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.

The dominant agent of erosion in many forests is water, which describes the detachment of soil particles by raindrops and overland flow, and their transport and deposition as sediment. Water erosion is further categorized as rill, interrill, gully, and channel bank erosion. Rills, which may evolve to form gullies, are erosional features characterized by concentrated flow to a depth of $<0.3\,\mathrm{m}$ (**Figure 1**). Interrill is the term used to describe the adjacent areas. As the hydraulic shear stress exerted by the flow in the rill is sufficient to overcome the binding forces between the particles, it is often seen as the primary detachment agent. The flow also acts to transport detached soil from both the rill and interrill areas. Detachment on interrill areas is primarily induced by raindrop impact, as flow depths are shallow and have limited erosive power.

The above forms of water erosion occur naturally in all environments, and can act singularly or in combination to determine the overall soil loss. Soil loss is defined as the amount of soil removed in a specified time period over an area of land that has experienced net soil loss (expressed in units of mass per unit area, $\mathrm{kg\,m^{-2}}$). It is different to the other frequently used term, sediment yield. Sediment yield refers to a mass of sediment that leaves a boundary, such as the edge of a plot, bottom of a hillslope, or the outlet of a catchment (expressed in units of mass per unit area, $\mathrm{kg\,m^{-2}}$ or $\mathrm{t\,ha^{-1}}$, or total mass, kg). The sediment delivery ratio (SDR) describes the proportion of detached soil particles relative to the gross erosion of the basin that are delivered to a stream edge or catchment outlet. Mass wasting, although specifically not a form of erosion as it does not involve agents like wind or water, generates huge amounts of stream sediment and thus affects the SDR. Logging operations, especially clear-cutting, and the construction of cut-and-fill roads have been shown to affect the occurrence and frequency of shallow slips, which in some catchments dominate sediment delivery rates.

Key Factors in Soil Erosion Control

Much of the understanding of soil loss and the effect of various conservation practices is derived from research in agricultural areas. However, many of the factors remain the major determining influences of water erosion in other environments. One of the most commonly applied soil erosion models, the universal soil loss equation (USLE) incorporates the effect of factors such as soil erodibility (K), slope steepness (S) and length (L), rainfall erosivity (R), surface cover (C), and conservation support practice (P). These factors have been used in the USLE in the following factorial form;

$$A = RKLSCP \qquad (1)$$

Only A, K, and R have dimensions. Rainfall erosivity (R) refers to the ability of rainfall to cause erosion. Soil erodibility (K) reflects a soil's ability to withstand the forces of detachment, a function of soil composition, and structure, and prevailing climatic factors, notably rainfall intensity and energetic loading.

Figure 1 Rills are regarded as the primary detachment agent in water erosion processes. Rill development can be exacerbated in forestry operations due to compaction and vehicular traffic on road and track surfaces. Photograph courtesy of estate of TC Whitmore.

Hillslope length (L) and slope (S) are expressed relatively to values from a standard 22.1 m and 9% hillslope used in the original experiments; cover (C) and conservation practice (P) vary between values of zero (full cover and conservation works in place) and 1 (no cover nor conservation).

Soil erosion strategies often aim to influence some of these factors, especially cover and conservation support, which are manipulated more effectively than topographic or climatic variables. Soil loss in many environments is managed, therefore, by controlling the rate of particle detachment through either maximizing surface cover or minimizing surface runoff. Surface cover management involves practices that aim to protect the soil from detachment by raindrops and water. Surface runoff reduction aims to minimize the accumulation of water into concentrated flows to reduce the detachment and transport of sediment in rills. Traditionally, on-site soil erosion has been managed through surface cover practices (e.g., mulching) and off-site soil erosion by reducing surface runoff (e.g., by terracing or bunding). However, large amounts of sediment cannot be moved off-site without sufficient discharges to transport this material. Surface cover management alone, for example, may reduce the erosional effects of raindrop impact but do little to reduce runoff accumulation, which may have a greater impact upon erosion processes both at a site and downstream in the catchment. This off-site delivery component of soil conservation is not well accommodated within empirical soil loss equations, which do not explicitly consider off-site sediment yield. Significant contributions from landslides and channel bank erosion are also not well considered in empirical approaches such as the USLE, although recognized to be major contributors to overall sediment supply in some cases. Research has highlighted the importance of sediment storage and redistribution which are often poorly represented in small plot scale studies of erosion. The deposition of sediment as runoff moves down the hillslope and in concavities has been recognized as an important, but largely unquantifiable component of the SDR. Spatial patterns of disturbance caused by logging, compaction, cover removal, and regeneration lead to complex patterns of erosion and deposition frequently leading to high rates of sediment redistribution within a compartment or hillslope but low overall rates of sediment yield. Our understanding of these processes and their contribution to catchment sediment yield is improved through larger scale plot studies incorporating sediment storage and redistribution terms together with the application of some sediment 'fingerprinting' techniques such as radionuclides that are used to trace the source and depositional history of sediment.

