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Hydrological principles for sustainable management of forest ecosystems

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Introduction

Forested landscapes around the world are changing as a result of human activities, including forest management, fire suppression, mountaintop mining, conversion of natural forests to plantations, and climate change (Brockerhoff *et al.*, 2008; Cyr *et al.*, 2009; Johnston *et al.*, 2010; Miller *et al.*, 2009; Kelly *et al.*, 2010; Palmer *et al.*, 2010). Forests provide some of the cleanest and most plentiful freshwater supplies, sustaining many downstream communities. Given the ongoing changes in forests, forest management needs to be forward looking, flexible, responsive to ongoing changes, place-based relative to land use and the types of forest management systems and prescriptions applicable at a particular location, and open to the application of a more diverse range of management options and prescriptions (Williamson *et al.*, 2009) to ensure sustained supplies of high-quality water.

Forest scientists and managers are aware of the importance of conserving water resources in a changing landscape. Specifically, they know that forest management strategies should lead to preservation of hydrological flows, mitigation of extreme hydrological events, retention of soils and sediments, support productivity and biodiversity, as well as maintenance and purification of water supply. Conservation of water resources is already a forest management objective in most institutional settings (e.g. a necessary criterion in forest certification systems). However, on a global basis, water is still not getting the recognition it deserves in forest management.

We believe two major barriers exist to effective conservation of water resources: lack of a well-articulated conceptual framework and lack of practical strategies for implementing such a framework. The framework should consist of a set of principles based on hydrological theory, which could form the basis of ecosystem management to ensure sustainability of water and related resources in forested landscapes since hydrological processes drive so many of the geomorphic, biogeochemical, and ecological processes in forest ecosystems. Hydrological principles will better enable the broad forest hydrological community (including industry, governments, academia, and citizens) to develop sustainable management policies and practices that lead to safe and secure water resources.

This commentary originates from a Canadian project seeking to synthesize the state of knowledge on the implications of forest management activities on water resources under a changing global climate funded by the Sustainable Forest Management Network (Creed *et al.*, in press, a, b). This synthesis included previous reviews of science based on decades of small watershed studies, policy, planning and operational practices, as well as interviews and workshops with scientists and managers. Our objective is to share our Canadian experiences, as we believe they have international relevance and to propose a set of principles embedded within a systems approach to guide forest management

Table I. Hydrological principles of sustainable forest management

Hydrological principles	Management actions
1. Delineate hydrological system boundaries	
Consider the entirety of the hydrological system within which management actions take place	A) Delineate hydrological system boundary based on knowledge of dominant hydrological flowpaths (many hydrological systems will coincide with topographic boundaries but in some places other factors control hydrological response units)
2. Conserve critical hydrological features	
Minimize disturbance to hydrological features with critical source, transfer and storage functions	A) Minimize disturbance to soils, especially within or near source areas that focus the recharge of water into subsurface pathways
	B) Minimize disturbance in filter areas around streams, wetlands and lakes, and other sensitive sites (required buffer width will depend on dominant hydrological processes in given locale to maintain water quality of receiving water bodies)
	C) Minimize disturbance to storage areas (such as wetlands and ephemeral saturated areas)
3. Maintain hydrological connectivity	
Minimize disruptions to water, sediment, nutrient flows within terrestrial system	A) Consider the interconnectedness and interdependence of water pathways through watersheds when developing management plans (i.e. look beyond the forest stand and consider where the stand occurs with respect to the watershed and water flows)
	B) Locate roads, bridges, culverts, and harvest areas to ensure surface and subsurface hydrological connectivity is maintained and flow is neither impeded nor enhanced
4. Respect temporal variability	
Acknowledge temporal (historic) factors that influence hydrological processes	A) Recognize there is natural variability in hydrological processes at multiple scales from daily to multi-decadal
	B) Recognize there is human induced variability in hydrological processes of different severity (from past management practices to climate change)
	C) Recognize the timing, frequency, and magnitude of extreme events may be changing because of the interplay between natural and anthropogenic factors that are hard to separate
5. Respect spatial heterogeneity	
Acknowledge spatial (geographic and scale) factors that influence hydrological processes	A) Consider how scale influences dominance of hydrological processes (moving from headwaters to regional basins)
	B) Consider how geographic context influences dominance of hydrological processes, including climate, bedrock geology, surficial geology, soil type and depth, topography and its influence on the drainage network, and forest type and age
6. Maintain redundancy and diversity	
Manage with the ethos that redundancy and diversity of hydrological form and function contributes to a forest that can absorb outside disturbances	A) Consider watershed functions that might be most impacted by future extreme events and plan to protect features that perform those functions
	B) Consider multiple ecosystem services when assessing "trade-offs" in making development choices
	C) Consider the interactive nature of the hydrological system with climatic, geomorphic, ecologic, and socio-economic systems

