controlling runoff. Soils with high infiltration capacities rarely have surface runoff and subsequent high rates of soil erosion unless rainfall intensity exceeds infiltration capacity. In most cases, forest soils have infiltration capacities in excess of common rainfall intensities, and therefore, surface runoff and erosion are often relatively insignificant in undisturbed forested catchments.

The interaction between rainfall and infiltration capacity is further modified by the composition and structure of the vegetation through its effect on transpiration, interception of precipitation, and resulting soil moisture. Vegetation also contributes organic matter through deposition of litter to the forest floor which provides a protective layer above the mineral soil surface. Plant roots help stabilize soil to further minimize soil erosion and soil mass movement. Additional factors affecting erosion rates and subsequent delivery of sediment to stream channels include slope length and steepness, and stream drainage density. Erosion rates are highest on long, steep slopes and delivery of sediment to stream channels is more probable (i.e., high sediment delivery ratio) where stream drainage density is high.

Even in forested watersheds that are not subjected directly to human disturbances, erosion rates are often highly variable both spatially and temporally. Natural events such as large storms, landslides, and fires can cause dramatic elevation of suspended sediment that exceeds water quality objectives. This natural variability is an important consideration in ascertaining the effects of forest management on suspended sediment.

Timber harvesting Accelerated erosion caused by forestry practices such as road construction, logging operations, and intensive site preparation can cause increased levels of suspended sediment as demonstrated by reports from timber producing regions worldwide. As such, excess sediment in streams is the most widespread water quality concern associated with forest management. Removal of vegetation and disturbance of soil, two activities that are inevitable at some level during forest harvesting, are driving factors that promote the erosion process. If mineral soil is exposed to rainfall through removal of the forest floor via machine disturbance or fire, then surface erosion can occur through detachment of unprotected soil particles and degradation of soil surface structure.

There is general agreement in the literature that forest road networks and skid trails developed to extract timber are the greatest threat to water quality because they are frequently a source of erosion and sedimentation. Compacted surfaces of logging roads and skid trails reduce infiltration and often carry surface runoff and suspended sediments during storms (**Figure 4**). The amount of sediment delivered to streams is often (1) proportional to the density of logging roads and skid trails within a watershed and (2) inversely proportional to the time since road and skid trail construction. Erosion rates are generally highest immediately after road construction and at times when roads are used during wet conditions. Water reduces frictional resistance and cohesion between soil particles making it much easier to

Figure 4 Improperly designed logging roads are often the source of increased levels of suspended sediment in streams.

dislodge soil particles via mechanical action of traffic on wet roads. These dislodged particles are immediately available for suspension and transport. Compaction and concentration of flow in tire ruts created in wet conditions can also concentrate flow and accelerate erosion on road surfaces. As roads age and vegetation becomes established, erosion rates decline. Therefore, minimizing the density of these disturbances through planned road and skid trail systems, followed by rapid revegetation of disturbed surfaces, which are not required for continued access, are likely to minimize stream sedimentation. Additional techniques commonly used to reduce road erosion and stream sedimentation include surfacing the road with gravel, decreasing the spacing of cross drainages, avoiding stream crossings, locating the road farther from streams to minimize direct drainage of roadside ditches into the stream, and limiting road gradients (*see* **Harvesting:** Roading and Transport Operations).

Soil mass movement such as landslides and debris flows can be triggered by improper road construction that disrupts drainage patterns and concentrates water flow under conditions of high rainfall in steeply sloped terrain. In cases where soil mass movement occurs, sediment delivery to streams far exceeds that from surface erosion and can cause extremely high levels of suspended sediment.

Increased sediment yields have also been noted as a result of ditching to provide drainage of peatlands and mineral soil wetlands. Drainage of these wetland soils is commonly utilized for commercial forest production and resulting changes in runoff as a result of drainage often increase sediment delivery to streams.

Soil disturbances and erosion caused by moving logs from the stump to a loading area vary with the type of skidding and yarding equipment. The most soil disturbance generally is caused by crawler tractors, followed by wheeled skidders. Cable logging systems are more expensive than ground-based systems but result in less soil disturbance because machinery is not traversing the site. Helicopter and balloon logging systems generally cause the least soil disturbance but are often prohibitively expensive for most operations. Logging systems designed to minimize compaction and disturbance of the forest floor generally result in minimum sediment delivery to streams.