The following discussion of soil conservation practices in managed forests thus uses a conceptual framework that considers the need to conserve soil on-site both for the sustainable production of forests and for off-site water protection.

Soil Erosion and Forestry Operations

In pristine or undisturbed forests, soil loss due to the erosional effects of water, wind, and gravity is typically low due largely to the protective cover of abundant over- and understory vegetation, and, above all, a well-developed litter layer promoting infiltration of rainwater and the slowing down of any surface runoff that may develop. Soil loss is exacerbated by disturbances associated with tree removal. The opening or removal of forest canopies during harvesting or land clearing results in potentially large areas of bare soil being exposed to the erosional processes of raindrop splash, overland flow, and, under certain conditions wind (**Figure 2**). The extent of bare soil exposed to these processes understandably is greatly influenced by the nature of the logging operation, and varies significantly between selective logging and the more intensive clearcutting operations. Some of the more commonly described, and somewhat universal impacts associated with logging include soil compaction, increased volumes of runoff, both surface and subsurface, and enhanced erosion. In some environments, the dominant hydrological regime will be dramatically altered due to compaction of the surface soil, in some cases changing subsurface dominated hydrological regimes to overland flow dominated regimes. Associated with these are corresponding

Figure 2 Canopy removal during harvesting exposes large areas of bare soil to the erosion processes of overland flow, raindrop splash, and wind. Photograph courtesy of LA Bruijnzeel.

reductions in soil permeability, soil fertility, and organic matter content.

Relative differences in the rate of soil loss are often the result of variations in the intensity of forest disturbances, quality of management and the prevailing climatic characteristics, notably rainfall erosivity. In both pristine and managed forests, rates of erosion and soil loss can be several orders of magnitude higher in areas characterized by high-intensity, short-duration rainfall events. Such intense rainfall events, typical of many lowland tropical environments, are characterized by large raindrop sizes that distribute high kinetic energy on impact, further exacerbating erosivity in areas of unprotected soil.

A recent advance in our understanding of water erosion processes in forestry environments has been recognition of the importance of the road and track network both in the generation and delivery of sediment (**Figure 3**). Forests roads and tracks are both a significant source of overland flow and sediment which if constructed and drained poorly often form a direct connection or pathway to the stream network. This coupling of the on-site erosion process with the subsequent delivery of the material off-site is a necessary advance in both the conceptualization and implementation of soil conservation practices in forests. Soil conservation practices should explicitly consider both the reduction of erosion on-site and the delivery of this material off-site through specific delivery pathways. Recognition of the importance of runoff-generating mechanisms in this process is paramount to the successful design of effective on- and off-site erosion control strategies.

Figure 3 Overland flow develops rapidly on compacted road surfaces that have infiltration rates in some environments as low as 1 mm h^{-1}. Photograph courtesy of A Malmer.

Runoff Production and Erosion Control

The first priority in designing effective erosion control strategies in managed forests is to develop an understanding of the dominant runoff production mechanisms and their potential alteration due to the harvesting regime. For example, infiltration-excess or Hortonian overland flow (HOF) is rare in undisturbed forests typically due to the generally very high infiltration capacity of the soil in most cases. In disturbed forest environments, overland flow generation, and especially HOF, is common because compaction from logging equipment and road building create areas of reduced hydraulic conductivity. Increased areas of compacted soil and altered groundcover due to timber harvesting and roading have been shown to alter hillslope hydrological processes, and overall catchment stream flows, to varying degrees.

