Watershed Challenges for the 21st Century: A Global Perspective for Mountainous Terrain

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Abstract.—Three global challenges for watershed researchers in the 21st century are examined in this paper. These challenges are obtaining better assessments of terrain stability; understanding hydrologic responses at different watershed scales; and developing better methods for analyzing and assessing cumulative watershed effects. These topics are only a subset of the pressing issues facing watershed management in the coming century. However, they are important examples in the continuum from contributing processes (landslides), driving mechanisms (hydrologic response), and integrated watershed behavior (cumulative watershed effects). Emphasis will be placed on examples and needs in steep forested watersheds in considering these challenges.

Introduction

Watershed management is a highly interdisciplinary field. Hydrologic behavior in watersheds is complex, and is controlled by interactions among physical, geomorphical, biological, and geochemical processes. Planning and decision making in watersheds must also consider socio-economic and political objectives in the broader context of land use practices, allocation, and regulation. Within such an integrated perspective, it is important to remember that the primary driver in watershed systems is *hydrologic response*. Especially when considered from the viewpoint of small watersheds, such response controls the timing, amounts, and fluxes of water, nutrients, sediments, organic material, and pollutants to larger watersheds and drainage basins; as such it is the driver. Without understanding the controls on these materials, it is difficult to formulate prudent long-term management decisions and policies in watersheds. An outline of this simple conceptual model of integrated watershed management is presented in figure 1.

Both spatial and temporal distribution of land uses must be considered in watershed management. The concept of *cumulative watershed effects* (Sidle and Hornbeck 1991) addresses these spatial and temporal dynamics in the context of natural ecosystem processes. While empirical approaches have been developed by land management agencies and private sector organizations in response to legislation that requires assessment of cumulative effects, a sound approach to analyzing cumulative watershed impacts based on hydrologic response at different scales is lacking. Certainly, many of the cumulative effects issues are site-specific and, thus, need to be addressed in a local context; however, more general approaches can be taken for certain processes-based cumulative effects.

Three global challenges for watershed researchers in the 21st century are examined in this paper; this examination is based on the integrated watershed model in figure 1. These challenges are obtaining better assessments of terrain stability; understanding hydrologic response at different watershed scales; and developing better methods for analyzing and assessing cumulative watershed effects. These three topics are only a small subset of the pressing issues facing watershed management; however,

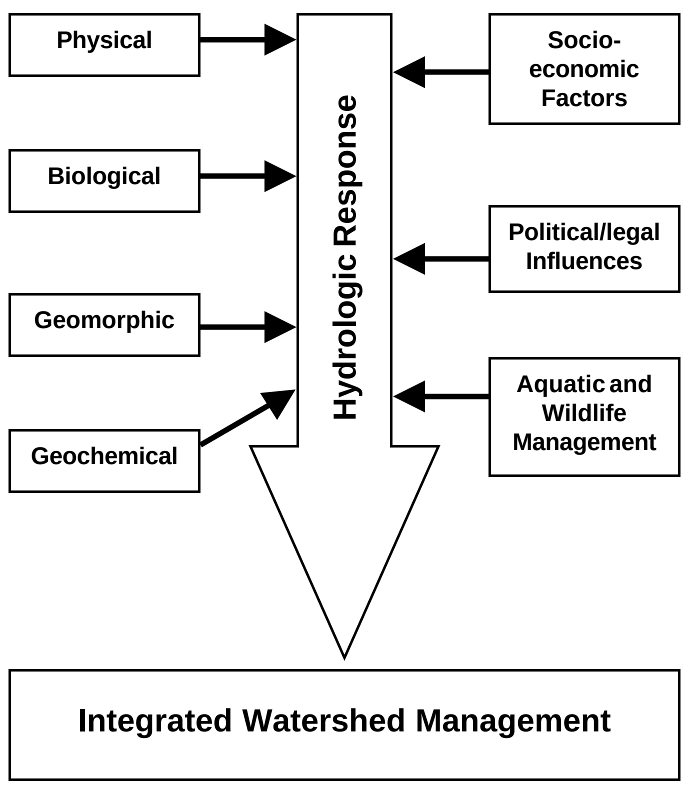

Figure 1. A conceptual model of integrated watershed management.

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they do represent important examples in the continuum from contributing processes (landslides), driving mechanisms (hydrologic response), and integrated watershed behavior (cumulative watershed effects). Emphasis will be placed on examples and needs in steep forested watersheds.

