FRST 497

Using Threshold Methods to Assess Cumulative Effects in Watersheds

Ian Sunde

April 10, 2016

Abstract

This paper reviews the physical properties of water quality in watersheds, assesses how forest harvesting operations in watersheds affects water quality, and identifies ways land managers attempt to measure the potential impacts of further development on water quality and watershed function through the use of threshold assessments. Threshold assessments are popular methods of measuring the potential impacts of landscape level development plans. They use measurable watershed indicators in an attempt to quantify the complex interaction of water quality properties and cumulative effects imposed by forest operations on watersheds. This paper reviews past research to identify evidence and support for the use of thresholds such as Equivalent Clearcut Area assessments and Equivalent Roaded Area assessments. The literature review found that the properties of water quality rely on forested landscapes for their regulation, and that ground disturbance and removal of forest can lead to negative impacts on water quality. There is a correlation between the percentage of watershed area harvested and average annual water yields from watersheds that suggests thresholds exist for average annual yields. For peak flow events and other causes of degraded water quality, the relationship between the percentage of a watershed harvested and the likelihood of impacts occurring is unclear, and they may be more dependent on spatially explicit factors. Threshold assessments can be valuable to land managers as they provide a measurable means of quickly determining a watershed's water regulating capabilities based on planned and historic developments. They are potentially limited by a lack of depth and detail that is necessary for a complete accounting and assessment of all water quality properties in a watershed.

Table of Contents

Introduction

Of all the resources that are required for the sustenance of life, water is arguably the most important. The many ways in which it influences the biotic, terrestrial, and aquatic worlds, is captivating due to the limitless bounds of its utility and value. For humans, a non-conclusive list of these would include anthropogenic consumption, aquatic habitat and life forms, resources for agricultural production, recreation, power generation, and other industrial uses (Brooks *et al.*, 2013) (Cobourn, 1989A). With the number and importance of resources that humans value in water, protecting its supply and quality has been, and is, a paramount issue in resource management. This is especially important in forestry, an industrial activity with the potential to seriously degrade water quality and quantity in our forests if not managed responsibly. The purpose of this paper is to quantify how threshold approaches are used to measure the cumulative effects of disturbances in forested watersheds, which affect hydrological characteristics and water quality. To bring context to how industrial operations in watersheds can affect water quality and quantity, timing of flow, downstream repercussions, and subsequently the effect on resource values, it is important to have an understanding of the causes, processes, and mechanisms of how this occurs (Brooks *et al.*, 2013).

Watersheds

Watersheds are areas of land that drain water to a focal point in a stream or a river. Watersheds act as a landscape level funnel that collects precipitation and transforms it into flows that accumulate downhill. The paths water takes in watersheds will define the qualities it has when it reaches a stream. As the water moves overland, it will collect or lose sediments, water volume, nutrients, and chemical constituents, depending on the interactions it has with vegetation and the landscape (Brooks *et al.*, 2013).

Water Quality Characteristics

The quality of water is determined by its physical, chemical, and biological characteristics. Physical characteristics include water temperature, pH levels, and total sediment load. Total sediment load is the sum of suspended sediment, which is the amount of fine inorganic particles that are suspended in the water column, and bedload, which are the cobbles that make up the substrate in the streambed. Bed load characteristics are important for determining the quality of fish habitat in streams. Suspended sediment has a large impact on the water column and has the potential to cause numerous different adverse effects. It is the most widespread cause of stream degradation (Brooks *et al.*, 2013). In high quantities it has the ability to restrict the amount of sunlight that passes through the water, thereby limiting the growth of photosynthetic aquatic plants. Suspended sediment can smother benthic communities and gravels that are important for habitat, it can carry high quantities of adsorbed nutrients and heavy metals, and it can damage hydroelectric turbines. It can lead to decreases in stream depth, increases in stream width, and fewer deep pools, all which impact the suitability of native fish habitat. Sediment can also hinder the breathing ability of fish, which in extreme quantities can prove fatal (Brooks *et al.*, 2013) (Gomi *et al.*, 2005) (Cobourn, 1989A). Extreme temperatures exacerbate this problem as the coping ability of fish is reduced.

Sediment in streams is a product of erosion, which may occur in different forms. It comes from the erosion of stream banks which can be accelerated by high flows, it can originate from increased runoff due to harvesting activities and from road building and maintenance activities (Brooks *et al.*, 2013).