on its way to a desired future with safe and secure water supplies (Table I). While some if not all these principles enjoy widespread use and recognition, their adoption may be selective or incomplete. Our question is: how generalizable are these principles? Our hope is to initiate a larger discussion among forest scientists, managers, and policy makers who either generate or use the science and to seek consensus for a core set of scientific hydrological principles for sustainable management of forest ecosystems.

A Principled Approach

Our principles are rooted in the classic systems approach including the description of a system's boundaries, components, spatial and temporal relationships, and its position within other systems. Hydrologists have long argued that as a society we need to adopt a hydrological systems perspective when addressing water-related issues. This provides the foundation for our principles. While some may argue 'why watershed' when other perspectives may be valid (e.g. a landscape), we argue that hydrological systems must be considered in our management objectives even at the landscape perspective. Water is, if not a dominant control, then at least a first order one on ecosystem structure and function—if it is not conserved it becomes very difficult to satisfy many other ecosystem services.

A hydrological systems approach encourages us to refocus management from purely ecological objectives, such as maintaining the habitat of a single species within a forest stand, to eco-hydrological objectives that try to preserve the hydrological, energetic, and biogeochemical basis of biodiversity, productivity, and integrity of all species within the watershed. Such an approach facilitates consideration of (1) transfer of both energy (photosynthesis and evapotranspiration) and matter (sediment, nutrients, and biota) along hydrological flowpaths at varying spatial scales; (2) interdependence and connections between ecosystem subunits; and (3) cumulative effects of management activities. A hydrological systems perspective integrates the often-divergent terrestrial and aquatic approaches to forest management.

Principle 1: Define system boundaries based on knowledge of hydrological response units

Forest management should define hydrological response units based on the dominant hydrological flowpaths on the landscape.

Determining a system's boundary is one of the most important and challenging aspects of working with ecosystems given that many ecosystem processes are very diffuse and dynamic. A good working definition of a hydrological system is required to place management activities in a hydrological context to know from where water is coming (upstream) and where water is going (downstream). This principle builds on the concept of ecosystem management already in use by forest managers, but applies it at the scale of a watershed rather than a forest stand or a landscape (Figure 1).

When considering forests as hydrological systems, the level of difficulty in delineating system boundaries depends on the dominant water processes and pathways. In many forest regions, hydrological systems can be delineated by topographic divides; however, in drier climates, and in regions with deep and heterogeneous geological deposits, water flow is best predicted by knowledge of local, intermediate, and regional ground water flow systems and not just topographic gradient (Devito *et al*., 2005). Water flows along preferred pathways resulting from macropore networks or substrates with much higher hydraulic conductivities than the surrounding matrix. The delineation of hydrological response units for these systems is much more difficult given subsurface controls on flows.

Digital elevation models have revolutionized the automatic delineation of topographically defined hydrological systems and implementing management boundaries based on topography is straightforward; the remaining challenge is to develop techniques for automatic delineation of nontopographically defined hydrological systems.

Principle 2: Conserve critical hydrological features along the hydrological system

Forest management should conserve areas where precipitation infiltrates into the ground (e.g. recharge zones), where water exits the ground and discharges into receiving bodies of water (e.g. discharge zones), and where water is stored along the hydrological network

Hydrological systems have critical features where certain hydrological processes dominate during specific time periods, and their consideration ensures the conservation of hydrological function. We need