Road surfaces may occupy less than 1% of the catchment area but contribute a disproportionate amount of water and sediment during low to moderate rainfall events. Infiltration rates as low as 1 mm h^{-1} have been reported on road surfaces which means that they respond very quickly to rainfall events and generate overland flow faster and in greater volume than other landscape surfaces. During long duration and higher intensity rainfall events, runoff contribution from other surfaces will be more dominant, simply because of their greater areal extent.

General harvesting areas (GHA) or logged hillslopes represent the largest land surface by area within a commercially logged forest. Although partially disturbed during selection harvesting operations, the retention of a high degree of forest vegetation contributes to reduced surface runoff accumulation and consequently limited sediment transport. Under such conditions, runoff generation on GHA is usually restricted to some Hortonian overland flow development, predominantly from bare or the more disturbed parts of the hillslope. Thus, widespread sheet flow is not common on the GHA and this is reflected in the relatively small volume of overland flow generated even under extreme rainfall events. Channelized flow in rills is also rarely reported within the GHA, limiting the ability of runoff to transport large amounts of sediment. A clear priority is to reduce the potential for run-on of overland flow onto these areas from the more disturbed and compacted areas. For example, runoff from tracks and roads which is discharged onto the GHA may increase the shear stress of the flow above some critical level and cause erosion of the surface soil layer. This will lead to rill and potentially gully development in these areas. In addition, increased runoff from compacted sources can contribute to the development of saturation-excess overland flow (SOF) on footslopes, in riparian zones, and other areas of near-surface flow convergence. The effective management of high runoff producing areas is paramount to the success of traditional on-site erosion control strategies. The hazard of managing high runoff production areas increases as the area of forest removed is increased, as is the case between a total clear cut operation compared with selectively logged slopes.

On-Site Soil Erosion Control

On-site control of soil erosion is designed to minimize the detachment and subsequent removal of soil from a range of disturbed land surfaces in a managed forest. There is a hierarchy of sediment sources in these environments ranging from the highly disturbed and compacted areas such as roads and tracks, logged hillslopes to the undisturbed streamside riparian areas (**Figure 4**). The greatest source of sediment in a managed forest is the road and track network, especially those used frequently by vehicles during logging operations. Logging tracks used by machinery during logging only and then often abandoned and regenerated tend to generate less sediment than primary roads. Sediment yields from logging roads show increases from twofold to 50-fold over background levels in undisturbed forests. As such, priority will be given here to discussing soil conservation strategies that may effectively reduce the generation and delivery of this material.

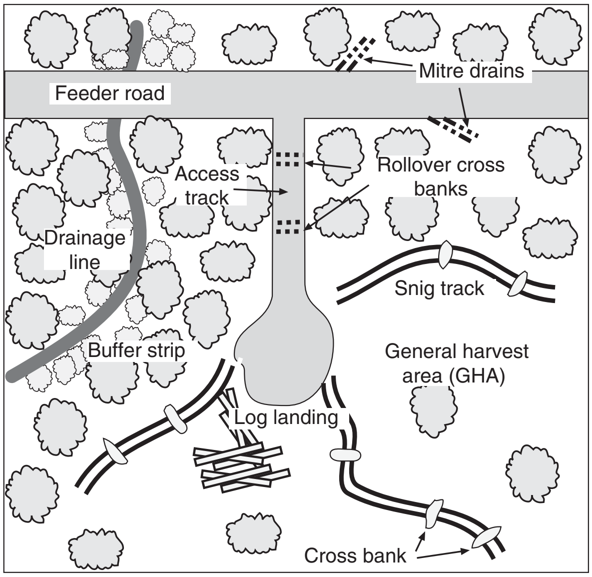

Figure 4 Range of sediment and runoff sources within a typical managed forest. Priority should be given to high runoff and sediment production areas such as roads and tracks.