Terrain Stability

Timber harvesting, road construction, and certain types of vegetation conversion practices have been empirically demonstrated to increase landslide occurrence. Processes that influence this increase in landslide activity are known to vary with disturbance type. Increases in shallow landslide occurrence and volumes have been observed 3 to 15 years after timber harvesting in many areas worldwide (Bishop and Stevens 1964, Fujiwara 1970, Swanson and Dryness 1975, O'Loughlin and Pearce 1976, Megahan et al. 1978). The timing of landslide initiation corresponds to the period of significantly reduced root strength after logging and the occurrence of a major storm or snowmelt event. The conversion of forest and brushland vegetation to pasture or grassland has been shown to significantly reduce rooting strength in the soil and, in steep terrain such as parts of New Zealand (O'Loughlin and Pearce 1976) and southern California (Rice et al. 1969), has substantially increased landslide frequency and volume. Similarly, slash and burn agriculture practices used in developing regions of Asia and Latin America reduce site stability when steep forest lands are converted to temporary cropland with weak root strength characteristics (Wright and Mella 1963, Starkel 1972). Road systems in steep forest terrain are the largest contributors of landslide erosion on a unit area basis and, in many cases, the primary contributor overall (O'Loughlin and Pearce 1976, Sidle et al. 1985). Stability problems associated with forest roads include overloading effects on the embankment fill material, placement of unstable fill material on steep slopes, undercutting the hillslope, and redirecting road drainage water onto unstable portions of the hillslope or fill material. The later problem, road drainage, is commonly blamed for many road-related failures but is quite difficult to predict due to the complex nature of drainage systems, imperfect knowledge of road hydrology, and problems associated with drainage system failure (clogged cross drains) during runoff events.

Predicting Slope Failures

Given our knowledge of these management effects on slope stability, we have not been particularly successful at predicting where slope failures will occur, what the downslope or downstream impacts will be, or even estimating the increase in overall probability of slope failure related to various management activities. At the landscape or large watershed level, terrain evaluation procedures have been developed that utilize topographic and geologic information to provide broad categories of landslide hazard related to potential harvesting, road building, and other management activities (Gage and Black 1979, Howes and Kenk 1988). In regions where good site data and landslide records are available, the effect of land use can be evaluated by weighted multi-factor overlays (Nielsen et al. 1979, Hicks and Smith 1981). Both of these terrain assessment methods are qualitative and successful application relies heavily on expert knowledge.

Potentials exist for improving qualitative terrain assessment procedures. One possibility would be to include weighted factors into the terrain stability assessment that reflect not only terrain attributes associated with landslides, but also that emulate the underlying processes that contribute to slope failure. Such causative factors as rainfall intensity and duration, seismicity, and snowmelt, and other parameters influencing landslide potential (root strength, slope gradient, topographic expression, groundwater concentration zones) may need to be incorporated into terrain hazard analysis. Another needed improvement is the application of stability assessment methods to larger geographic areas or to areas that experience multiple failure types (slump-earthflows, debris avalanches, etc.).

An example of a simple GIS-based terrain hazard analysis applied in the Ramganga Catchment of the Lower Himalayas (Gupta and Joshi 1990) is shown in figure 2. Weightings for various factors used in the analysis are shown in parentheses, with larger weights representing more unstable conditions. In this region, earthquakes and rainfall trigger landslides. However, because of the paucity of spatially distributed data (particularly in steep mountain regions), causative factors were not included in the analysis of landslide hazard potential. Also, the assessment only incorporated recent and older failures, that is, not potential failures; thus, slope gradient was not included. This important parameter together with information related to vegetation, topographic expression, and causative factors would obviously improve the GIS hazard zonation especially if inferences on future land use changes are desired. Suggestions for improving the terrain hazard analysis are incorporated in figure 2 in the stippled boxes. As better remotely sensed data for some of the causative and related factors become available, such improvements for remote regions and developing nations can be feasible.

The U.S. Geological Survey developed an advanced, real-time forecasting system for shallow landslides in the

San Francisco Bay area. This method uses terrain attributes together with established rainfall intensity and duration thresholds for initiation of debris flows on susceptible slopes in the region. These thresholds were then linked with real-time rainfall data to develop a warning system for landslides during major storms in the region (Keefer et al. 1987). While such an advanced warning system is dependent on spatially distributed, accurate, and timely dissemination of triggering data (rainfall, snowmelt, seismic activity), it is possible that similar applications could be successful in densely populated regions where local governments made commitments to support regional networks of remotely accessed triggering and antecedent moisture data. Real time rainfall forecasts using Doppler radar are improving and may have future application in such hazard warning systems. Additionally, continuing advancements in microwave remote sensing (Verhoest et al. 1998) can be helpful in assessing antecedent soil moisture in potentially unstable terrain.

Distributed landslide analysis has recently been employed to predict landslide potential in larger watersheds and to design appropriate land management strategies. When distributed, physically-based modeling is applied to landslide analysis, not only are the distributed properties of the parameters of concern, but also the model output represents a spatial problem, because we need to know the locations of landslides. Although GIS

