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The role of forests in reducing hydrogeomorphic hazards

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Abstract

Increasingly, forests are being valued for goods and services beyond wood fibre; one of these is protection forests. Functions provided by natural and managed forests have been associated with reduced hazards from floods, debris floods, debris flows, snow avalanches and rockfalls. Maintaining a high level of protection may require active management, as forests are dynamic and the protection capabilities are strongly determined by forest condition. The nature of protection provided varies depending upon the hazard processes and pathways, and the relative spatial orientation of the hazard, the forest, and the features being protected. Hazard processes and pathways need to be understood for protection forest management so that the expected protective functions can be well predicted. Protective functions of forests include: 1) retaining material in upslope positions; and 2) containing, confining and resisting material during transport and deposition. These effects are primarily realized through: 1) soil conditioning and macropore creation; 2) root reinforcement and 3) presence of above ground structural elements. Recognition of these functions of protection forests and their relations with hydrogeomorphic hazards will contribute to the best management of protection forests.

Keywords: protection forests, hydrogeomorphic hazards, debris flow, debris flood, flood, snow avalanche, rockfall, forest function

1 Introduction

Forests protect people and resources from hydrogeomorphic hazards including floods, debris floods, debris flows, snow avalanches and rockfalls (SIDLE *et al.* 1985; BRANG *et al.* 2001; CHENG *et al.* 2002; SIDLE and OCHIAI 2006). Landslides and debris flows are known to cause loss of life as well as high financial costs (SIDLE *et al.* 1985). Debris floods can also cause severe damage and are a source of concern for municipalities (JAKOB *et al.* 2003) and forestry operations (WILFORD *et al.* 2003). Floods can be devastating and have resulted in the loss of many lives (SEPTER and SCHWAB 1995; PIEGAY and BRAVARD 1997), particularly where the water is transporting high volumes of sediment. Rockfalls are a major threat to settlements and transportation routes (PERRET *et al.* 2004). Snow avalanches are capable of great destruction in mountainous terrain (MCCLUNG and SCHERER 1993).

Forests offer protection from hydrogeomorphic hazards in two broad ways (MOTTA and HAUDEMAND 2000). Indirect protection refers to the general role of forests in reducing soil erosion or improving watershed condition and air quality. Direct protection forests specifically protect people, buildings, or utility corridors. For episodic hydrogeomorphic hazards, protection forests of both varieties are an attractive measure due to their risk reduction services and relatively low costs (SCHÖNENBERGER and BRANG 2004). The appropriate designation and management of protection forests can make mountain regions safer for people and protect resources.

The concept of protection forests has developed over time. Documents referring to protection forests in Italy have been found from as early as the 14th century (MOTTA and HAUDEMANN 2000). Japanese land managers have been using protection forests for the purpose of protecting railroads for more than 100 years. In Taiwan, protection forests have been designated for more than a century (CHENG *et al.* 2002). In the United States, the Organic Administration Act of 1897 introduced national forests that were intended to be working forests for multiple use and sustained yield. Improving and protecting the forest, water flows and timber extraction were the primary concerns. Later in the United States, the Weeks Law of 1911 emphasized the regulation of flow in navigable streams. Protection forests have also been used in many other areas of the world. Although the concept of forests protecting other resource values including water quality, human settlements, and transportation corridors (WELSCH 1991; SHIMAMURA and TOGARI this issue), is not new, the movement to establish and extend protection forests is gaining interest (MOTTA and HAUDEMAND 2000; SCHÖNENBERGER and BRANG 2004). Some of these newly designated forests are to protect against hydrogeomorphic hazards (CHENG *et al.* 2002).