Water temperature is a function of all temperature inputs and outputs that a stream is subject to. This includes the temperature of incoming water, net radiant energy inputs, and heat extraction due to evaporation. Radiant energy is regulated by the amount of sunlight that is able to reach a stream and is therefore a function of the amount and density of riparian vegetation along the stream. Vegetation cover is important in regulating temperature at the site level in streams, as well as downstream as flowing water carries the increased or decreased temperature with it. Along with affecting suitability for fish themselves, temperature may affect aquatic vegetation which may be important fish habitat (Brooks *et al.*, 2013).

The acidity or alkalinity (pH) of stream water is an important physical characteristic, as it will affect chemical and biological reactions that occur within the stream. pH is largely a function of the water's source whether it be precipitation or snowpack. It is also influenced by the substrate through which it passes prior to entering the stream (Brooks *et al.*, 2013).

The chemicals in stream water originate from the material that water comes into contact with. Known as the universal solvent, surface water will dissolve chemical constituents from the substrates it passes over on its way to entering streams. It is through these processes that water will pick up nutrients such as nitrogen, phosphorous, calcium, potassium, magnesium, sodium, chlorine, manganese, and sulphur. The quantities of each will influence the biological productivity of a stream. Many streams in watersheds with agricultural activity will experience higher levels of these nutrients due to the use and distribution of fertilizers. Conversely, undisturbed watersheds exhibit low quantities of nutrients and are subsequently less productive (Brooks *et al.*, 2013).

Biological characteristics of water are of particular interest to people largely for human health reasons. Harmful pathogenic organisms can proliferate in water if the physical and chemical characteristics are conducive to their production. Should the physical and chemical characteristics of stream be degraded to cause biological changes, it can have adverse effects on the health of the watershed and its downstream users. This is one of the primary reasons to monitor, maintain, and protect watersheds that have critical human values to ensure the water quality characteristics are not threatened (Brooks *et al.*, 2013).

Because we rely so heavily on water and on forest and aquatic resources that themselves depend on water, natural watershed function and water quality are critically important to us. The processes that occur within watersheds will determine the quality of water and its suitability as a resource.

Forested land and water supply

The terrestrial portion of the water cycle is heavily influenced by its interactions with vegetation. Regardless of form, the movement of water that occurs between precipitation and entry into streams is variable, and depends on interactions with vegetation. This will affect the volume and timing of water entering a stream (Moore & Wondzell, 2005).

Vegetation influences the volume of water potentially available for stream flow by removing it from the ground through uptake, or by catching precipitation through interception.

The amount of water that is transpired by vegetation depends on the plant communities present on a site and their current life stages. This is also the case for the amount of water that is intercepted and then evaporated (Moore & Wondzell, 2005). (Moore *et al.*, 2016) states that approximately 26% of annual rainfall can be intercepted and evaporated in areas of old coniferous forests, making it an important regulator of stream flow and response to precipitation. The effect of this is demonstrated following harvesting operations where vegetation is removed, where resulting trends show that annual water yields increase in streams (Moore & Wondzell, 2005).

The timing of water entering a stream is dependent on how much water is released during a given period of time and the flow patterns it takes en-route to a stream. The flow patterns and routes that water takes downhill is important for timing because they determine how far surface water must travel, how fast it moves, and what barriers it might incur. A forested landscape naturally slows the movement rate of precipitation and surface water through tree crowns, ground vegetation and undisturbed soil. Harvesting operations can affect this by altering historic drainage patterns through interference by roads, loss of tree and ground cover, and changes to percolation through compaction of soils. These can result in faster overland flows and rapid flushing from ditches, with water reaching a streams generally more quickly than at natural rates. Runoff rates are important as they can influence the generation of peak flow events. These are the highest flows in streams in a given period of time, and they are closely associated with water quality issues such as sedimentation and stream restructuring (Gomi *et al.*, 2005) (Moore & Wondzell, 2005).