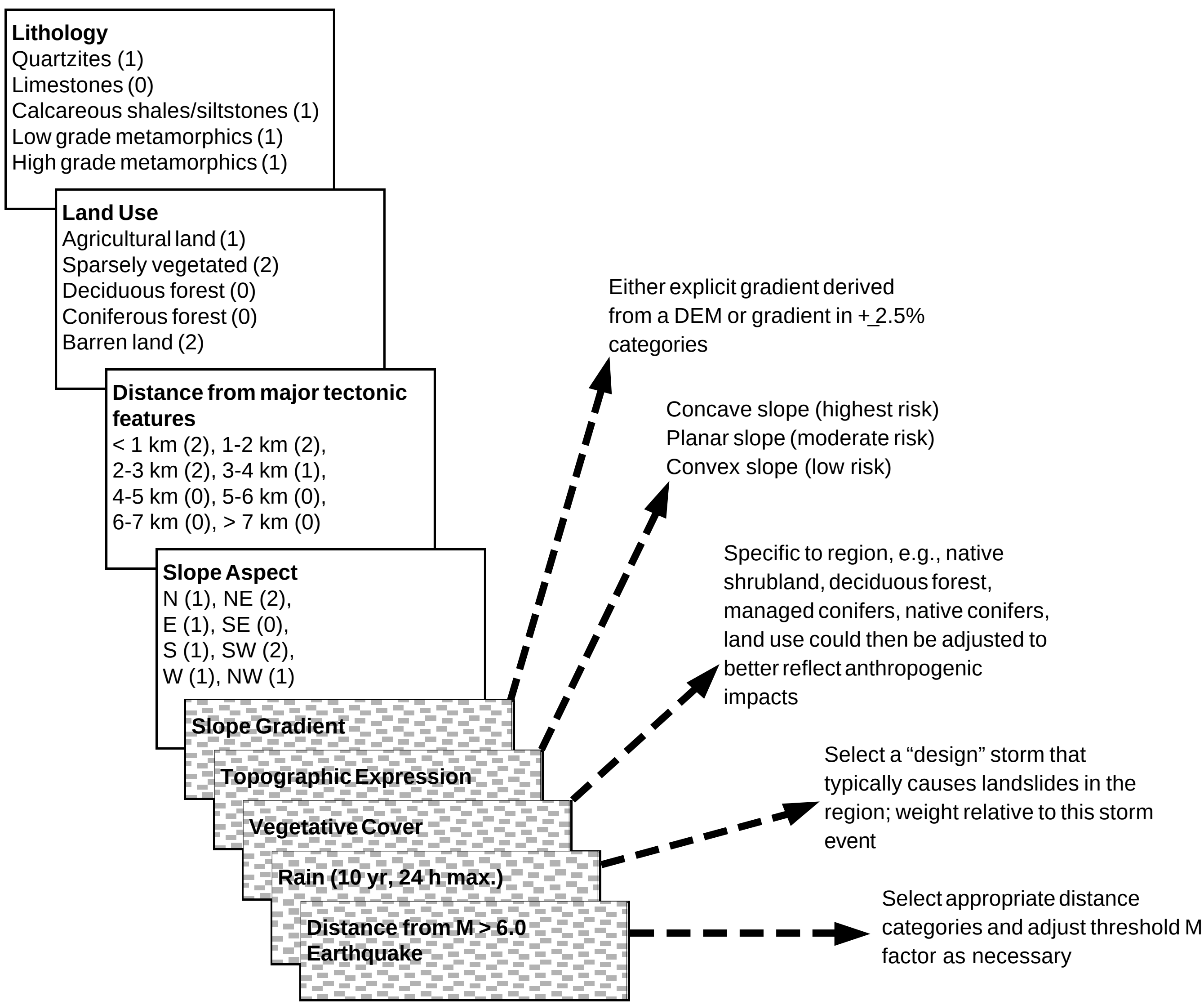

Figure 2. A weighted, multi-factor analysis for assessing terrain stability based on methodology of Gupta and Joshi (1990) for the Ramganga Catchment in the Lower Himalayas. Weightings for factors in the analysis are shown in parentheses, with larger weights representing more unstable conditions. The stippled boxes represent suggestions for improving the GIS-based terrain hazard analysis.

technology is highly regarded as a tool for landslide analysis in terms of spatial data extraction and display (Shasko and Keller 1991), little progress has been made to incorporate distributed, physically-based slope stability modeling with GIS. A recent physically based model (SHALSTAB) for shallow landslide analysis developed by Montgomery and Dietrich (1994) couples digital terrain data with near surface through flow (TOPOG, O'Loughlin 1986) and slope stability models. Recent versions of SHALSTAB assume that soils are cohesion-less and ignore the effects of vegetation root strength. Another distributed landslide (dSLAM) is based on an infinite slope model, a kinematic wave groundwater model, and a continuous change vegetation root strength model (Wu and Sidle 1995). This model has the advantage of predicting the effects of actual or hypothetical forest management scenarios, including clear-cuts, shelterwood cuts, alternate thinnings and clear-cuts, and partial cuts. The model has the flexibility to utilize either actual storm records or synthesize a random Monte Carlo series of storms. Two successful applications of dSLAM in managed forested basins in coastal Oregon (Wu and Sidle 1995, 1997) suggest this to be a promising tool that can be applied to unstable, intensively managed forest sites. Both SHALSTAB and dSLAM predict only shallow, rapid failures (debris slides, debris avalanches) triggered by rainstorms.