The maintenance of protection forest functions through active management appears to be a more recent idea. For centuries, the only action in some European forests was to ban woodcutting (MOTTA and HAUDEMAND 2000). This has resulted in a series of problems as the forests became over-mature from a lack of disturbance and under-utilization (MOTTA and HAUDEMAND 2000). Some Japanese forests are also experiencing reduced protective capacity as a result of similar issues (SHIMAMURA and TOGARI this issue); recently depressed timber prices have led to the inadequate management of hinoki *(Chamaecyparis obtusa)* forests. Disease and windthrow become more common in many older forests and canopy gaps are created. These gaps are areas of reduced structure (SCHÖNENBERGER *et al.* 2005) and root cohesion (SAKALS and SIDLE 2004) that may increase snow avalanche, rockfall and landslide hazards. Untended forests will continue to provide a level of protection regardless of their designation or management regime; however, as noted above, the capacity of the forest to mitigate effects may be reduced. Protection forests in Malaysia are currently under a no-harvesting management strategy (THANG and CHAPPELL 2004). While this may be an appropriate management action for the short-term, active management is likely to be required in the future.

Due to the probabilistic nature of natural hazard risk analysis, maximum protection is an inappropriate target. Returns on investment diminish as the residual risk, that risk associated with hazards beyond the design level, is reduced to relatively small values (Fig. 1) (MOTTA and HAUDEMAND 2000; WISE *et al.* 2004). At some point the situation becomes not only economically and socially inappropriate but also physically impossible. The optimum level of protection and management effort should therefore be assessed on an individual basis and should consider the condition and potential future condition of the protection forest, the desired levels of management and protection, and the associated socio-economic issues.

The extent of forests managed for protection services has been included as an indicator in the 1995 Montreal Process[1], the Helsinki Process (MCPFE 2002) and the Forest Resources

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[1] http://www.mpci.org/rep-pub/1995/santiago_e.html#c4 (28 June 2005)

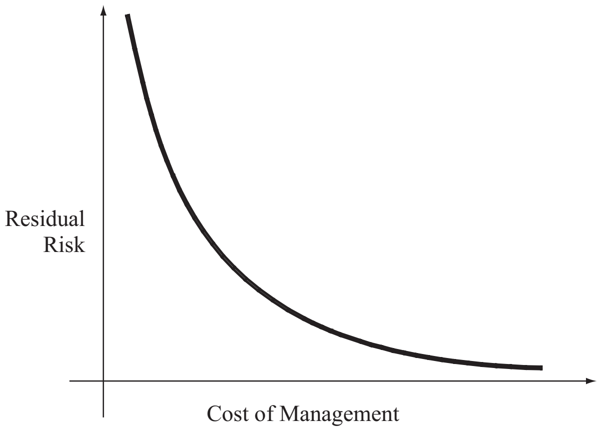

Fig. 1. A conceptual diagram relating residual risk to costs of risk management.

Assessment of the FAO (FAO 2000) in relation to sustainable forest management. Interest in maintaining forest influence is likely due to the increased utilization of the forest landbase and the lesser protective function of many industrial forests (e.g. SCHMIDT *et al.* 2001). In this paper we explore the general principles underlying the functions of protection forests as they relate to hydrogeomorphic hazards.

2 Forests and hydrogeomorphic hazard reduction

There are two ways by which forests reduce hydrogeomorphic hazards: 1) forests retain organic and inorganic material *in situ;* and 2) the physical structure of forests resists, confines, and contains the transport of mobilized material, thereby limiting the extent of destruction along the transport pathway as well as in the deposition zone. Here we explore each of these influences.

2.1 Material retention

Forests act to retain material on hillslopes and around channels. The main services provided by protection forests with respect to material retention are summarized in Table 1.

Hillslopes

On hillslopes, the forest function varies according to the hazard process. With respect to landslides, the forest influence is primarily related to soil cohesion and drainage; for rockfalls, forests increase surface roughness; and for snow avalanches, surface roughness as well as precipitation interception is increased by forests.

Forest vegetation supplies abundant below-ground root biomass that reinforces hillslopes against landslides. This root reinforcement is often included as an apparent cohesion in infinite-slope models of slope stability (SELBY 1993). In shallow soils, roots can penetrate through the entire soil column and act as anchors into the substrata (GRAY and MEGAHAN 1981). Roots in the upper soil horizons can create a root mat that reinforces the soil mass

(Sidle *et al.* 1985). Schmidt *et al.* (2001) found that the median root cohesion of old-growth forests was greater than that of post-harvest, second-growth stands up to 123 years old. This extended period of reduced root reinforcement agrees with a spatial and temporal model of root cohesion in Douglas-fir forests (Sakals and Sidle 2004). While investigating landslides in southeast Alaska, Johnson and Wilcock (2002) found that on slopes with soil depths <0.7 m, root cohesion was the most important factor governing slope stability. Root reinforcement is a key stabilizing factor provided by protection forests on many mountain slopes (Kitamura and Namba 1981; Marden and Rowan 1993; Ekanayake and Phillips 1999).