Numerous strategies, including revegetation, graveling, regulation of use or traffic volume, and regular maintenance have been found to be successful in limiting sediment generation from forest roads and tracks. For example, the discontinued use of tracks and logging roads between cutting cycles is seen as a significant factor in limiting sediment availability for transport. The intensity of traffic usage is also seen as a key factor in the persistence of these areas as a sediment source (**Figure 5**). Sediment yields have been shown to decrease rapidly after road use is discontinued and logged areas regenerate (**Figure 6**). Road yields measured 5 years after logging produced less than five times the background values. Thus controlling vehicle access during wet weather conditions and limiting recreational use of roads in close proximity to streams should be considered integral to any erosion control strategies in the forest. The remobilization of previously deposited sediment during extreme events may pose a major problem in heavily disturbed areas, especially around hollow log culverts which tend to decompose over time.

The spacing of road drainage features is a key design variable for the effective management of overland flow on roads and tracks. Redistributing runoff at water bars or water diversion structures

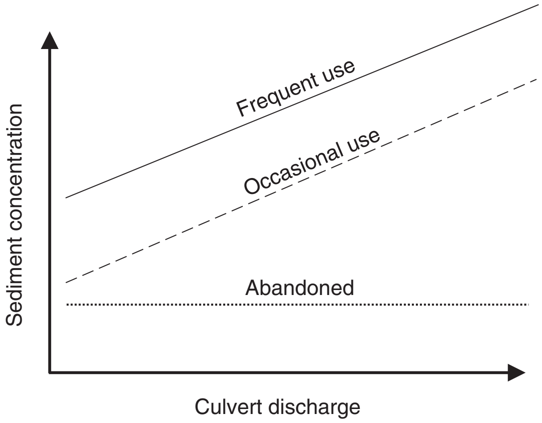

Figure 5 Generalized relationship between sediment concentration in road runoff and road usage. Well-used roads may have up to four loaded logging truck passes per day with lower-frequency traffic usage on the remaining use.

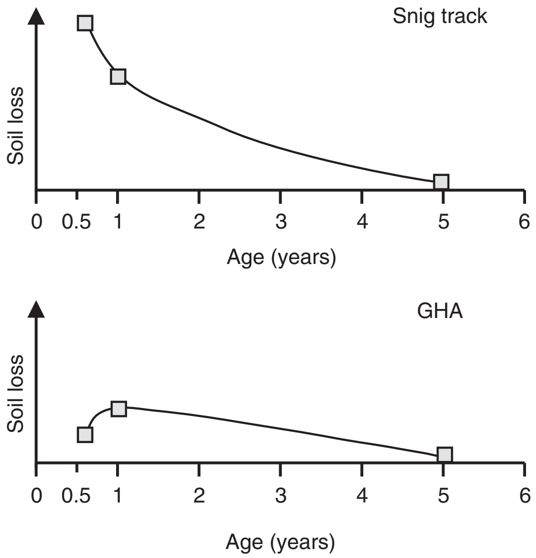

Figure 6 Generalized relationship between soil loss and time since disturbance typical of a humid temperate environment. Studies confirm the notable reduction in soil loss within a period of less than 5 years since harvesting. Erosion control strategies are essential in this period immediately post-logging when soil is exposed and natural regeneration has not occurred.

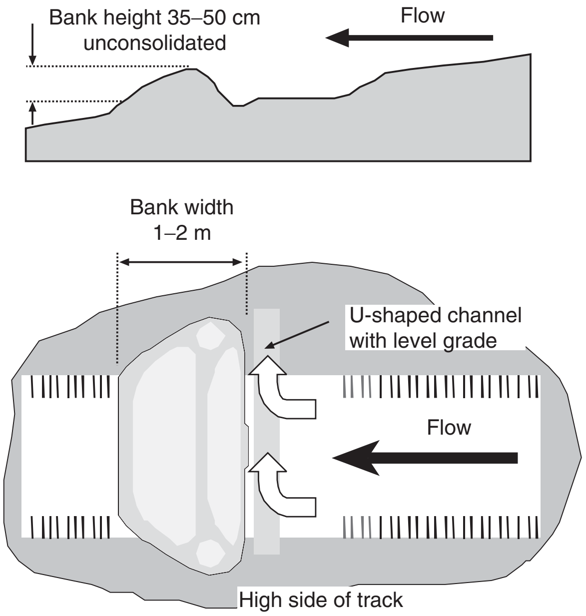

Figure 7 Construction of cross-banks or water bars at regular intervals along forest tracks is an effective control of overland flow development and sediment transport. These features do not need to be great tall mounds and are designed primarily to divert track runoff onto an adjacent hillslope so that roughness and cover can be effectively used to promote infiltration and sediment deposition.