Another factor in the generation of peak flow events is the formation of seasonal snowpacks and their melting patterns. In areas prone to seasonal snowpacks such as the Pacific Northwest, peak flows generally coincide with spring melts. Harvesting operations will influence the characteristics of these snowpacks as forest canopies have a role in their formation. As with precipitation in a liquid state, forest canopies intercept snowfall and slow the development of the snowpack below. Compared to a snowpack below the forest canopy, those that develop in open areas such as clearcuts, are typically 30-50% deeper (Moore & Wondzell, 2005). Forest canopies will also influence snow melt rates as they reduce incident solar radiation felt at the snow surface, they reduce wind speeds, and they intercept rain, all of which help to moderate melt rates. Snowmelt rates in the open can be 30-100% higher than those under cover. Peak flows frequently occur during rain-on-snow events where the combined volume from rain and melt waters discharge at the same time. Peak flows have been shown to increase 13-40% following harvesting though there is little correlation in frequency with the percentage of the watershed cut (Moore & Wondzell, 2005).

Forest Operations and Sediments

Harvesting operations in forested watersheds are known to cause increases in suspended sediments in streams. Harvesting operations, including road-building and harvesting, can increase sedimentation through changes to hydrologic regimes and through creating sources of sediment. Sediment sources exist both external to, and within streams. Internal sources of sediment may become available through movement of structural features such as large woody debris and channel substrate, through bank erosion, upward extension of headwaters, and subsurface soil erosion. These sources can be activated when a system is subjected to forces of higher magnitude than normal such as storms and peak flow events, and may be exacerbated by a previous harvesting-related disturbance of those structural features. External sources of sediment are those that originate outside streams and are then transported into a watercourse. These include mass wasting, surface erosion, windthrow, and bank erosion. They occur more frequently in areas where soil strength has been compromised, but they can also result from extreme events (Gomi *et al*., 2005).

Forest operations potentially cause sediment increases from both internal and external sources. Harvesting can create external sources of sediment in a variety of ways. Ground based machinery and yarding operations can expose sediment sources for surface erosion. Decaying roots in the years following harvesting reduce the strength of the soil substrate making it more vulnerable to gullying, landslides and mass wasting. Exposed treelines at harvesting boundaries are susceptible to increased blowdown which produces localized sources of sediment, which are particularly significant when the effects are felt in riparian buffers. Perhaps even more so, roads are key sources of sediment as they provide draining water opportunities to pick up sediment from bare, loose road surfaces and ditches (Gomi *et al*., 2005). Coupled with disruption of drainage patterns due to road construction, and insufficient maintenance of stream crossings and culverts, there is potential for increased sediment introduction into streams and rivers.

Harvesting can affect internal sources of sediment by acting as a catalyst for larger than normal drainage events. Through decreased runoff times into streams from roads and cutblocks, peak flow events occur more frequently creating a higher likelihood for internal sediment to be released (Gomi *et al*., 2005).

Recovery rates for increased sedimentation are variable due to a dependence on the causal factors. Surface erosion is often quickly reduced with the establishment of fast growing grasses and shrubs, whereas core slope stability can take longer due to the time requirements for establishing a new crop of trees on harvested sites. Impacts of roads are felt for as long as they are active and maintained. Unless roads are fully debuilt, some natural drainage patterns may not recover to historic states (Wilford, 1987) (Gomi *et al*., 2005).

Forest Operations and Temperature

An important factor in regulating the total energy inputs in streams, and the subsequent reflection in water temperature, is the characteristics of the forest canopy above a stream. Forest canopies are important in regulating riparian microclimates due to the relationships it has with key factors in determining its characteristics. The riparian microclimate is influenced by the amount of solar radiation received, the effective wind speed at ground level, and precipitation inputs. Forest canopies have the ability to reduce all of these through their blocking ability. Through provision of shade, foliage in forest canopies reduces the incident solar radiation. Through interception and uptake of moisture, trees and their canopy reduce the amount of precipitation throughfall, and water inputs from the soil profile. Forest canopies also have the ability to deflect and diffuse wind, protecting the air column below. With multiple roles in determining the characteristics of the riparian microclimate, removal of the canopy creates cumulative effects (Moore *et al*., 2005).

Stream temperatures are affected not only by harvesting in riparian areas, but also by developments in other areas of the watershed. Roads can have a warming effect on stream temperatures through their ability to route and pool water in ditch lines before entering streams. The shallow nature of water in ditches makes the warming effects by solar radiation particularly strong, especially considering the frequent lack of canopy above resource roads. Warming in ditches can also interrupt groundwater flow which is often a source of cool water in streams (Moore *et al.*, 2005).