Some of the challenges that currently limit the successful prediction of landslide hazards using distributed, physically-based models include data limitations; inaccuracies in the groundwater model component; need to incorporate effects of low volume roads; need to simulate snowmelt processes as a trigger mechanism; inclusion of multiple failure types; and better simple routing models for debris flows. Limitations of data range from lack of spatially distributed data on soil depth, soil physical and engineering properties, and vegetation parameters (including rooting strength) to the need for better digital elevation models (DEMs) to characterize topography. In some cases, algorithms for parameters like soil depth and cohesion can be developed from more easily obtainable attributes such as topographic index and soil texture. Currently, such tested algorithms are not available. By the nature of the desired spatial application of distributed landslide models, hydrologic models that are more detailed than the stream-tube model (Moore et al. 1988) incorporated in dSLAM will be difficult to implement. However, with improved knowledge of fundamental stormflow pathways (see next section), some modification of existing subsurface flow models can be possible. Progress is currently underway to incorporate the effects of road systems into dSLAM. Issues related to the redistribution of surface and subsurface water by roads are critical to our understanding of managed watershed behavior. Such information is needed not only to assess landslide hazard but also to evaluate effects of roads on peak flows. Snowmelt has been successfully simulated in the context of other distributed hydrology models (DHSVM, Wigmosta et al. 1994), but no such applications have been incorporated into landslide models to emulate this important trigger mechanism. Little progress has been made in incorporating multiple landslide types into physically based models due to the differences in processes, movement rates, and periods of activity. Because theoretical models for debris flow routing require excessive parameterization, it is likely that simple empirical models will need to be developed and tested on a regional basis (Benda and Cundy 1990).

Linkage Between Processes

Another topic related to terrain stability that is poorly understood is the linkage between hillslope processes (debris avalanches, earthflows, etc.) and headwater and main channel processes (debris flows, bedload transport, suspended sediment transport, channel scour and fill). Knowledge of this linked behavior is important for predicting long-term effects of forest management on aquatic habitat, fluvial geomorphology, and water quality. While low gradient downstream reaches have been studied in terms of sediment movement, hydrologic response, and aquatic productivity, headwater systems have been largely ignored. In steep terrain, headwaters are subject to active erosion processes such as shallow landslides, debris flows, bank failures, and surface erosion. Woody debris in headwater channels provides temporary storage sites for this sediment. The dynamics of sediment storage and release related to woody debris is largely unknown. Management of riparian zones in headwaters has recently come under intense scrutiny. Issues, such as the width of buffer-leave strips necessary to protect channels and supply a sustainable level of large woody debris to streams, have been intensively debated (Streeby 1971, Murphy and Koski 1989) with little long-term data to support various economic, environmental, and political objectives. Furthermore, the effects of changes in inputs of woody debris over entire forest rotation cycles (40 to 100 years) on the overall attributes of headwater systems, particularly with respect to sediment movement, channel condition, and aquatic habitat, are virtually unknown. Such interactions will be briefly discussed in the context of cumulative watershed effects.

Control Methods

Given the current state of knowledge about landslide mechanisms and related effects of land management practices, there are some practical applications that need to be greatly improved. A notable example is the use of surface erosion control methods to attempt to ameliorate active landslide sites. Because landslides involve the mass displacement of the entire soil mantle and possibly some of the weathered regolith, grasses with shallow and weak roots offer almost no protection against landslide movement. However, grass seeding on active landslide sites remains a common "remediation" practice on private and public lands. True, establishment of grass cover will offer short-term protection against surface erosion; however, this benefit is negated if mass wasting remains active. Such phenomena can be observed on unstable over-steepened road cuts that have been reseeded: clumps of sod-covered soil often lay in the ditch-line as the result of bank sloughing. This case is an example of where improvements in technology transfer information are needed.

Hazard Assessment

Hazard assessment on colluvial and alluvial fans is a related area where advancements are needed in both technology transfer and scientific understanding. Such sites are conspicuously mismanaged in terms of residential development, water supplies, road construction, and other infrastructures. In steep forested watersheds, these sites are superficially attractive to developers since they represent some of the gentlest terrain. In arid and semi-arid environments, fans are much easier to delineate due to the paucity of vegetation, while in humid forested environments it is often difficult to detect evidence of older fan surfaces. Channels in fans are subject to avulsions and, thus, engineering methods commonly applied in flood control are typically doomed to fail since these avulsion channels have no defined floodplain, and it is nearly impossible to predict the direction of new avulsion channels. However, important features of channels on fans can be identified that provide insights into the susceptibility of channels to avulsions (channel depth, number of channels, degree of vegetation establishment). It is also important to distinguish between the causation factors related to fan development. Colluvial or debris fans are formed by debris flows and are directly linked to upslope landslide activity. Thus, geomorphic linkages among upslope landslides, debris flow initiation, and fan formation must be considered in hazard assessments for colluvial fans. In contrast, alluvial fans are formed by flood events and related sediment transport. They tend to have a gentler gradient and materials are better sorted compared to colluvial fans. In this case of hazard analysis for alluvial fans, stormflow generation mechanisms, flood magnitude and frequency, and bedload transport are major factors to be considered. In some cases, both processes can occur together, although one process usually dominates. Additionally, individual fans can be composed of both alluvial and colluvial components that are temporally separated. Most current hazard analysis conducted on fans does not distinguish between hydrogeomorphic formation characteristics.