along tracks immediately after logging is a successful method in reducing the contribution of water and sediment to streams, particularly during small to medium-size rainfall events (**Figure 7**). Design principles to guide the spacing of water bars and road drains have been developed based on maximum contributing track lengths and track slope (**Table 1**). Although not highlighted in the example provided in **Table 1**, rainfall intensity, frequency, and duration are important additional variables in determining the appropriate spacing of road drainage features for any given climatic area, but especially in tropical environments. The objective of these drainage features is to minimize the contribution of runoff and promote infiltration into the rough surface of the adjacent GHA. The high infiltration properties and roughness of these hillslope areas should be used as a natural erosion control strategy. The velocity and sediment transport capacity of runoff from tracks and roads passing through these areas will be reduced, promoting deposition and limiting sediment delivery to streams. Poor construction of these features can lead to the destruction of banks and water bars, especially under extreme rainfall events, resulting in catastrophic consequences for sediment supply and delivery.

Another important design variable is the position of the drainage outfall point in the landscape. For example, a culvert discharging into a stream head or first-order stream (gully) will greatly increase the impact of road runoff and sediment on the stream (**Figure 8**). In contrast, if a culvert directs road runoff onto a large divergent slope, surface erosion will be minimized, thereby reducing sediment delivery to the stream. In some instances, however, prevention of concentrated runoff on hillslopes at culvert outlets will also require implementation of protective measures such as masonry, grassed waterways, stone drops, etc. to provide resistance to scour at the culvert outlet.

Surface cover management provides an effective measure for the reduction of erosion and soil loss. Numerous studies confirm that surface cover of between 30–50% is effective at significantly reducing soil erosion processes at a site (**Figure 9**). There is also the potential to use effective time management in the harvesting process or provide artificial cover (e.g., straw bales, grass seeding) to protect more disturbed or bare areas until natural regeneration occurs. Natural or artificial regeneration procedures such as ripping or plowing up and fertilizing log landings have been used successfully to enhance the return of roughness and surface cover in these bare areas.

Off-Site Soil Erosion Control

Controlling the generation and delivery of sediment and attached nutrients is an important process in

Table 1 Example of road drain spacing guidelines, giving distance (m) between drainage structures varies with road travelway slope and the gradient of the hillslope at the discharge point. This table is developed for a forested catchment in Australia and can not be applied in other environments

Road travelway gradient (degrees)	*Drain discharge hillslope gradient (degrees)*							
	2.5	5.0	7.5	10	15	20	25	45
0	—	110	95	90	85	80	75	75
1	155	110	95	90	85	80	75	75
2	155	110	95	90	85	80	75	75
3	150	110	95	90	85	80	75	75
4	125	110	95	90	85	80	75	75
5	100	100	95	90	85	80	75	75
6	90	90	90	90	85	80	75	75
7	80	80	80	80	80	80	75	75
8	70	70	70	70	70	70	70	70
9	65	65	65	65	65	65	65	65
10	60	60	60	60	60	60	60	60
11	55	55	55	55	55	55	55	55
12	50	50	50	50	50	50	50	50
13	45	45	45	45	45	45	45	45
14	40	40	40	40	40	40	40	40
15	40	40	40	40	40	40	40	40

Figure 8 Erosion of the hillslope at road drainage outlets is a significant contributor to off-site sediment delivery in forested catchments. Large volumes of overland flow from road surfaces are discharged at single outlet points, often causing increased shear stress and the development of rills or gully erosion. These features form efficient transport pathways to streams enhancing the risk of off-site impacts to water quality.