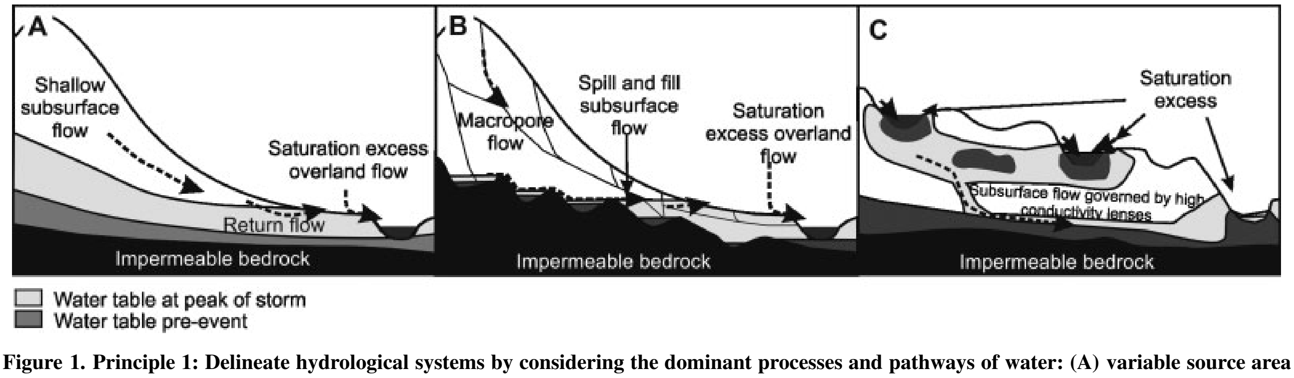

Figure 1. Principle 1: Delineate hydrological systems by considering the dominant processes and pathways of water: (A) variable source area hydrology where surface topography controls hydrological flows, (B) variable source area hydrology where bedrock topography controls hydrological flows, and (C) nonvariable source area hydrology in sub-humid, flat landscapes where surficial geology controls hydrological flows (from Creed and Sass, 2011)

to extend the traditional concept of buffer zones widely used in forest management to a broader range of features with recharge, storage, and discharge functions, given their importance based on regional biophysical and climatic conditions. This principle promotes a more sophisticated approach to protect water resources by identifying critical areas across the landscape rather than simple, fixed-width buffers around water bodies (Figure 2; Buttle, 2002).

The forest floor is an important recharge area characterized by low bulk density, high macroporosity, high saturated hydraulic conductivities, and consequently high infiltration rates that create conditions where most water reaching the forest floor enters shallow or deeper subsurface flowpaths (Neary *et al.*, 2009). Forest management can disturb the forest floor and compact soil, forcing water to flow overland and increasing sediment and nutrient transfer to receiving water bodies (Croke and Hairsine, 2006; Kreutzweiser *et al.*, 2008). These impacts can be minimized by avoiding areas of focused recharge on hillslopes such as topographic depressions and by conducting work during biologically and hydrologically inactive parts of the year.

Furthermore, water is stored in various surface (e.g. wetlands) and subsurface (e.g. soil matrix and aquifers) features along the hydrological system. Water storage is important for biological uptake and also attenuates water release from watersheds to reduce flood potential. Forest management planning should consider how activities may alter water movement into and out of storage and how they will affect sediment and nutrient load.

Finally, riparian and hyporheic zones along ephemeral and permanent stream corridors and adjacent to wetlands, rivers, and lakes are important discharge areas. Water is transferred from subsurface flowpaths to surface flowpaths, making these areas important for biogeochemical activity. Nutrient laden water emerges into the rooting zone and is consumed by organisms, converted to gaseous forms, or exported to surface waters (Creed and Beall, 2009). Forest management planning must recognize the hydrological and biogeochemical importance of discharge areas and conserve them using buffers while recognizing that not all landscapes may have this biogeochemical filtering functionality (Buttle, 2002).

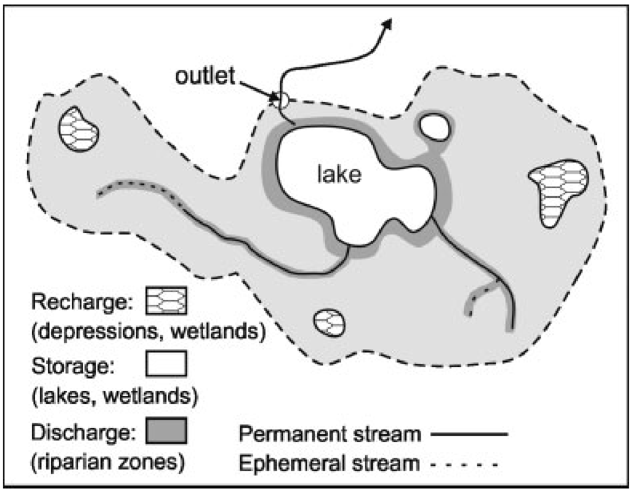

Figure 2. Principle 2, Conserve hydrological features that serve critical functions such as recharge, storage, and discharge of water along surface and subsurface pathways