Studies have shown that clear-cutting sites without the use of skid trails to transport trees to loading areas does not cause significant increases in sediment yield via surface erosion. In timber harvesting operations, contributions of felling, limbing, and bucking of trees do not contribute directly to sediment levels in streamflow because these activities do not often expose the mineral soil surface. However, clear-cutting often leads to greatly increased water yield and thus to the potential for enhanced streambed and bank erosion.

Increases in sedimentation from timber harvesting are commonly short-lived. Revegetation usually minimizes continued soil loss at rates first observed after the disturbance. Speed of revegetation is variable, depending on harvesting intensity, site preparation for re-establishment of trees, soil properties, and climate. In most studies, if elevated concentrations of suspended sediment are observed after logging activities, they return to preharvest levels within 1-5 years.

Fire Forest management practices sometimes utilize prescribed fire to control vegetation, reduce fuel loads, or to prepare sites for replanting after harvesting. Effects of fire on erosion and sediment yield are directly related to fire severity and degree to which the forest floor is consumed. Low-severity fires that do not completely remove the organic layer of

Figure 5 Surface erosion occurring after a severe forest fire.

the forest floor often do not cause significant increases in erosion and sedimentation. However, if fire severity is sufficient to remove the protective litter layer of the forest floor, thereby exposing mineral soil to raindrop impact, then increased erosion and sedimentation are likely (**Figure 5**). An additional concern that often causes accelerated erosion after fire is development of water-repellent hydrophobic layers in the soil surface that impede infiltration. Increases in suspended sediment after fires are most pronounced in steep watersheds with severe fires. Finally, fire lines that are established by bulldozers to control the spread of fire can be potential sources of sediment in streams. If fire lines are established under emergency circumstances, concerns for proper planning, avoidance of sensitive areas (i.e., very steep or excessively wet), and erosion control are not always paramount and accelerated erosion and sedimentation may result.

Temperature and Dissolved Oxygen

Water temperature is a key water quality parameter because of its direct effect on chemical and biological processes and properties in the stream. It is also a determinant of the amount of dissolved oxygen available for aquatic fauna (**Figure 6**). Solubility of oxygen decreases rapidly with rising temperature. Increases in water temperature generally accelerate biological activity and place greater demand on dissolved oxygen. Metabolism, reproduction, and other physiological processes of aquatic biota are controlled by heat-sensitive proteins and enzymes. A 10°C increase in temperature will roughly double the rate of many chemical reactions and the metabolic rate of cold-blooded organisms. Furthermore, the inverse relationship between water temperature and

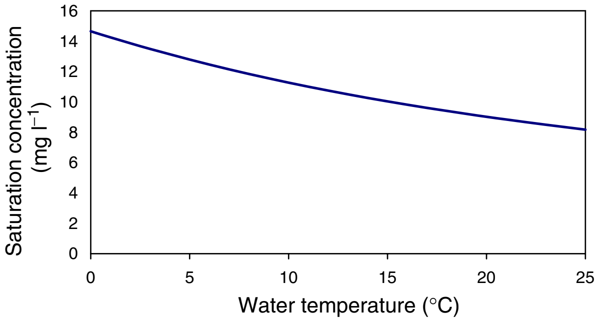

Figure 6 Solubility of oxygen as a function of temperature.

dissolved oxygen exacerbates the consequences of increased temperature. As such, temperature has a strong influence on composition of aquatic communities and maintaining stream temperature is a primary concern to many forest land managers.

Clearing of riparian vegetation is the primary forest management practice that can cause elevated stream temperature, particularly in small headwater catchments. This is the result of increased stream exposure to direct solar radiation. Temperature increases of as much as 15°C have been observed in forest streams when riparian vegetation has been removed. However, the magnitude of the response is tempered by stream discharge, streambed characteristics, channel morphology, stream surface area, and degree of hyporheic exchange and groundwater influx along the stream length. For example, streams with high degrees of hyporheic exchange and/or groundwater inflows may have less of a temperature increase when exposed to direct solar radiation.

Maintaining shade in riparian zones by retention of riparian buffers is a management practice that can be used to avoid most temperature increases in small streams. The key consideration in maintaining stream temperature is to maintain shade conditions that do not alter direct solar radiation from that of undisturbed conditions. However, as stream width increases, more of the water surface is exposed to direct sunlight and the influence of riparian canopy on stream temperature decreases.