Hydrologic Response in Forested Headwaters

Several features of headwater forested catchments result in different hydrologic response compared to similar sized agricultural and urbanized watersheds and larger scale basins with mixed land use. First of all, most forest soils have high infiltration capacities; thus, infiltration excess (that is, Hortonian) overland flow rarely occurs. This is particularly true in temperate, sub-tropical, and tropical forests where substantial accumulations of soil organic matter occur. It is the general consensus that subsurface flow either plays an active role in stormflow generation in these headwaters or a more passive role in recharging wet riparian areas. Of course, such sites are susceptible to disturbance and compaction from various land use activities. Additionally, certain types of artificial forests can promote overland flow due to exclusion of understory species and lack of organic litter. Because this paper focuses on steep forest terrain, slope gradients and the related incised topography influence hydrologic processes. As such subsurface flow pathways to channels have a high elevation head and riparian corridors are typically narrow with little storage capacity for subsurface water (Sidle et al. 1995).

Streamflow Generation

From the mid-1960s until recently, the variable source area concept of streamflow generation has been accepted as a working paradigm for forested hydrology (Tsukamoto 1963, Hewlett and Hibbert 1967, Kirkby and Chorley 1967). This concept invokes a dynamic riparian source area that shrinks and expands in response to rainfall or snowmelt and fluctuating water tables. However, the model does not specify flow mechanisms or pathways functioning at different spatial scales within the watershed. Although the original research behind the variable source area concept was conducted in the steep, forested Coweeta Experimental Watershed in the southeastern United States, later insights into hydrologic mechanisms were derived from work in a mixture of agricultural and forested catchments with gentle slopes and broad riparian corridors. These later investigations cited saturation overland flow and return flow within broad, flat riparian areas as the dominant stormflow generation mechanisms (Dunne and Black 1970, Eshleman et al. 1993, Fujieda et al. 1997). Alternatively, Sklash and Farvolden (1979) attributed stormflow generation in such gently sloping basins to a groundwater "ridging" effect. Many such inferences have been incorrectly applied to steep, incised forested terrain in attempts to explain stormflow response.

In steep forested catchments, specific stormflow mechanisms have been cited, such as capillary fringe response (Gillham 1984), pressure wave effect (Yasuhara and Marui 1994), and preferential flow associated with macropores (Mosley 1979; Tsukamoto and Ohta 1988), soil pipes (Jones 1971; Kitahara and Nakai 1992), deflection over bedrock (McDonnell et al. 1996, Noguchi et al. 1999), and channeling through surface bedrock discontinuities (Montgomery et al. 1997, Noguchi et al. 1999). These studies in steep forested terrain typically ignore Hortonian overland flow because of the high infiltration capacity of soils. Thus, lateral subsurface runoff is at least partly caused by the presence of a hydrologic impeding layer (bedrock, till) below the soil profile (Harr 1977).

Although subsurface flow is generally regarded as a significant process in steep forested hillslopes, the importance of preferential flow pathways as direct links to stormflow production is still questioned. Large discharges from soil macropores and pipes during natural and simulated storms have been measured or inferred at steep forest hillslope sites (Mosley 1979, Tsukamoto and Ohta 1988, Kitahara and Nakai 1991). Studies with applied conservative tracers have shown that macropore systems increase in importance (Chen and Wagenet 1992) and can expand during wetter conditions by interacting with surrounding mesopores (Tsuboyama et al. 1994). Such expansion can also include a lateral expansion of preferential flow networks by developing a complex linked network in the upslope direction (Tsuboyama et al. 1994, Sidle et al. 1999).

Macropore Flow

The issue of the relative importance of macropore flow was clouded by a series of potentially conflicting findings from the same catchments in New Zealand. Although Mosley (1979) measured high macropore discharges during storms, later oxygen isotope tracer studies questioned the importance of macropore flow because of proportionally high measured discharges of "old" water during storm runoff (Pearce et al. 1986, Sklash et al. 1986). These later investigations that associated "old" water discharge with matrix flow and "new" water discharge with macropore flow can be misleading because of the potential for inter-compartmental mixing in the hydrologically active regolith (DeWalle et al. 1988, Sidle et al. 1995, 1999, Buttle and Peters 1997, Tsuboyama et al. 1998). Later investigations at the New Zealand study site noted predominantly "old" water discharging from macropores and hypothesized that continuous macropores in the soil purge stored "old" water when shallow groundwater tables rise during storms and intersect these flow paths (McDonnell 1990). However, the upslope connectivity of such macropore systems was not confirmed and results from other forest sites suggest that such long distance spatial connections rarely exist (Noguchi et al. 1997, 1999). Thus, although these studies in New Zealand advanced certain understanding of specific hydrological methods and processes, many of the inferences related to flow pathways were misleading.