In an effort to protect the qualities of riparian areas around streams, buffers are commonly retained to provide residual canopy influence. The effectiveness of this is largely dependent on spatial and physiological factors of the buffers and the streams themselves. It is also unclear what the downstream effects of warmed water is, whether it will continue to warm, or cool down (Moore *et al*., 2005).

Non Point Sources of Pollution and Cumulative Effects

Typically, the cause of change in water quality characteristics is due to a change in the status quo of the hydrologic functioning in a watershed. In watersheds, this pollution is generally caused by activities dispersed throughout the catchment area, and which have accumulating downstream impacts. The decentralized nature of the pollutants has led them to be coined “non-point” sources of pollution (Binkley, 1993). Their effects are characterized by changes in water quality such as supply, temperature, sediment, and nutrient concentrations (Lynch, 1985) (Binkley, 1993). When a defined unit is subject to multiple disturbances, the effects can have additive or even synergistic responses to one another if they persist in time and space (Spafford, 2004) (McDonald, 2000). These are known as cumulative effects. The unpredictable nature of cumulative effects means that their consequences can be quite variable. They are determined by a combination of unique inputs with complex relationships (Brooks *et al.*, 2013) and the interactions of those inputs with the environment they are subjected to. Their convoluted nature means that cumulative effects often produce results that are indirect, and skewed from expected bounds (McDonald, 2000).

Addressing Water Pollution and Cumulative Effects in Forest Operations

As forest managers develop plans to operate within watersheds, it is their responsibility to ensure that water quality and aquatic values are not negatively impacted. To do this, they need to know if proposed plans will have potential impacts on water quality, either on their own or in addition to other pre-existing conditions. The first step in doing this is understanding the current natural capacity of the watershed to maintain water quality and values. The next is knowing how large of an impact proposed plans will have (Spafford, 2004). Forest managers and researchers have developed assessment techniques to aid in determining the magnitude of potential impacts. The difficulty in doing this is that the multitude of circumstances that need to be addressed are often variable in spatial scale and duration and therefore require different approaches. There is also the issue that driving forces of hydrologic processes and geomorphic conditions cannot be considered constant (Pike *et al.*, 2010). Compounding these difficulties, with the cumulative nature the effects have on one another, makes measuring the impacts of operations in watersheds an extremely convoluted task (Pike *et al.*, 2010). Analyzing cumulative watershed effects and implementing measures to ensure they do not get too big is a way of controlling non-point sources of pollution to protect key water values (Cobourn, 1989A).

Watershed Assessment in British Columbia

Prior to the mid 1970's, there were no published watershed assessment methods available to help guide and standardize the reporting of hydrological impacts with vegetation changes. This meant that hydrologists were largely left to measure and study what they deemed as appropriate in order to gain an adequate image and understanding of the hydrological state of individual watersheds. Some of these included discussing historical or current issues with land managers, using remote sensing indicators, and physically exploring the land base to help create a representative image. Assessments were typically prompted by potential issues or activities that might affect water quality such as sediment increases and changes to peak flows, as well as fish habitat and stability of alluvial fans. They documented risks or changes to the natural state of the watershed that could cause these problems, such as the harvesting history of the watershed, site level impacts that harvesting equipment may have caused, effects of logging in riparian or other sensitive areas, sediment sources, landslides, and the status of regeneration (Pike *et al.*, 2010).

Threshold methods

When assessing watershed condition, it has become common practice to use thresholds determine what level of disturbance is appropriate within a spatial area. Threshold approaches are based on the notion that watersheds are able to withstand a certain amount of disturbance before they start showing adverse effects to watershed function above and beyond acceptable quality thresholds. As a disturbance threshold is approached or surpassed, the likelihood of adverse effects occurring within the area of operation greatly increases. (Cobourn, 1989A). This is a ‘black and white’ approach, in that, if land managers are operating below the determined threshold for their area, they can essentially continue as if their prescriptions are not creating any adverse effects on water quality (Reid, 1993). If they exceed the threshold, they can expect that adverse effects will occur and further assessments will be required to determine a more accurate likelihood and extent of their occurrence (Cobourn, 1989A).