Forest canopies intercept precipitation. Water intercepted in forest canopies is typically evaporated (Hewlett 1982). This evaporation reduces water availability for other hydrogeomorphic processes, such as surface erosion or landsliding. The amount of water removed depends both upon the structure of the forest and characteristics of the precipitation event; the forest effect diminishes as the intensity and duration of the rainfall event increases (Hewlett 1982).

Precipitation that reaches the soil surface is often rapidly drained. Roots create hydrologic pathways that form macropores that are connected with other preferential flow pathways to form a hydrologic drainage network (Noguchi *et al.* 2001). Organic matter increases drainage through surface layers (Buttle *et al.* 2000) and the soil matrix. These processes decrease the development of high pore water pressures that are associated with slope failure, unless the macropores terminate or converge, thereby concentrating subsurface drainage (Uchida *et al.* 2001; Sidle and Ochiai 2006). Even in Taiwan, where precipitation can exceed 100 mm/h, overland flow occurs infrequently due to the high permeability of forest soils (Cheng *et al.* 2002). This tends to limit surface erosion and the formation of rills and gullies.

Initiation of rockfall may be increased by roots as they may promote detachment while penetrating cracks and fissures in the rock. Rocks are slowly forced apart by root growth forming a pathway for water to further enter the rock mass. However, roots have also been found to bind rock particles together. The net effect is expected to be dependent upon site conditions (Perret *et al.* 2004).

Compared to open areas, snowpacks in forest areas have increased variability due to the influence of trees and other structural elements. The uneven and patchy structure of a forest, both horizontally and vertically, prevents extensive weak layers from developing across a hillslope, inhibiting avalanche initiation (McClung 2001). Snow and water falling from trees, and interception in tree canopies, contribute to snowpack heterogeneity in forested areas. Slopes exposed to snow loading by wind are more prone to develop snow avalanches; forests shelter slopes to decrease wind transport (McClung 2001). Forests also increase snowpack stability through the microclimate effect of decreased radiative losses and reduced daily temperature variation (Weir 2002). The most substantial increase in snow stability from forests is the increase in ground surface roughness from tree stems, and downed wood and stumps; these structures positively affect snow stability (McClung and Schaerer 1993; McClung 2001; Weir 2002). Studies in forests with windthrow and insect-damage found that fallen stems may provide structure to limit avalanche initiation for up to 30 years (Frey and Thee 2002; Kupferschmid Albisetti *et al.* 2003). However, the protection afforded by the dead and decaying forest debris decreases during this period as it comes into closer contact with the ground surface. Unless regeneration establishes structure in snow avalanche initiation zones, costly construction and maintenance of prevention structures may be required (Weir 2002). Retention of snow by protection forests allows people to inhabit many areas in the valleys of the Alps where they could not otherwise live (Schönenberger *et al.* 2005).

Channels and riparian areas

The role of forests in retaining material in channels is not as pronounced as on hillslopes; however, forests do exhibit some influence. Considerable debate has surrounded the effects of forests in reducing flood flows. Hydrogeomorphic floods consist of both water and sediment, with the sediment comprising <20 % by volume or <40 % by weight (WILFORD 2003). Generation of the two components occurs somewhat independently. Water is delivered by rainfall or melting snow or ice or in combination. Water flows downslope by various processes, eventually joining channels and progressing downstream. Sediment is mobilized from hillslopes as mass movements that are often associated with precipitation events, or sediment is entrained from the margins of channels often associated with peak flows.