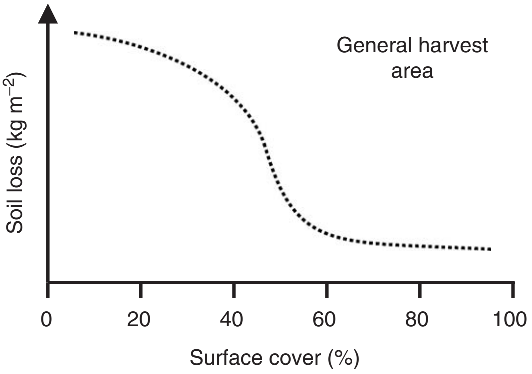

Figure 9 Generalized relationship between soil loss and surface cover. Most studies confirm that surface cover of >50% is sufficient to reduce surface erosion.

minimizing off-site impacts of forestry operations. The most effective measures of reducing sediment delivery for off-site protection in forestry environments include:

1. Reducing the volume of overland flow.
2. Minimizing direct connectivity of sediment sources with the stream network.
3. Promoting vegetative filtering.

Volume of Overland Flow

Reduction of the volume of overland flow can be achieved by reducing the contributing area of disturbed surfaces draining to a particular point in the landscape. This is effectively managed through conservation planning and practices that limit the size of harvesting coupes or include some strategy for alternate-coupe or patch harvesting. Likewise, adequately planned and constructed road and track drainage plays a key role in minimizing the volume of overland flow generated from compacted surfaces.

Minimizing Connection of Sediment Sources with Streams

The term connectivity is now commonly applied to describe the level of interaction between disturbed areas such as roads and tracks and the stream. There are a variety of degrees of connectivity that express whether a sediment source is fully or partially connected to the stream. For example, a road network is fully connected to a stream at a stream crossing or when there is a continuous gully that extends the full length from the source to the streams (**Figure 10**).

Opportunities to reduce overland flow through vegetated hillslope areas and streamside buffer strips are plentiful in forested catchments, as long as gully erosion does not occur. Runoff from roads and tracks can disperse in vegetated areas where flow is not concentrated and shear stresses remain low. The risk of gully development is increased as a result of poor road and track drainage and this should be avoided where possible. Once initiated, gully erosion is difficult to halt and these features then effectively bypass the potential filtering effect of vegetation in reducing runoff and sediment fluxes.

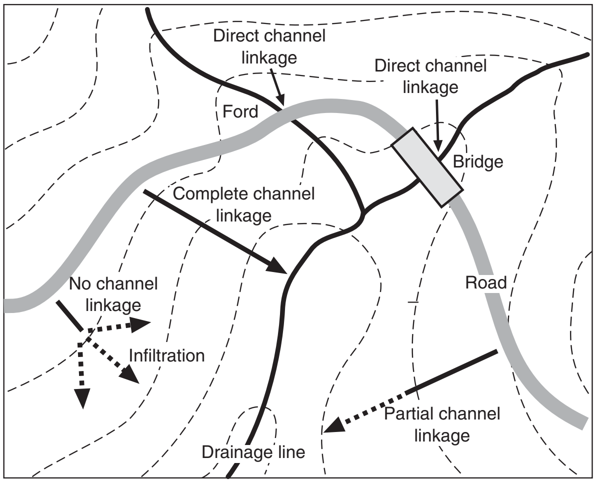

Figure 10 There is a range of degrees of 'connection' between sediment sources such as roads and receiving waters. Sources may be fully connected to a stream, as occurs at stream crossings or where a gully has formed at a road drainage outlet. Partial or nonconnected pathways also exist. Direct connection between a sediment source and stream should be avoided by appropriate planning of road location and drainage.

Connection between sediment sources and the stream can also be minimized by appropriate road and track planning. Minimizing the number of stream crossings by the location of roads along ridge-tops is preferable to the distribution of roads along valley bottoms where the distance to streams is short. The procedure of uphill yarding or snigging is also a key measure in minimizing connection between compacted surfaces, sediment sources, and the stream. This encourages the location of roads and tracks away from the streams and results in a downslope divergence of the associated skidder track pattern.

Vegetation Filtering

Riparian or streamside vegetated zones are recognized worldwide as having a key role in moderating the impact of land use on stream water quantity and quality (**Figure 11**). Riparian zones have several functions and the emphasis placed on each of these functions depends on a wide range of environmental and organizational issues. This riparian zone or buffer strip has a range of functions including maintaining the stability of the stream channel, providing riparian habitat and a long-term recruitment of woody debris, regulating light and water temperature in the stream, and acting as a vegetative filter for runoff between the areas of disturbance and the stream network. This final function may be considered as the last line of filtering as sediment generated on roads, tracks, and other compacted areas frequently pass through the general harvest areas prior to entering the buffer strip.