Hydrogeomorphic Linkages

Insights into hydrogeomorphic linkages are needed to elucidate spatial and temporal attributes of flow paths that affect both headwater and downstream systems, including cumulative impacts of land use (Sidle and Hornbeck 1991, Burgess et al. 1998, Sidle et al. 1999). With increasing computational capabilities, it will be possible to simulate the behavior of more and more complex flow systems that deviate from the treatment of hillslope soils as isotropic and that only consider matrix flow (Freeze 1974). As such, priorities should be placed on understanding the dynamics of flow pathways in headwater systems related to changing antecedent moisture conditions, topographic attributes, and management impacts. Linkages between hydrologic and geomorphic attributes need further investigation, as do the factors influencing nonlinear or threshold responses on such hydrologic functions as runoff from hillslope hollows, expansion of preferential flow networks, and redistribution of subsurface water storage (Sidle et al. 1999, Tsuboyama et al. 1998, 1999). There is evidence that these thresholds can have different scale dependencies even within the range of relatively small zero-order through second-order basins. Improvements in microwave remote sensing can offer future possibilities for analyzing basin scale soil moisture, an important parameter controlling hydrologic thresholds and linkages, and even variable hydrologic source areas (Verhoest et al. 1998). However, such methodology is still plagued by backscatter problems attributed to vegetation cover and surface roughness (Cognard et al. 1995). Additionally, potential problems can arise if catchment hydrologic response is inferred in the context of simplistic or even incorrect conceptual models (Van De Griend and Engman 1985, Verhoest et al. 1998).

Routing of Water

Another important issue related to hydrologic response is the routing of water from headwater channels to lower gradient channels. Roughness elements, such as woody debris and boulders, more significantly influence water routing in headwater channels compared to large stream systems (Abbe and Montgomery 1996, Gomi et al. 1999). Dynamics of woody debris and hillslope processes that are related to various forest management practices can influence hydrologic routing. This issue is discussed in the context of cumulative watershed effects.

Cumulative Watershed Effects

In larger watersheds, a variety of land uses are typically distributed according to ownership, zoning restrictions, site productivity, and resource availability. The spatial distribution of such land uses can change through time depending on changing economic conditions, environmental issues, land ownership, technology, and regulatory constraints. These spatially and temporally distributed anthropogenic effects can interact with natural ecosystem processes to produce cumulative effects on watershed resources (Sidle and Hornbeck 1991). Additionally, larger scale anthropogenic factors, such as global change and changing demographics, contribute to cumulative effects. Affected resources can be both on site or occur downstream of the impact (figure 3). On-site cumulative effects can include increased landslide susceptibility due to repeated timber harvesting (Sidle 1991), progressive gully development in response to forest clearing (Prosser and Soufi 1998), and increases in soil