When watersheds are subject to extensive development, their inherent regulatory abilities are shown to decrease through negative impacts in water quality. However, they are capable of maintaining their function during smaller disturbance regimes, without showing significant impacts. This is due in-part to the exponential nature of cumulative effects (McDonald, 2000). For example, numerous paired watershed studies within the United States have shown that approximately 20% of a watershed needs to be harvested before statistically significant changes to water yields become apparent. There is significant scatter with this figure and is often dependent on geographical characteristics (Stednick, 1996). In this example, land managers could use the 20% harvested land base figure as a threshold for indicating what level of harvest is acceptable in order to maintain naturally occurring annual water yields. While the large variability in the data makes it difficult to create a reliable curve to accurately estimate the likelihood of increased water yield, an incremental nonlinear response can be applied to describe the results of harvesting (Stednick, 1996) (Bosch, 1982).

Threshold methods are popular among land managers because they provide an easy way of measuring impacts of landscape level plans (Pike *et al.*, 2010). Their validity as a tool for protecting water quality is proven through the observation that acceptable levels of disturbances do exist before certain adverse effects become prevalent (Stednick, 1996) (Bosch, 1982). In cases where land managers don't need to be concerned with incremental effects of harvesting below a threshold, they provide the bounds within which activities can take place without being hampered by continual measurements to ensure that water qualities are not threatened.

While the theory behind threshold methods is sound, there are numerous factors that undermine their ability to fully protect water quality within watershed. One of the key issues with them is that they are one dimensional (Pike *et al.*, 2010) (McDonald, 2000). Threshold methods typically focus on one variable with one reaction. When measuring outputs as complex as water quality, this isn't always sufficient to ensure that all parameters are being maintained. They lack the comprehensiveness required to take into account all causes and effects of water quality degradation (Pike *et al.*, 2010).

There is also the issue of determining exactly what threshold is the lowest denominator for causing water quality issues (Reid, 1993), and finding exactly where it lies (Brooks *et al.*, 2013). The complexity of determining this is exponential due to the convoluted nature of how cumulative effects appear, and the often non-point sources of pollution that cause them (McDonald, 2000). Measuring the cause and effect of water quality changes is often challenging due to ambiguous relationships and inherent uncertainties in measuring physical systems (McDonald, 2000).

Threshold methods can be a valuable part of a land manager's toolbox when assessing impacts. Their implementability and generalized estimates provide quick information on how water quality responds to disturbances. Caution should be taken when using them, however, because they are often unable to encompass sufficient water quality inputs due to their inability to take into account spatially explicit factors and their lack of dimensional diversity (Reid, 1993) (McDonald, 2000). When used in combination with other assessment measures that take into account the shortcomings of threshold methods, their utility should be considered (Pike *et al.*, 2010).

Equivalent Clear-cut Area

Equivalent Clear-cut Area (ECA) is a popular watershed assessment procedure that uses thresholds. Following the loss of mature forested area in a watershed, hydrologic function will be altered due the reduction of canopy cover and its associated function in influencing the timing and magnitude of water runoff (Lewis, 2010). Watershed hydrologists have attempted to define thresholds for watersheds that indicate how much area can be harvested before hydrologic function is degraded to the point where critical water values become threatened. This is often expressed in terms of the percentage of the landbase that can be clear-cut. Since land managers need to take into account the durational dynamic of forest disturbances, they also have to consider past disturbances and their lingering negative effects (Spafford, 2004) (Pike *et al.*, 2010). That is, a partially regenerated stand will have a portion of the capacity of its unaltered state to influence water runoff (Lewis, 2010). In the 1970's, the USDA Forest Service came up with the Equivalent Clear-cut Area to quantify this. They concluded that regenerating stands can be considered to be clear-cut, and then have discounts applied to them to account for their partially recovered influence on water supply as they age (McDonald, 2000b) (Reid, 1993) (Spafford, 2004). With a discount applied, a fraction of regenerated area can be considered clear-cut, with the remainder being considered fully regenerated, hence the name "equivalent clear-cut area" (Wilford, 1987).