In terms of their sediment trapping ability, riparian zones have several characteristics that encourage deposition. Riparian zones are normally characterized by a very rough soil surface, often with an intact litter layer. Hence, the soil is porous, with many macropores; and the rooting zone is frequently deep. Sediment deposition occurs as a result of a decrease in flow velocity and volumes as the flow moves into areas of relatively high infiltration and dense vegetation. The very porous nature of the undisturbed riparian zone soil assists in this process, although the presence of a wet zone from a water table may inhibit total sediment deposition. Nevertheless, the surface roughness of the riparian zone continues to aid in trapping sediments even if saturated.

Overall, the literature confirms that vegetated areas perform well in relation to sediment deposition. Consensus on their ability to trap the very fine-grained silt and clay material under certain

Figure 11 Location of riparian or buffer strips along streams in a logged catchment. Vegetative filtering as runoff passes through these areas, often demarcated a set width from a major watercourse is an effective control strategy for reducing sediment delivery to streams.

hydrological conditions is less conclusive. The ability of the buffer strip to reduce the volume of overland flow by infiltration processes is sensitive to the prevailing hydraulic properties of the area and to the moisture-holding properties of the soil. Streamside buffer strips may also act as runoff sources themselves due to rising groundwater levels in wet areas immediately adjacent to the stream. The trapping of very fine-grained material is likely to be highly dependent upon runoff infiltration mechanisms within the buffer strip.

Soil Erosion Strategies for Off-Site Protection

Several best management practices (BMPs) are used in forestry operations to mitigate the potential impacts of logging on stream ecology and water quality. Some of the more universally applied practices include the use of riparian buffer strips, patch harvesting, siting and design of roads and road crossings to minimize sediment inputs, and restrictions to logging activities in relation to slope and soil type. There is little doubt that the effective implementation and construction of these practices can significantly reduce sediment delivery to streams in managed forests. While the positive effect of catchment-scale BMPs has been widely observed, the relative contribution of specific on-site practices is rarely reported. However, there are two erosion control strategies that are imperative to reducing off-site delivery of sediment in forested catchments. These are:

1. The standard implementation of an undisturbed vegetated area adjacent to the stream network.
2. The proper planning of the road network to avoid source-to-stream connectivity.

Riparian or buffer strips in forests Forest management practices in many countries are now obliged to leave an undisturbed vegetated buffer strip immediately adjacent to the majority of streams and drainage lines (**Figure 11**). The placement and width of buffer strips in catchments is a contentious issue due to potential economic loss of harvestable timber from streamside reserves. There are two possible approaches for locating buffer strips to mitigate the inflow of sediment and associated pollutants from the upslope areas; one is based on determining appropriate sediment transport distances through the buffer strip; and the other is predicated on protecting wet areas in the landscape as these are more liable to overland flow generation through saturation excess from rising water tables during rainstorms. In the case of the former, a 30 m buffer is typically regarded as effective in trapping most of the sediment from cleared areas, although absolute width is dependent upon specific site. In general, significant impacts of logging are more likely to occur where buffer widths are less than 30 m. However, the application of a universal buffer width remains a contentious issue as large parts of the forest resource can be locked away. For example, in many upland situations with high rainfall, drainage density is so high that the blanket application of 30 m buffer zones severely limits the area available for commercial logging.

Road planning and position Given the recognized importance of the road network in both the generation and delivery of runoff and sediment, emphasis should be given to these areas during the planning stages of forest harvesting. The connectivity concept as outlined above (**Figure 10**) provides a useful conceptual framework for forest managers to incorporate with other factors such as economical and topographic constraints. Maximizing the distance between the road and track network can be readily accommodated at the planning stage through the location of roads away from streams and by yarding the logs uphill (**Figure 12**).