Many maps used for the identification of hydrological features are out of date and/or have inadequate spatial resolution. For example, important hydrological features such as ephemeral and first-order streams and wetlands underneath the forest canopy that influence recharge, storage, and discharge functions (Creed *et al.*, 2003; Bishop *et al.*, 2009) are often missing on government topographic maps. This omission may partly reflect the expense of field inspections for mapping hydrological features at the appropriate temporal and spatial scales. However, recent developments using digital terrain analysis (Creed and Sass, 2011) combined with a time series of monitoring using remote sensing techniques and/or modelling techniques (Sass and Creed, 2011) show promise for delineating surface hydrological features, including recharge, storage, and discharge areas, under a forest canopy.

Principle 3: Maintain hydrological connectivity between hydrological features

Forest management should maintain all existing hydrological connections and prevent the creation of new connections to ensure that the hydrological system can handle the rate of water, sediment and nutrient movement.

Management activities undoubtedly sever (e.g. by disruption of existing ephemeral or permanent streams) or enhance (e.g. by formation of extensive road networks) some connections between hydrological features, and disturbance can be minimized with knowledge of where and when hydrological connectivity is most vulnerable. This principle considers hydrological connectivity as a system property that reflects the degree to which a system facilitates or impedes water flows between system elements (Figure 3).

Hydrological connections may occur along surface and subsurface flowpaths and can be transient or permanent. They are naturally dynamic due to such factors as changes in climatic conditions and ecological activity both at the surface (e.g. beavers creating dams) or subsurface (e.g. roots creating macropore networks). Most landscapes are hydrologically disconnected most of the time; however, they may quickly