The effect of forests on the generation of the water component of floods is variable. Interception and evaporation of precipitation will reduce the water available for flood generation, but the effect is small for hydrogeomorphically significant events (HEWLETT 1982). However, in areas of continental climate, forests influence the seasonal accumulation and melting of snow. Recent modeling work indicates that the location of cleared forest areas is one of the more important factors in increasing peakflows from seasonal snowpack melting in these areas (SCHNORBUS and ALILA 2004). The structure of the forest is also important to the rate and timing of snowmelt as it affects the energy balance within the forest; less snow and slower melt rates have been found in forests compared to cleared areas (WINKLER *et al.* 2005). Further forest effects include a dampening of the flood hydrograph relative to impermeable surfaces. This is due to the infiltration of water into the soil and the storage capacity of unsaturated soils. This effect is reduced as the soil becomes wetter; the excess water effectively bypasses the soil matrix and is rapidly drained via preferential flow pathways (SIDLE *et al.* 2000). The dampening of the hydrograph is much more strongly affected by the intensity, size and the routing of the storm relative to the size and shape of the basin. Analyzing the effects of forest harvesting on the peak flow response is nearly always confounded by the presence of roads that have a different, and generally larger, influence on the hydrology than does the felling of trees (WEMPLE *et al.* 1996; SIDLE *et al.* 2006).

Forests have a strong effect on the presence of sediment in floods and debris floods. In addition to the influence of forests on hillslope hazards as covered in the previous section, forests affect the hydraulic roughness of the bed and banks of channels. Roots are important in limiting bank erosion along stream channels (ABERNETHY and RUTHERFORD 2000) and in reinforcing the soil mass where avulsions occur (WILFORD *et al.* 2005). Woody debris derived from forests stabilizes the bed and banks of channels such that floods and debris floods transport less sediment (LISLE 1996). Channel widening by the erosion of the channel bed and banks is linked to the removal of vegetation and in-stream woody debris (ERSKINE and WEBB 2003). Trees and woody debris, along with other riparian vegetation, increase channel roughness, resulting in more energy dissipation and sediment retention around channels (PIEGAY and BRAVARD 1997; GOMI *et al.* 2001; WILFORD *et al.* 2005). In a fourth-order stream in the Oregon Coast Ranges, REEVES *et al.* (2003) found that about half the wood was from upland sources, likely transported downstream by debris flows. Thus, protection forests influence downslope and downstream areas rather than just their immediate vicinity. The combined effect of riparian forests is to decrease the erosive energy of high discharge flows.

Table 1. Summary of hydrogeomorphic hazards and protection forest influences that assist in hazard mitigation for the retention of material on hillslopes and in channels.

Retention			Hydrogeomorphic Hazard		
Forest Influence	Debris Flood	Debris Flow	Flood	Rockfall	Snow Avalanche
Physical Structure	Forest cover in the watershed can influence snowmelt to decrease peak streamflows	Forest cover in the watershed can influence snowmelt to affect soil moisture	Forest cover in the watershed can influence snowmelt to decrease peak streamflows	Nil	Increases snow stability due to surface roughness and anchoring, and microclimate influence on snow metamorphisis
Root Reinforcement	Increases slope stability, reinforces channel banks	Increases slope stability, reinforces channel banks	Increases slope stability, reinforces channel banks	Depends on site conditions – can increase or decrease hazard	N/A
Soil Conditioning	Reduces overland flow and increases slope stability by increasing hydraulic conductivity	Increases slope stability by increasing hydraulic conductivity	Reduces overland flow and increases slope stability by increasing hydraulic conductivity	N/A	N/A

Table 2. Summary of hydrogeomorphic hazards and protection forest influences that assist in hazard mitigation for the containment of material in transport zones on lower slopes and in riparian areas.