Maintaining stream temperature at levels observed in undisturbed conditions is vital for aquatic organisms because of their dependence on dissolved oxygen. Use of streamside buffers to protect from temperature changes will also generally protect streamwater from corresponding changes in dissolved oxygen. However, dissolved oxygen is a function of its solubility in water (largely temperature driven) as well as the balance between oxygen consumption (e.g., respiration, decomposition) and oxygen replenishment (e.g., photosynthesis of aquatic plants, turbulent mixing of streamwater). Levels of dissolved oxygen are influenced by chemical oxidation of organic matter and decomposition of organic matter by aquatic microorganisms. Thus, addition of nutrients and logging debris to streams in response to logging practices has the potential to increase oxygen demand through increased decomposition. However, this demand generally decreases exponentially with time as decomposition proceeds; and if oxygen is readily available and the organic loading is not excessive, then oxidation proceeds without detrimental decreases in dissolved oxygen levels. Presence of streamside buffer zones generally prevents excess delivery of logging slash to stream channels, thereby helping to maintain dissolved oxygen levels similar to prelogging conditions.

Critical periods for water temperature and dissolved oxygen are during summer low-flow conditions when discharge is at a minimum and solar radiation is at or near a maximum, resulting in conditions of maximum stream temperature. Lethal levels of dissolved oxygen vary with aquatic species. For example, dissolved oxygen levels of $<1\text{–}2\,\mathrm{mg\,l^{-1}}$ are lethal for juvenile salmonid species and growth of these species is inhibited in the range of $5\text{–}8\,\mathrm{mg\,l^{-1}}$. In contrast, species occurring in warmwater streams are adapted to low levels of dissolved oxygen.

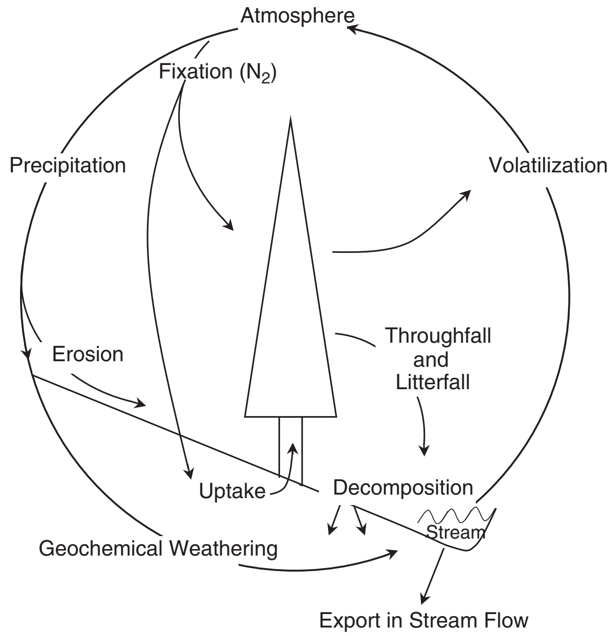

Figure 7 Nutrient cycling in a forest. Adapted with permission from Brown GW (1988) *Forest and Water Quality*, Corvallis, OR: Oregon State University.

Dissolved Nutrients

Nutrient concentrations in surface and groundwater draining undisturbed forest are generally very low because nutrients are used rapidly by ecosystem biota. Because of this limited nutrient availability, inputs of nutrients, particularly nitrogen (N) and phosphorus (P), in excess of background levels often lead to increased primary production, altered aquatic food webs, and potential eutrophication. Dissolved nutrient concentrations are a function of nutrient cycling processes that include (1) inputs from weathering of geologic parent materials (primary source of P, calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K)) or directly from the atmosphere (primary source of N), (2) storage in the soil, (3) plant uptake from soil and storage in biomass, (4) release of organically bound nutrients via decomposition, and (5) outputs of nutrients via streamflow or leaching to groundwater (**Figure 7**). Precipitation and leaf fall are two additional important sources of dissolved nutrients to streams in forested ecosystems.

The two primary dissolved nutrients of concern to forest managers are phosphate-P (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$) and nitrate-N (NO_3^-) because they often limit productivity of aquatic plants and both can be elevated by forest practices such as harvesting, fertilization, and prescribed fire. Changes in stream P are uncommon after logging, but can increase after fertilization or high-severity fires. Both N and P are commonly applied as fertilizer in intensively managed forests and thus have the potential to alter nutrient cycling processes and affect water quality.