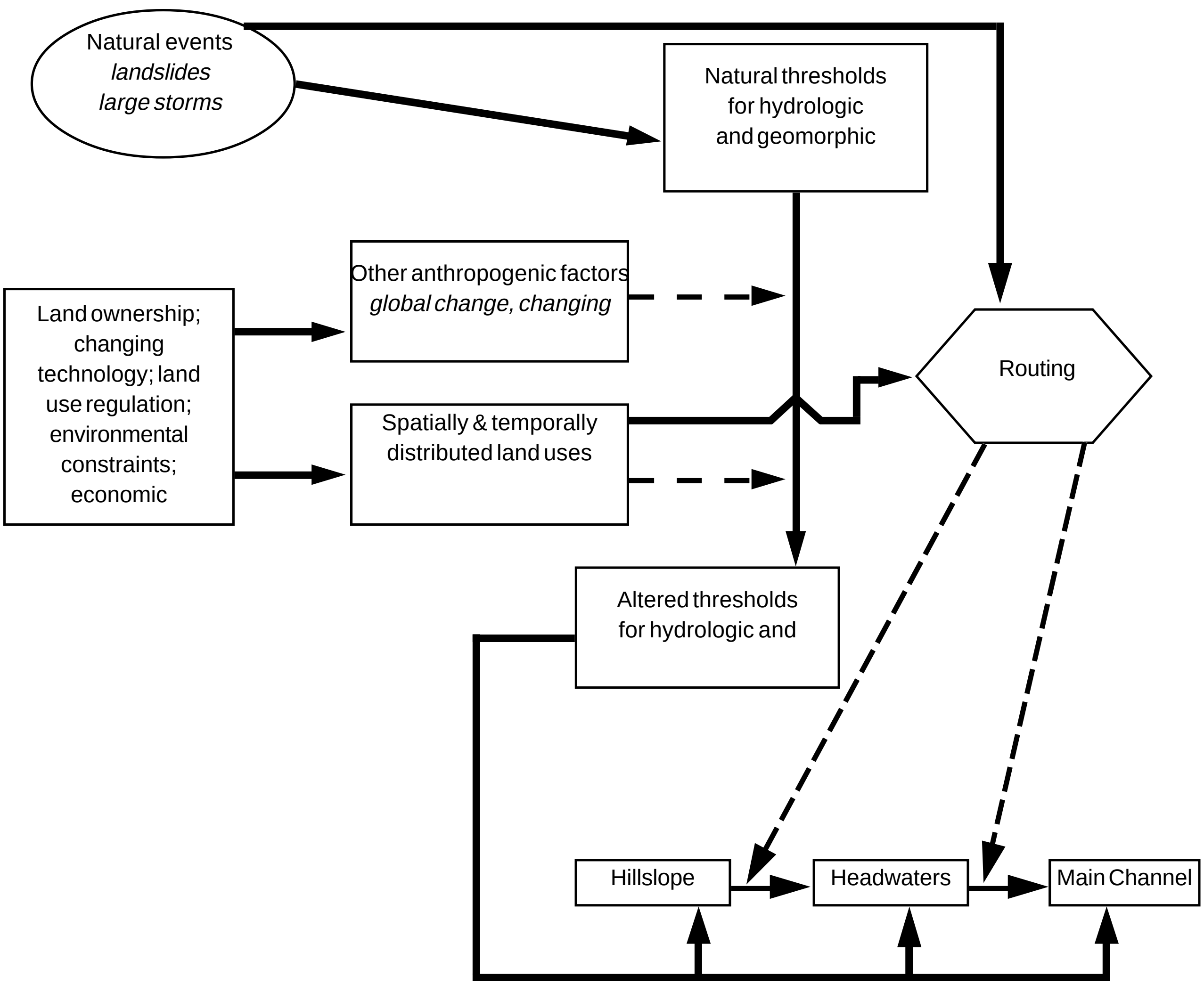

Figure 3. A linked system analysis for assessing cumulative effects of land uses on hydrologic and geomorphic processes in the watershed. Green denotes natural ecosystem processes; yellow external factors; pink ecosystem thresholds; orange routing functions; and blue affected system components. Solid black arrows represent compartmental connections; broken orange arrows represent process transfer or routing links.

compaction and surface runoff (Warren et al. 1986). Offsite or downstream cumulative effects include alteration of channel morphology and sedimentation regime (Lyons and Beschta 1983, Sidle and Sharma 1996), changes in water quality (Boyer and Perry 1987, Sidle and Amacher 1990), riparian vegetation response (Kauffman and Kreuger 1984), and stormflow changes (Jones and Grant 1996, Thomas and Megahan 1998).

Critical to the assessment of cumulative watershed effects is an improved understanding of how water and related materials (sediment, nutrients, pollutants, organic material) are routed through complex landscapes and what changes, if any, occur along the way. Understanding these routing processes requires careful consideration of spatial and temporal scaling issues such as hydrologic thresholds that trigger stormflow (Sidle et al. 1999, Tsuboyama et al. 1999), process linkages (Sidle et al. 1995, Tsuboyama et al. 1998, Brown et al. 1999), spatial variability in landscape properties (Sinowski and Auerswald 1999, Bierkens et al. 1999), "coarse-graining" in hydrologic observations (Kavvas 1999), disaggregation and aggregation criteria for hydrologic behavior (Becker and Braun 1999), and self-organization patterns and processes related to hydrologic behavior (Sidle 1999). Details of chemical and biological transformations, and the sinks and sources for these components will not be discussed. These issues are important to our understanding of cumulative effects on water quality.

The role of episodic natural events is particularly important in assessing cumulative effects. Episodic events can define thresholds of concern for certain ecosystem processes. Thus, if the occurrence of events above such thresholds should increase, the related effects on ecosystems would be much greater than if increases in events below the threshold occurred. Similarly, lowering of thresholds due to cumulative impacts of land use is also of concern. Geomorphic consequences of large storms vary not only by region but also by location in the catchment. Storm return periods of as large as 100 yr can be necessary to trigger major landsliding in some areas (Selby 1976), whereas events of much lower magnitudes (return intervals of about 5 yr) are believed to shape the course of large streams and rivers (Wolman and Miller 1960). Headwater channels can be influenced by intermediate sized events. Within such a continuum we need to focus on multiple hydrologic and geomorphic thresholds to adequately define the conditions and susceptibility of watersheds for analysis of cumulative effects (figure 3).