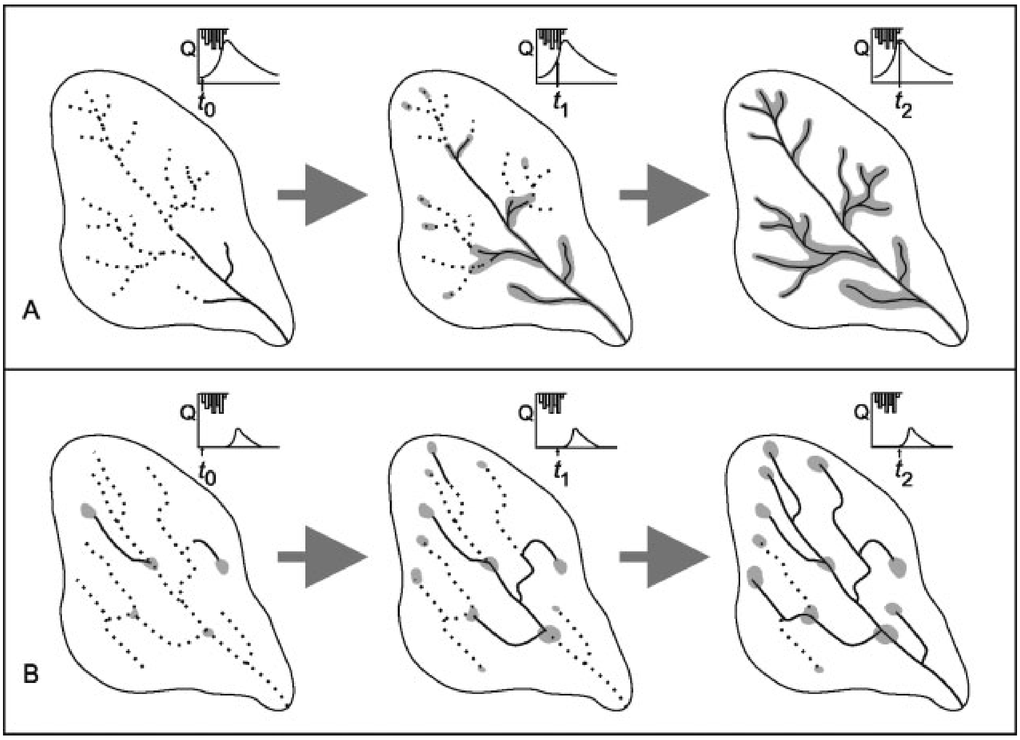

Figure 3. Principle 3: Maintain hydrological connectivity among the critical hydrological features. Hydrological system (A) exhibits a rapid increase in surface connectivity in response to an event, whereas system (B) exhibits a much lesser degree of surface connectivity with much smaller expansion of its variable source areas. Solid and dotted lines represent saturated and dry stream channels, respectively. Shaded areas represent surface saturation. The inset hypothetical hydrographs are measured at the basin outlet (from Todd *et al.*, 2006)

reach full connectivity in a nonlinear, step-wise fashion (Lehmann *et al.*, 2007; Sass and Creed, 2008). Hillslope features that increase connectivity are surface saturated and inundated areas, macropore networks, and water tables bridging hillslopes to streams across riparian areas (Tromp-van Meerveld and McDonnell, 2006; Sass and Creed, 2008; Jencso *et al.*, 2009). Hydrological connectivity is critical for determining the timing and magnitude of discharge (Western *et al.*, 2001; Lindsay *et al.*, 2004) as well as determining nutrient, sediment, and organismal transfers within and between terrestrial and aquatic systems (Pringle, 2003; Stieglitz *et al.*, 2003; Croke and Hairsine, 2006).

Forest managers must recognize where these transient and permanent hydrological connections are located since placement of road networks and other management activities (e.g. skid trails and landings) can have severe downstream consequences. In steep landscapes, roads may route water to road fills and culverts and contribute to mass movements (Wemple *et al.*, 2001; Eisenbies *et al.*, 2007). On the other hand, in flat landscapes, roads may enhance blockage of drainage pathways, especially where culvert design is inappropriate for site conditions (Alpac, 2008). Given their dynamic nature, information on hydrological connections is needed not only at spatial scales relevant to forest operations but also across temporal scales representative of the broad range of climatic conditions in a given forest region.

The potential for incorporation of mapping of hydrological features and the return periods of their hydrological connectivity using field measurements coupled with digital terrain modelling and/or airborne or satellite remote sensing in forest management plans has recently been illustrated (e.g. Creed *et al.*, 2008).

Principle 4: Respect temporal variability of hydrological systems

Forest management should respect the shifting dominance of hydrological processes due to climatic oscillations, climatic change, and forest management strategies such as fire suppression.

Hydrological systems are dynamic due to constantly changing meteorological and/or climatic conditions; hydrological processes therefore shift in dominance with time. From a management point of view, it is important to understand these shifts over both short (e.g. intra-annual timing of peak runoff) and longer time periods (e.g. inter-annual timing of peak runoff). This principle recognizes that interactions of climatic factors (water and energy) create diversity in hydrological form and function that can defy simple generalizations and that forest management strategies should respect this temporal variability when defining management targets (Figure 4).