Dissolved N also exists as nitrite (NO_2^{2-}), ammonia (NH_3), ammonium (NH_4^+), and organic N. Dissolved P also occurs as complexes with metal ions and as sorbed phosphate on colloidal organic and inorganic particulate material. High concentrations of dissolved nitrate are a concern because of potential risks to human health if the water is used for drinking. The US Environment Protection Act and Canadian drinking water standard is $10\,\mathrm{mg\,l^{-1}}$ NO_3-N, whereas the World Health Organization and the European Union use a standard of $11.3\,\mathrm{mg\,l^{-1}}$ NO_3-N. Dissolved ammonia can be toxic to aquatic organisms, with concentrations as low as $0.03\,\mathrm{mg\,l^{-1}}$ NH_3-N being potentially toxic as acute concentration and toxicity associated with chronic concentrations of $0.002\,\mathrm{mg\,l^{-1}}$ NH_3-N. Nontoxic ammonium forms from ammonia at pH levels commonly observed in forested streams and is the predominant form observed. Phosphate is not toxic. The range of suggested water quality standards for P is 0.025–$0.1\,\mathrm{mg\,l^{-1}}$ as total P.

Worldwide, pristine rivers have average concentrations of ammonia-N and nitrate-N of $0.015\,\mathrm{mg\,l^{-1}}$ and $0.1\,\mathrm{mg\,l^{-1}}$, respectively. The concentration of nitrate-N averages approximately

$0.23\,mg\,l^{-1}$ for large forested watersheds in the USA. Nitrate-N concentrations $>1.0\,mg\,l^{-1}$ generally indicate anthropogenic inputs. Because N is essential for plant growth, seasonal differences in plant uptake can cause variations in the concentration of N in soil and surface waters. In addition, rate of removal of N from forest streams is generally high. As water flows downstream, N compounds may be removed by biotic uptake, movement into sediments, or conversion to gas. Finally, the literature on synoptic patterns of streamwater chemistry suggests that influences of vegetation type, vegetation age, geologic substrate, stream order, basin size and morphology, and climate are controlling factors of dissolved nutrient levels. As a result, water chemistry can be highly variable within and among streams. For example, conifer forests tend to have more dissolved N in the organic form and hardwood forests tend to have more dissolved N in the inorganic form. Some regions, such as the red alder (*Alnus rubra*)/Douglas-fir (*Pseudotsuga menziesii*) forests of the Oregon Coast Range in the USA have high levels of nitrate naturally from N fixation provided by the alder stands that dominate the riparian zones. This interaction among controlling factors of streamwater chemistry illustrates a fundamental challenge in detecting significant responses to anthropogenic influences.

Timber harvesting Despite the confounding factors described above, studies throughout the world show that following intensive timber harvesting on well-drained soils, there is frequently an increased loss of nutrients from the logged area. Increased nutrient export from intensively logged watersheds is often partly caused by increases in water yield that usually accompany removal of vegetation. When trees are harvested from a site, a sequence of alterations in nutrient cycling occurs that can lead to loss of nutrients from the terrestrial ecosystem. Removal of vegetation results in less nutrient uptake, increased soil temperature, and increased soil water content. Accelerated release of nutrients occurs as decomposition of logging slash is stimulated by warmer, wetter soil conditions that generally favor decomposition. Enhanced decomposition increases mineralization of organic matter and nitrification, resulting in release of cations and nitrate that are available for leaching loss to streams and groundwater in the absence of adequate nutrient uptake and soil retention.

Nitrate-N concentrations in streams have received the most study and have shown increases in response to harvesting in some cases. However, extent of nutrient loss from sites disturbed by timber harvesting is highly inconsistent because of variable climate, geology, soils, plant community composition, and revegetation dynamics. Losses are generally lowest in deep soils with high clay contents which have a high capacity to fix leaching nutrients on exchange sites within the soil profile. The most susceptible sites to nutrient loss occur on shallow soils with low exchange capacity in systems where relatively high levels of nutrients are supplied to the site via precipitation and/or weathering. For example, in areas that are subject to N saturation from deposition of N compounds in air pollution, forest harvesting, or fertilization can produce significantly elevated concentrations of nitrate-N in streams and groundwater. Nutrient mobility from disturbed forests generally follows the order $N > K > Ca = Mg > P$. Thus forest practices such as timber harvesting generally produce larger responses in N concentrations in streamwater and groundwater than other nutrients. In contrast, P is delivered to streams primarily adsorbed to fine-textured sediments via erosion.