Examples of Cumulative Effects of Forest Management on Water and Sediment

Timber harvesting or vegetation conversion on steep slopes would potentially lower the threshold for a landslide-producing storm. Thus, the net effect would be a short-term (in a regenerating forest) or long-term (in a permanent vegetation conversion) increase in the probability of failure. Such effects could be simulated with distributed models like dSLAM (Wu and Sidle 1995). Thresholds for surface erosion would likely be lower and focused almost entirely on rainfall intensity. Changes in surface erosion response would depend greatly on the level of disturbance and site conditions. In most cases, we need to improve our understanding of what constitutes a significant geomorphic threshold – such as total storm rainfall, short-term rainfall intensity, antecedent moisture conditions, or a combination of these factors. For example, Prosser and Sofi (1998) attributed extensive gully development in Australia to ground disturbances caused by vegetation conversion and related these geomorphic changes to daily rainfall thresholds. However, many other investigations (Sidle et al. 1993) have shown that surface erosion is closely related to short-term rainfall intensities; thus, the thresholds proposed by Prosser and Sofi (1998) are potentially misleading.

Routing of sediment and water from hillslopes to main channels is an important and poorly understood linkage (figure 3). In landslide-prone terrain, the transition and timing from hillslope failures (debris slides, debris avalanches) to channel failures (debris flows) must be known to assess cumulative impacts. Questions such as - Do landslides convert directly to debris flows during an initiation event? or, Does a threshold of material need to accumulate in headwater channels prior to debris flow initiation? - must be answered. Such questions can require extensive field investigations; however, generalizations should be possible at local or even regional scales.

Once in the channel, routing of sediment and water needs to be considered in cumulative impact assessment. This becomes a complex issue that depends on the topographic characteristics of the channel and the interaction with riparian vegetation and related management effects. For sediment, both the storage capacity and longevity of storage related to hydrologic events and timber management are important. In the case of water routing, channel roughness due to boulders and dynamic inputs of woody debris can potentially influence the timing of runoff to larger streams. For both sediment and water routing, the influence of episodic debris flows on channel conditions must be considered. Factors influencing the more chronic transport of suspended sediment and bedload material need to be elucidated for headwater systems, particularly the supply of sediment available for transport during various peak flow conditions and changes in such supplies for different management scenarios. At this time, we are only able to identify important processes, construct sediment budgets, and develop crude models of water and sediment routing in complex headwater systems.

For lower gradient channels in the catchment, thresholds need to be established for bedload transport (Sidle 1988) and related channel changes (Lisle 1982), particularly in response to changes in woody debris volumes (Smith et al. 1993a, 1993b). The relationship between discharge and suspended sediment transport is better understood in managed forested catchments (Beschta 1978). However, for both bedload and suspended sediment transport in supply-limited streams, we need to develop better models that predict changes in sediment sources within the linked main channel system. Recent findings on "fingerprinting" techniques (radionuclide, magnetic properties, nutrients, carbon, heavy metals, etc.) for sediment samples are useful for identifying source areas (Walling et al. 1999). Response of peak flows in larger forest streams to management activities is a controversial topic (Jones and Grant 1996, Thomas and Megahan 1998). To progress, we need to investigate specific processes and conditions that can cause increases in discharge and determine over what range of discharges or storms such increases occur. Additionally, we need to establish links related to such increases with fluvial geomorphic effects and upslope conditions. Distributed hydrologic models such as DHSVM (Wigmosta et al. 1994) hold promise for evaluating cumulative impacts of land uses on peak flows, although better representation of certain hydrologic functions (road hydrology) can be necessary.

Although lower gradient channels serve as "integrators" for hillslope and headwater processes and have received the bulk of the attention to date, we need to now focus on linkages among all of these complex system components and related management practices to adequately address cumulative watershed effects. Such a simplified linked system analysis of the cumulative effects of land use on water and sediment is outlined in figure 3.

Practical Issues Related to Cumulative Watershed Assessments

From a practical perspective, it is reasonable to expect that empirical cumulative watershed effects procedures will continue to be used by land management agencies and industrial landholders. Such procedures like the Watershed Assessment Procedure (WAP) used by the Ministry of Forests in British Columbia offer an "all inclusive package" to address important cumulative effects issues such as water quality, slope stability, peak flows and aquatic habitat changes. These methods are based on local managers and scientists best knowledge of sensitivities to various watershed parameters and their response to management practices. The effective implementation of WAPs and similar cumulative effects procedures is contingent largely on user expertise. We now need to move beyond the point where cumulative watershed analysis is merely a regulatory compliance exercise to where it is representative of realistic long-term, spatially distributed processes in the watershed. Certainly, new research findings on watershed system responses and management effects need to be incorporated into the existing framework of empirical cumulative assessment procedures. Additionally, with advances in modeling technology and increased computing power, it appears possible to develop distributed, process-based models that have application directly to management, rather than just research tools. However, as with any model application, the most important consideration is ensuring that the underlying natural systems processes are adequately depicted. For cumulative effects analysis this implies both accurate temporal and spatial representation; thus, considerable basic field research will be necessary to define relevant processes.

Acknowledgment

Dr. Peter F. Ffolliott, University of Arizona, and Dr. Weimin Wu, University of British Columbia, are thanked for the reviews of this paper. This paper was prepared during my appointment as recipient of a Research Award for Foreign Specialists administered by the Forestry and Forest Products Research Institute, Tsukuba, Japan. My host, Shoji Noguchi, is acknowledged for his cooperation and support.

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