Containment			Hydrogeomorphic Hazard		
Forest Influence	Debris Flood	Debris Flow	Flood	Rockfall	Snow Avalanche
Physical Structure	Provides structure for energy dissipation, impedes flow, facilitates log jam formation	Provides structure for energy dissipation, impedes flow, facilitates log jam formation	Provides structure for energy dissipation (increases Manning's n), impedes flow, facilitates log jam formation	Provides structure for energy dissipation	Provides structure for energy dissipation, impedes flow
Root Reinforcement	Reinforces channel banks and soil mass to limit channel avulsions	Reinforces channel banks and soil mass to limit channel avulsions	Reinforces channel banks and soil mass to limit channel avulsions	Nil	N/A
Soil Conditioning	N/A	N/A	N/A	N/A	N/A

2.2 Material containment

Following mass movement initiation, forests limit the extent of disturbance along the transport path of hydrogeomorphic events. This process becomes more pronounced during deposition, when the energy of the moving mass declines, which generally happens when the slope decreases. This effect has been found for a variety of processes (WEIR 2002; WILFORD *et al.* 2003; GOMI *et al.* 2004). Table 2 relates the role of protection forests with the containment of material from hydrogeomorphic processes and protection forest elements.

Hillslopes

Forests in rockfall initiation areas have been observed to arrest rockfalls before they accumulate much momentum (DORREN *et al.* 2004). Rockfall energy is dissipated by forests through collisions with standing trees and other debris (DORREN and SEIJMONSBERGEN 2003; DORREN *et al.* 2004). Rockfall events may uproot or break the stems of trees; thus both the uprooting strength and the stem strength, both of which are dependent on species, will determine the effectiveness of individual trees (STOKES this issue). Stem density is important in determining the capacity of the stand to arrest rockfall events.

Snow avalanches are also confined by the structure of the forest. The containment of snow avalanches by forests is limited to lower-energy situations such as small avalanches or the margins of the flow and deposition area of larger events. In many situations, the energy of the avalanche is too great to be significantly affected by the forest structure (WEIR 2002).

Channels and riparian areas

The hydrogeomorphic riparian zone refers to the geomorphic, hydrologic, and forest factors that influence water and sediment during hydrogeomorphic events (WILFORD *et al.* 2005). Features of this zone include buried trees, scarred trees, downed woody debris stored sediment, and more. The features are generated as the energy of the water and sediment during an event are decreased in the forests adjacent to the channel. The forest enhances sediment deposition in the zone and limits the extent of destabilization (WILFORD *et al.* 2003). The hydrogeomorphic riparian zone is not process-specific but applies to floods, debris floods, and debris flows (WILFORD *et al.* 2005).

Research supports the idea that forests reduce debris flow runout distances (IRASAWA *et al.* 1991; LANCASTER *et al.* 2003). The effect has been investigated using a physical laboratory model, with the results indicating that debris flow velocity is reduced and sediment deposition is enhanced in the presence of wood (IRASAWA *et al.* 1991). LANCASTER *et al.* (2003) used a mixed empirical, stochastic and physical model to demonstrate that woody debris entrained by debris flows decreased runout distances. In an empirical study of debris flows and adjacent forest age in the Oregon Coast Range, data collected on 53 debris flow channels did not support statistical separation of runout distance based on the age class of the surrounding forest (MAY 2002). However, it was noted that debris flows initiating in clear-cuts and mixed aged forests did have instances of exceptionally long runout lengths that were beyond the variability present in the data from the completely forested debris flows initiation sites.

For floods, JOHNSON *et al.* (2000) found that more stream channel erosion occurred within timber-harvested reaches than in old-growth forests. The history of land management was important in determining the conditions of the channel margins and the riparian forests. Also, in the case of a potential avulsion (rapid lateral movement of the stream channel) where topographic confinement is not strong, the forest influence maintains a high hydraulic roughness relative to the channel (WELSCH 1991; PIEGAY and BRAVARD 1997); this inhibits stream avulsions (WILFORD *et al.* 2005). Flow resistance due to the presence of debris and vegetation has been widely studied and a substantial increase in Manning's n (channel roughness factor) has been found (COWAN 1956; CHOW 1959; DUDLY *et al.* 1998; KOUWEN and FATHI-MOGHADAM 2000).

3 Management for hazard reduction by forests

Land managers using protection forests may realize substantial savings over engineered structures, even if intensive forest management is required (BRANG *et al.* 2001). Protection forests represent a balance between protection and production. Protection forests may not prevent hydrogeomorphic events from occurring, but may decrease their effects even for very large events (SIDLE *et al.* 1985; MOTTA and HAUDEMAND 2000; CHENG *et al.* 2002; WEIR 2002).