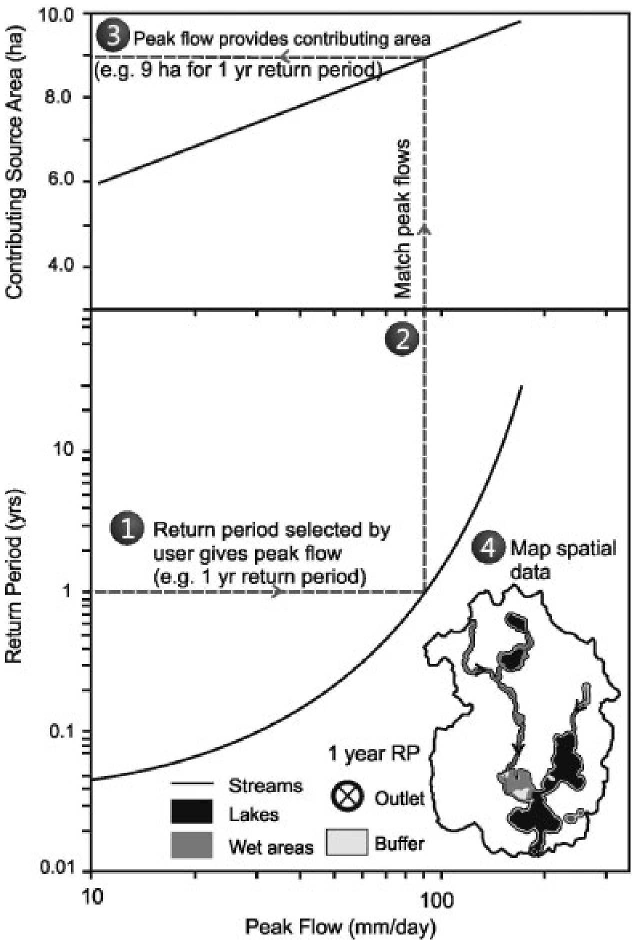

Figure 4. Principles 4 and 5: Respect temporal variability and spatial heterogeneity of hydrological systems. This hypothetical nomogram illustrates how management plans can be based on the return period of peak flows (temporal variation) and their associated contributing source areas (spatial variation). Cut block, road, or buffers could then be designed based on the degree of risk (i.e., return period of soil saturation or inundation) that the manager is prepared to accept (modified from Krezek, 2001, and Creed *et al.*, 2008)

Temporal variability in hydrological patterns and processes occurs at multiple scales and is influenced by human activity. Natural cycles, from day-to-day stochastic weather variability to longer term climate cycles (e.g. El Niño-Southern Oscillation, Stenseth *et al.*, 2002), are superimposed on directional changes driven by anthropogenic forcing (through forest conversion and afforestation as well as greenhouse gas emissions; Brooks, 2009). It has been suggested that forest watersheds be managed to sustain the natural flow regime (Poff *et al.*, 1997) or the natural range of variability (Landres *et al.*, 1999). Such management is predicated on historical conditions. While these concepts are appealing as a forest management tool, their practical utility is limited by such factors as the difficulty of obtaining relevant records, uncertainty about defining the reference period for assessing 'natural', and controversy about how to use the information (Bishop *et al.*, 2009). Their practical utility is also limited by uncertain future conditions (Millar *et al.*, 2007).

The best way to respect temporal variation is maintaining, reinforcing, and innovating long-term monitoring networks. These networks are required to understand the dynamic interplay amongst anthropogenic forcings (climate change, forest management) and the preservation of forest values, such as productivity and biodiversity, to assess the efficacy of mitigation strategies and plan adaptation strategies. Also, long-term monitoring is essential to quantify the "non-stationarity" in dynamic hydrological systems in order to pro-actively plan adaptation.

Principle 5: Respect spatial heterogeneity of hydrological systems

Forest management should consider the spatial variation of hydrological systems that is a consequence of the interplay of the spatial hierarchy of factors influencing hydrological processes both within a single watershed and among watersheds in different geographic settings.

Watersheds of different scales (catchments to continental drainage basins) and different geographies will have substantial differences in hydrological behaviour. Forest management strategies should respect this hydrological variation when transferring data, tools, and knowledge to different geographic areas. This principle recognizes that while the uniqueness of place is a general characteristic of nature, there are useful conceptual and practical approaches to address spatial variation when defining management targets (Figure 4).

The factors that control variation in space have been known for many years (Lotspeich, 1980) but have only recently begun to be organized into a predictive tool (Winter, 2001; Blenckner, 2005; Devito *et al.*, 2005). While standard operating practices are often customized to a specific site, more information is needed to make them a 'custom fit'. A scientific understanding of the changing dominance in hydrological processes is needed, so that 'rules' developed from one region are not arbitrarily applied to another. A formal watershed classification system that reflects the changing dominance of hydrological processes would provide a solid foundation for the development and application of site-specific best management practices including buffer widths, road placement strategies, and harvest block design.

A watershed classification needs national datasets on climate, bedrock, and surficial geology, soils, topography, and vegetation at appropriate spatial resolutions (i.e. at least 10–25 m). While access to data and computer resource requirements may present challenges in some jurisdictions, the lack of generally accepted method for watershed classification presents the greatest impediment. Until a clear methodology