The USDA Forest Service designed ECA to predict increased peak flows following harvesting (Spafford, 2004) (Reid, 1993) (Pike *et al.*, 2010). It attempts to achieve this through determining the cumulative effects of both past and proposed disturbances on streamflow (Spafford, 2004) (Lewis, 2010). This allows land managers to model the hydrologic impact of proposed activities to determine if operations will surpass a prescribed threshold with consideration to present conditions (Spafford, 2004). To foresters the ECA method is desirable because it is simple, easy to implement, requires comparatively few inputs (Pike *et al.*, 2010), and can be used for large areas over long periods of time. ECA provides quick means of generating water runoff models for areas impacted by cumulative effects. It was not designed to provide extremely accurate streamflow data but rather a general projection of what could be expected assuming current trends remain constant (Spafford, 2004)

Without disregarding the inherent generalizations of the model, the accuracy of its projections are still dependent on the quality of the data inputs. The model requires information on: the tree species in the watershed (both mature and regenerating), the size of the cut block in question and total basin area, the year(s) of harvest, elevation, site index, average annual precipitation, and average annual streamflow (Spafford, 2004) (Reid, 1993). Unfortunately, it is often costly and time consuming to acquire accurate data of all the inputs, which can lead land managers to use best available information and professional judgment to fulfill the criteria (Reid, 1993). The model is also hampered by key limitations. It is difficult to quantify rates of recovery with regeneration, there is uncertainty and variability in management effects, results are often difficult to substantiate, it does not relate results to indirect effects or other key water values, and there is a lack of certainty in future conditions (McDonald, 2000). It does not take into account important spatial characteristics of disturbances, or the effects of other management activities (Reid, 1993).

The drawbacks and disclaimers associated with Equivalent Clear-cut Area makes the apparent popularity of the procedure seem unfounded. In addition, literature on the subject also highlights chronic misuse of the procedure. ECA was designed to predict the potential for impactful increased peak flows (McDonald, 2000b) (Lewis, 2010) (Reid, 1993). In reality, ECA is better for predicting average annual water yields (Spafford, 2004) (Reid, 1993) (Lewis, 2010) (King, 1989) (Bosch, 1982) (Schnorbus *et al.*, 2004), which are poorly correlated with highest peak flows (Moore & Wondzell, 2005) (Reid, 1993). Peak flow generation is more dependent on the physical characteristics of the watershed basin and climatic conditions (Lewis, 2010) (King, 1989). For ECA to model increased peak flows, it has to be assumed that peak flows are proportional to average annual streamflow (Reid, 1993). Multiple researchers have published criticisms of the procedure, but it is still commonly used to assess cumulative effects across North America (Spafford, 2004).

Equivalent Roaded Area

Another frequently used threshold method for assessing cumulative watershed effects is the Equivalent Roaded Area (ERA). ERA is used to measure the likelihood of cumulative watershed effects. It does so by calculating the proportion of disturbed area to watershed area, not unlike in ECA. ERA accounts for more factors than ECA, including roads for which it uses different discount rates. ERA applies discounts to disturbed areas of interest to determine its equivalent roaded area. It also applies equivalent roaded areas to a watershed's road network by finding the total area that is roaded (length x average width), and discounting for road inactivity/recovery. The sum of the ERA can then be applied to the watershed’s predetermined

ERA threshold to see if it has reached its estimated capacity for disturbance (Reid, 1993) (McGurk, 1995).

Much like the ECA approach, ERA suffers from an inability to take into account spatially explicit factors. It fails to address additional water quality issues such as sedimentation caused by road development (McDonald, 2000A) (Cobourn, 1989B). Despite these drawbacks, they are less important in the utility of ERA compared to ECA because the method does not attempt to directly quantify the effects of cumulative watershed effects. Instead, it is used as an index that alerts land managers if proposed activities are too intense. As with ECA, once an ERA threshold is passed, further assessments should take place to more accurately determine the likelihood of adverse effects (Reid, 1993) (McGurk, 1995).

The ERA method is prone to the issues inherent with threshold methods. Thresholds need to be defined, which are often ambiguous, variability in thresholds exists between watersheds which limits their transferability, and water values and criteria for maintaining them need to be identified. Fortunately ERA accounts for this by not attempting to directly quantify its effects on water qualities, and just acts as an indicator of the need for further assessments (McGurk, 1995).