Fertilization Fertilization of managed forests is a common practice in the northwestern and southeastern USA, Canada, Japan, Australia, New Zealand, and regions of Europe and South America. Young commercial forest stands ($\sim$15–40 years) are commonly fertilized with N at $\sim 200\,kg\,N\,ha^{-1}$ as urea, ammonium nitrate, diammonium phosphate, or ammonium sulfate. Various forms of phosphate fertilizers are applied less commonly and at lower rates. In most cases, increases in dissolved phosphates after fertilization have not been observed in streamwater or groundwater.

The potential for negative effects of fertilization on streamwater quality has long been recognized and has resulted in considerable research and review in the literature. Studies have reported that applied fertilizer N can affect N concentration in streams, with losses to the stream ranging from 0% to as much as approximately 30% of applied N. Losses from the site of application depend on numerous factors, including amount and form of fertilizer, timing of application, weather during and immediately following application, stand composition and age, width of riparian buffers, amount of direct input to streams, N status of soils, quantity of organic matter in the soil, hydrologic processes (e.g., groundwater residence time, hyporheic exchange), and land use history (**Table 3**).

Fertilization of forests with urea-N often shows subsequent elevation in stream nitrate-N concentration, but not until nitrification of the urea-N has proceeded in the soil and several rainstorms have occurred to transport the resultant nitrate to the stream. As such, maximum nitrate-N concentrations

Table 3 Factors affecting nitrogen loss from forested watersheds via leaching or streamflow after nitrogen fertilization

Factor	*Characteristic*
Fertilizer	Form, amount, timing
	Amount of direct input to stream
Weather	Conditions during and immediately following application
Stand	Composition, age
	Width of riparian buffers
Soil	Nitrogen status
	Nitrification potential
	Quantity and properties of soil organic matter
	Soil depth, texture, cation exchange capacity
Hydrologic processes	Hyporheic exchange
	Groundwater residence time
Watershed geology	Landforms, soils
Land use history	Previous fertilizer applications

in streamwater are sometimes not observed until the winter after fertilization with urea. Most fertilization studies have shown peak concentrations of nitrate-N of $<2.0\,\mathrm{mg\,l^{-1}}$. In cases where high nitrate-N has been observed (e.g., Fernow Experimental Forest in West Virginia, USA and in Sweden), N-saturated soils are present and excess atmospheric N deposition is well-documented. Most occurrences of elevated nitrate are short-lived, lasting for a few days to several weeks, because of uptake within the soil profile as well as N processing within the stream. Instream pathways for N processing include downstream transport and dilution, hyporheic retention and processing by microbial communities, uptake by benthic algae, and downstream transport and recycling via sloughed, particulate forms of algae.

Inadvertent application of fertilizer to unintended areas occurs to some extent during most aerial applications. Highest concentrations of streamwater N occur where fertilizer is applied directly to streams. Typically, pulses of dissolved urea, ammonia, or nitrate resulting from direct application quickly decline in concentration and are short-lived – usually lasting less than 1 month and often only a few days. Even under conditions of direct application, nitrate-N concentrations rarely exceed the standard of $10\,\mathrm{mg\,l^{-1}}$ and ammonia toxicity is rarely observed because of rapid conversion to non-toxic ammonium.

Fire Numerous studies have reported increases in streamwater nutrient concentrations after wildfires and prescribed management fires, but these increases are usually limited in magnitude and duration. Nutrient loss to streams following prescribed fire is generally undetectable or very low. However, as fire severity increases, organic materials are oxidized creating oxides of metallic cations such as Ca, K, Mg, and Fe, which react with water and CO_2 to become soluble and more susceptible to leaching. This process increases potential for leaching loss of nutrients from the ash into and through the soil. Nutrients in the ash are also susceptible to loss by surface erosion. Overland flow from a rainfall event of high intensity following a severe fire can move large quantities of soluble ash compounds into streams, especially during the first year after the fire. This effect quickly diminishes as vegetation is re-established.

The potential for increased nitrate concentrations in streamflow is generally a function of accelerated mineralization of organic N, followed by nitrification in soils after burning. Where severe fires have removed vegetation, plant uptake of N is diminished and available nitrate resulting from the fire is susceptible to loss via leaching or erosion. This effect is also usually short-lived, and generally declines as revegetation occurs.