The resistance to disturbance, and the recovery rate following disturbance, form the long-term capacity of protection forests. Resistant forests are less susceptible to losing their protective function as a result of hydrogeomorphic events or other disturbances; resilient forests will recover protective functions more rapidly after a disturbing event (O'HARA this issue). Healthy, mature forests tend to have higher levels of resistance and resilience, but not always. The explicit inclusion of forest management objectives that aim to increase these attributes will help maintain protective forest services in the face of natural and human disturbances such as windstorms, pest outbreaks or forest harvesting. The silvicultural challenge in many situations is to develop multiple-aged stands to maintain acceptable levels of resistance and resilience without allowing them to drop below the levels required for protection (O'HARA this issue). There are two factors that make this difficult. First, if the forest is even-aged, the protective capacity may be reaching a maximum due to the size and strength of the trees; however, the resilience will be nearing a minimum. Such a narrow distribution of tree ages should be expected to result in a temporally fluctuating level of protection similar to that of a single tree. Second, as trees get old they begin to die. Although dead trees have both protective and ecological functions, the protective service is decreased relative to living trees, particularly over time (SCHÖNENBERGER *et al.* 2004). Even without a large disturbance, old forests begin to disintegrate and continuous tree cover is lost as canopy gaps form. O'HARA (this issue) discusses some of the silvicultural practices surrounding these issues.

Forested reserves provide a protection role to fulfil management objectives (e.g. forested riparian reserves for the maintenance of stream ecosystems). Although not officially designated as protection forests in British Columbia, Canada, the area of the commercial forest land base dedicated to the protection from hydrogeomorphic hazards is growing. This is particularly evident on forested alluvial and colluvial fans where although the forests are attractive for timber harvesting, the protective role of forests is crucial and forests are being preserved. This de facto designation is made with the understanding that the forest may provide strong protective services for a limited time due in part to the lack of a management regime to maintain the protection services.

The lack of formal protection forests goes hand-in-hand with the potential for degradation. This is highlighted by an anecdotal story from Japan describing a fan that was prone to overbank flows (SATO 1991). "Flood-control forests" were planted along the watercourse in 1905 to protect the adjacent areas. During the period following 1905, some of the riparian protection forests were cleared for residential developments. In 1990, a hydrogeomorphic event occurred and caused considerable damage, particularly in reaches where flood-control forests had been removed. In reaches where the riparian forests remained, the damage by sediment and flow broadcasting was limited.

Protection forests, by designation or default, are instrumental in maintaining the quality of life and productivity of people and the environment in many mountain regions. It must be realized that science is only beginning to identify the stand characteristics that will optimize the protective functions of forests for specific hazards (BEBI *et al.* 2001; DORREN *et al.* 2004; PERRET *et al.* 2004). As this research progresses, management of protection forests should maximize the resistance to change from hydrogeomorphic and other disturbances and maximize the resilience, or the rate of protective function recovery following disturbances (BRANG 2001; O'HARA this issue). This will maximize benefits over the long-term.

4 Conclusions

Forests can reduce hydrogeomorphic hazards by retaining material in upslope and upstream positions and by limiting the extent of disturbance caused by events once they have initiated. The protective functions affect both above- and below-ground processes. The above-ground functions relate to the physical structure of the forest: increased ground surface roughness decreases the initiation of snow avalanches through a variety of processes; forest canopies intercept precipitation that is often evaporated, rendering it hydrogeomorphically inactive; and the stems of trees, both standing and down, reduce the areas disturbed by snow avalanches, rockfalls, floods, debris floods and debris flows. The major below ground functions are the influences on hillslope hydrology, allowing rapid subsurface drainage to avoid high pore water pressures, and the cohesive effect of vegetation roots binding the soil mass and anchoring the soil to the bedrock.

If the protection service is desired for the long-term, the management of the forest must be sensitive to the age distribution of the forest as it affects the rapidity of protective function recovery after disturbance. Given the expected magnitude-frequency relations of many hydrogeomorphic hazards, protection forests are an attractive solution for aesthetics, economics, safety and sustainability.

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