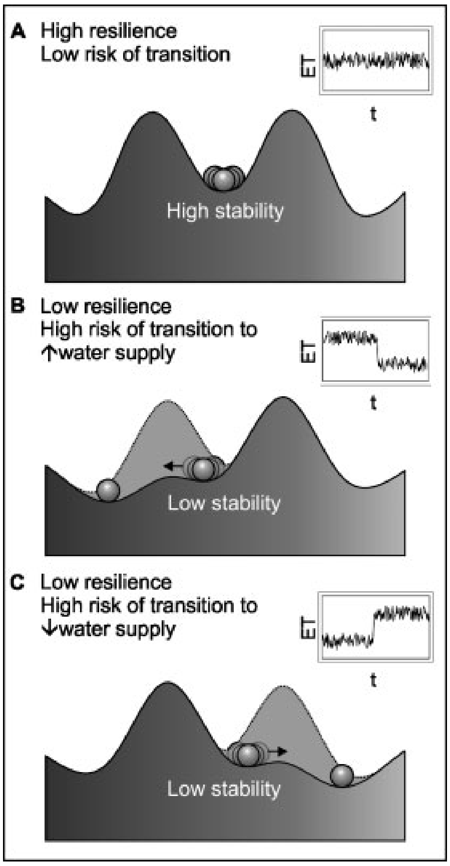

Figure 5. Principle 6: Maintain redundancy and diversity of hydrological form and function. Forest ecosystem stability is defined by the depth of the basin of attraction. A deep basin of attraction (A) indicates a stable ecosystem and one that is resilient to small perturbations. A shallow basin of attraction (B and C) indicates an unstable ecosystem susceptible to a change in state from small perturbations. Forest management practices may reduce the ecosystem's stability (reflected in the shallow basin of attraction) during which small perturbations (arrows) may then force the ecosystem into a change of state. In this example, the ecosystem state is characterized by evapotranspiration (ET); thus, a change in ecosystem state can result in either an increase (B) or a decrease (C) in water production (Q). In (B), changes that reduce ecosystem stability and result in a shift to a decrease in ET (and increase in Q) may include conversion from forest to residential lands (modified from Scheffer, 2010). In (C), changes in forest structure that reduce ecosystem stability and result in a shift to an increase in ET (and decrease in Q) may include forest fire suppression or forest biofuel plantations

emerges, managers will have to work from first principles of hydrological theory.

Principle 6: Maintain redundancy and diversity of hydrological form and function

Forest management should respect the redundancy and diversity of hydrological features to ensure maintenance of hydrological function over the range of natural variability of the system.

This principle recognizes that forest ecosystems have evolved to contain redundant processes that lead to resiliency (Figure 5, Holling, 1973; Chapin, 2009). When considering the hydrological basis for resiliency, we argue that a critical number of hydrological features performing diverse functions (recharge, storage, and discharge) are needed to buffer the system against disturbances (natural or not). For example, clear cutting a watershed will result in a shift of hydrological flows from subsurface to surface pathways, potentially leading to substantial increases in water, sediment, and nutrient yields. However, cut blocks interspersed with forest to encourage infiltration will retain enough recharge and storage functions to prevent significant sediment and nutrient yields. Put another way, forest management that focuses on maximizing production of a single objective (e.g. timber production) may create systems with reduced redundancy that may be subject to ecosystem collapse.

Coupled hydrological monitoring and modelling provides a valuable tool for managers facing the challenge of quantifying an adequate level of hydrological redundancy, since this presents the best way to ask 'what if' questions regarding the hydrological consequences of forest management activities (e.g. Peterson *et al*., 2009).

Outcome of a Principled Approach: A Resilient Forest

Resilience is an emergent system property that determines how systems deal with disturbance. Systems with resilience are able to respond to disturbance by reorganizing into a system with similar form and function. In contrast, systems with no resilience reorganize as completely different systems with different forms and functions. The concept of resilience is beginning to filter into the hydrological sciences (Peterson *et al*., 2009). We argue that forest management that adopts a principled approach along the lines suggested here will maintain hydrological resilience. Implicit in this principled approach is that the principles are 'non-negotiable': they cannot be traded off if ecosystem services from the forest are to be sustained.

Conclusions

The many forces that modify forests create challenges for managers to provide safe and secure water supplies. One unifying approach to forest management could be based on considering our future dependency on water from forests and adopting hydrological principles to help guide us to this future. We suggest six hydrological principles based on our state of knowledge of the science, which could provide the basis for forest management practices to secure our forest water supplies for future generations. Most of these principles are obvious to forest hydrologists and managers, but they will require work to be translated into effective policies and practices.

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