Pesticides

Applications of pesticides to forest lands are just a fraction of those applied to agricultural lands and pesticide concentrations associated with forest management practices are generally many times less than those used on agricultural lands. However, there are circumstances where forestry applications can cause degradation of water quality and potential impacts on stream biota. Pesticides, including herbicides for vegetation control and insecticides for control of damaging insects, are often used for intensive forest management.

Herbicides are used to control competing vegetation during forest stand establishment. This practice eliminates on-site soil and organic matter displacement, prevents deterioration of soil physical properties (i.e., compaction), and minimizes erosion when compared with mechanical means of site preparation and vegetation control. In most cases, these chemicals are distributed aerially and therefore a portion of the aerial spray can fall directly on surface water and create immediate contamination. Amount of spray drift is influenced by the pesticide carrier, size of spray droplets, height of spray release, wind speed, temperature, and humidity. Concentration of pesticide chemicals in streams is often a function of whether the stream originates in or flows directly through spray areas.

Pesticide risk to aquatic systems depends on persistence characteristics of the pesticide, hydrologic processes (i.e., leaching, surface runoff), and properties of the site. Rainfall rates, soil infiltration capacity and hydraulic conductivity, soil texture, soil depth, amount and character of organic matter, and slope can all affect pesticide transport. Conditions that slow rate of surface runoff and leaching will minimize stream contamination because a longer residence time in the soil provides more opportunity for volatilization, plant uptake, adsorption to soil colloids and organic matter, and chemical or biological degradation. Most currently labeled pesticides degrade rapidly and are available for overland flow for a short period (hours or days). Furthermore, in most forest soils, infiltration capacity exceeds most common precipitation intensities and overland flow rarely occurs. As a result, pesticide delivery to streams via runoff in forested settings is uncommon and water contamination is generally precluded.

Pathogenic Organisms

A broad spectrum of disease organisms can be transported by water. Of particular interest are waterborne pathogenic bacteria (e.g., *Escherichia coli*) and protozoal parasites (e.g., *Giardia* spp. and *Cryptosporidium* spp.) which can cause gastrointestinal illnesses in humans. Water samples are often tested for fecal coliform as an accepted surrogate for potential presence of pathogens. In general, there is a direct relationship between increased human and animal use of forested watersheds and concentrations of bacteria which indicate fecal contamination of water resources. However, most forest management practices with the exception of livestock grazing do not affect the occurrence of these pathogens directly.

Converting Farmland to Forestland

In cases where marginal farmlands (supporting either crops or pastures) are being converted to forestlands through afforestation efforts or simply through abandonment of the farmland, there is growing evidence that water quality improvements are likely to occur after the land use is altered. However, impacts of this type of conversion on water quality have received limited evaluation because there is limited documentation of comparisons between farmland and forestland on the same site. Net impacts on water quality depend on prior land use and crop management, current forest management practices, soil type, local hydrology, and climate. In general, conversions to forestland have the potential to reduce erosion and subsequent sedimentation (**Figure 8**), as