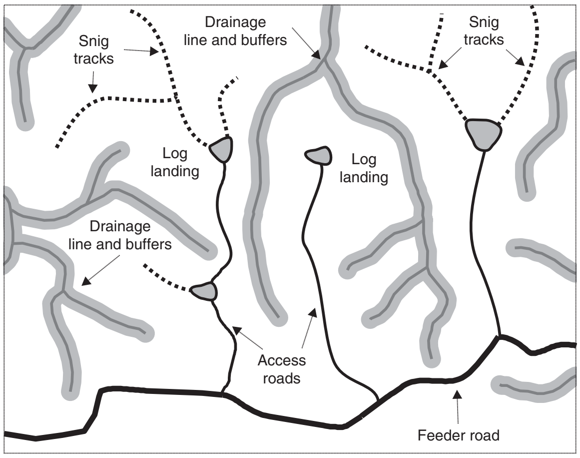

Figure 12 Road network in a logged catchment. The distribution of road networks throughout the catchment is best achieved during the planning phases where roads can be located along ridge-tops or at maximum distances from the stream. Uphill skidding and yarding is to be strongly encouraged as it results in a network of tracks that are divergent and away from the main stream network.

In many countries, forest managers are dealing with the legacy of an old road and track network that was constructed relatively close to the stream network. Rehabilitation of these surfaces or their removal from the catchment though expensive rehabilitation programs has been adopted in some countries. Ideally, many of the best strategies to minimize the potential for off-site impacts should be considered at the forest planning stages and optimum decisions made regarding the location and rehabilitation of these surfaces during the post-logging phase.

Summary

The understanding required to implement effective soil conservation strategies to manage surface erosion now exists. In many countries, harvesting and vegetation clearance is taking place at an alarming rate and the conservation and protection of many forest environments, and the associated water resources, are in jeopardy. Traditionally erosion control strategies have focused only on minimizing the detachment of soil particles through approaches such as surface cover management and runoff minimization. This review has examined both the generation and delivery of sediment in forests with a view to protecting the sustainable use of forests for future generations and the water resources located in these catchments. Effective erosion control strategies must be approached with this twofold objective in mind. Priority should be given to high runoff and sediment producing areas such as roads and tracks in both the planning and protection phases of forest harvesting. The combined beneficial effects of BMPs such as maintaining riparian buffer zones, the proper planning and construction of roads, and patch harvesting are now widely reported. The principles and processes for managing sediment delivery in forestry environments are basically understood. The effective implementation of these practices is thus often limited by economics or political pressure. Continuing development of practical and economical forest code prescriptions should be an ongoing focus of erosion research in forestry environments.

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

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Snow and Avalanche Control

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Introduction

Snow has a strong effect on the hydrology of forests. In contrast to rain, much more snow is intercepted by the branches and temporarily stored on the forest floor. Snow also modifies the radiation balance of trees. Snow–forest processes are much more complex and important due to the increased three-dimensionality of trees than in open land (**Figure 1**). Management practices can strongly influence the snow storage capacity of forest, and therefore significantly contribute to runoff and runoff timing. This is especially important where water from mountains is used for irrigation and water supply (e.g., the Sierra Nevada in California, southern slopes of the Himalayas). Another locally very important effect in mountain regions concerns the prevention of snow avalanches. The preventive effect of forests on the formation of snow avalanches was recognized in different Alpine regions in Europe as early as the Middle Ages. By then, the intensified logging and clearing of mountain forests for timber and the creation of pastures had caused the formation of new starting zones and avalanche paths and required the relocation of farms and primitive measures for the protection of buildings. In addition, mountain forests were protected and declared untouchable by decree of local authorities. The physical processes underlying the formation of snow avalanches and the most effective ways of reducing their occurrence and intensity were investigated more intensively in the latter part of the twentieth century, mostly in the European Alps and the Rocky Mountains. The effect of forests on avalanche formation is limited; forests are unable to stop avalanches as soon as their size exceeds a few hundred square meters. In fact, avalanches carrying trees in their debris often cause larger damage than 'clean' snow avalanches. In this article an overview is presented of forest–snow relationships, which are important for the understanding of the hydrology of forests in regions where snowfall occurs, and snow avalanche formation in forested areas. In addition, the implications for forest management with respect to snow hydrology and avalanche protection are discussed briefly.