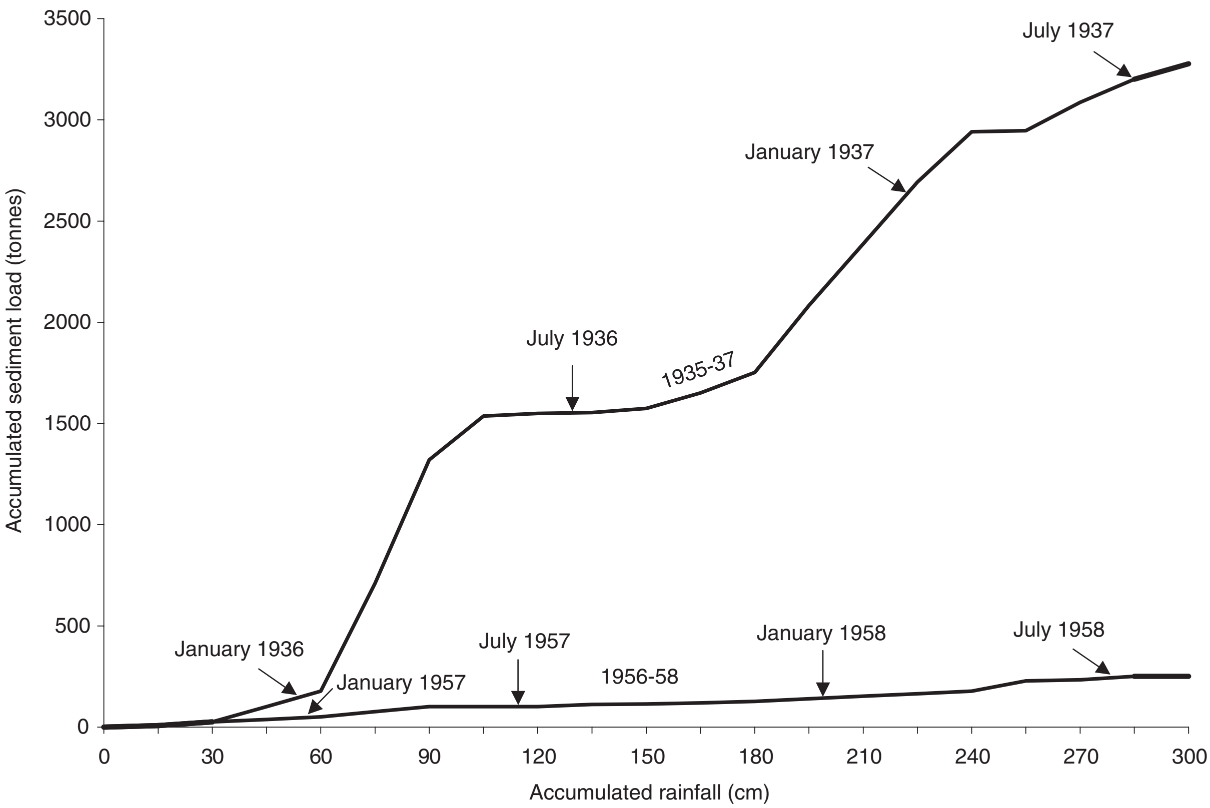

Figure 8 Cumulative sediment yields from White Hollow Watershed, Tennessee, USA, before and after reforestation. Adapted from Tennessee Valley Authority (1961) *Forest Cover Improvement Influences upon Hydrologic Characteristics of White Hollow Watershed, 1935–1958*. Report no. 0-5163A. Knoxville, TN: Tennessee Valley Authority.

well as reduce levels of dissolved nutrients and pesticides in surface runoff and groundwater. These improvements in water quality are a function of lower amounts of runoff and leaching as well as lower concentrations of potential pollutants that are expected to result from the conversion to forestland. For example, declines in quantities of runoff and leaching have been observed in response to increased interception and evapotranspiration occurring as forests become established. Increases in infiltration capacity also occur via increased litter cover, and resultant improvement in soil structure and porosity. Fertilizer and pesticide applications are eliminated or drastically reduced after conversion to forestland and thus, these potential sources of water quality degradation are eliminated or minimized. Establishment of new forests and sustainable management of existing forests are widely viewed as management practices that will improve or retain high quality water resources.

See also: **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging; Roading and Transport Operations. **Hydrology**: Impacts of Forest Conversion on Streamflow; Impacts of Forest Management on Streamflow; Impacts of Forest Plantations on Streamflow; Soil Erosion Control. **Soil Development and Properties**: Nutrient Cycling; Water Storage and Movement.

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Soil Erosion Control

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Introduction

Soil erosion control in managed forests is undertaken, and best achieved, for two main reasons. The first relates to soil protection for the sustainable productivity of the forest resource. The second relates to the protection of valuable water resources located in forested catchments. The potential impacts of increased soil erosion and the subsequent delivery of this material off-site, include a general reduction in water quality, adverse health effects on aquatic species, and an increase in the delivery of nutrients and sorbed chemicals to watercourses. This article discusses soil erosion control in managed forests from this twofold perspective. It uses a conceptual framework that emphasizes the link between on-site erosion and the subsequent delivery of this material off-site to the stream channel. The importance of adopting erosion control practices that encourage the reduction of surface runoff, and thereby off-site sediment delivery, is emphasized. The role and effectiveness of selected best management practices used in the control of soil loss and sediment delivery in forestry environments is also discussed within this framework.

General Principles of Soil Erosion

Soil erosion is the detachment and movement of soil by the physical agents of gravity, water, and wind.