Discussion/Conclusion

For humans, the value of water is tied to its characteristics. Its suitability for use and subsequent desirability is dependent on its physical, chemical, and biological qualities. Unfortunately, maintaining water quality frequently finds itself in conflicting arenas with other anthropogenic development interests. Development activities have the ability to disrupt the natural historic hydrologic functions, and are often the suspect for sources of pollution. Harvesting in watersheds has effects that are felt cumulatively. They often compound one another and can synthesize in unpredictable ways. Factors related to cumulative watershed effects include peak and low flows, reduction in slope stability, surface erosion, and stream channel stability, all of which have implications for downstream water quality characteristics such as supply, sediment loads, and temperature.

Hydrologists have created numerous assessment procedures in an attempt to quantify the difficult-to-encompass cumulative effects and their sources. Some of these use thresholds to indicate what maximum level of disturbance is acceptable. While desirable in theory, threshold systems lack the dimensional diversity required to account for all cumulative watershed effects, and contain numerous assumptions that undermine their validity. Two commonly used threshold systems are the equivalent clear-cut area assessment, and the equivalent roaded area assessment. These are popular due to their presumed ability to easily account for non-point sources of pollution over large areas and time. Unfortunately they are limited in their scope, and are sometimes used in unsound ways. As a complete measure of cumulative watershed effects to protect key water values, neither is sufficient.

The equivalent clearcut area and the equivalent roaded area assessments are hampered by the data requirements for completion of the models. Systems such as these that involve the accounting of recovery rates are limited by the accuracy and availability of the data used to generate them. Collecting data that is accurate enough to develop recovery rates is a labour intensive and time consuming process, which does not match the quick-to-implement nature of these assessments. For application into these models, recovery rates need to be considered constant in spatial scale as well as in duration. This is a large assumption to make as site-specific factors and climactic conditions influence growth, neither of which can be described as uniform.

Uncertainty in growth and recovery rates will also be spurred by the onset of climate change. Changes in average climactic conditions could bring an influx of new species, alterations to precipitations, and trends away from historic ecological characteristics, which would lead to changes in hydrologic functioning. Another factor that could undermine the confidence in future growth and recovery rates is the growing popularity of alternative silviculture practices such as Variable Retention and Ecosystem Based Management. Most of the studies that have looked at hydrologic response to harvesting have been done in basins subjected to clearcutting prescriptions. The presence of higher levels of in block retention could alter the hydrologic response meaning material published on response to harvesting may not be suitable for transfer to these newer systems (Moore *et al*., 2016).

When used appropriately, threshold methods can be a valuable tool in a land manager's repertoire for maintaining water quality and watershed function and reducing the risk of adverse effects. They do not encompass all the factors necessary to fully account for all facets of water quality and should be used accordingly.

References

Binkely, Dan., and Brown, Thomas C. (1993). "Forest Practices as Nonpoint Sources of Pollution in North America." *Water Resources Bulletin* 29.5: 729-740. Web.

Brooks, Kenneth N., Ffolliot, Peter F., and Magner, Joseph A. (2013). *Hydrology and the Management of Watersheds.* Retrieved From http://onlinelibrary.wiley.com.ezproxy.library.ubc.ca/book/10.1002/9781118459751

Bosch, J.M., and Hewlett, J.D. (1982). "A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration" *Journal of Hydrology.* 55: 3-23. Web.

Cobourn, J. (1989A). An application of cumulative watershed effects (CWE) analysis on the Eldorado National Forest in California. Pages 449-460 in W. Woessner and D.F. Potts (eds.), Symposium on Headwaters Hydrology, Amer. Water Resources Assoc., Bethesda, Maryland.

Cobourn, J. (1989B). Cumulative Watershed Effects Analysis in Federal and Private Forests in California. Pages 441-448 in W. Woessner and D.F. Potts (eds.), Symposium on Headwaters Hydrology, Amer. Water Resources Assoc., Bethesda, Maryland.

Gomi, T., Moore, R.D. and Hassan, M.W. (2005). Suspended sediment dynamics of small forest streams of the Pacific Northwest. *Journal of the American Water Resources Association* 41:877-898.

Holtby, L. Blair. (1988). "Effects of Logging on Stream Temperatures in Carnation Creek, British Columbia, and Associated Impacts on the Coho Salmon (*Oncorhynchus kisutch*)." *Canadian Journal of Fisheries and Aquatic Sciences* 45: 502-515. Web.

King, John G., and Tennyson, Larry C. (1984). "Alteration of Streamflow Characteristics Following Road Construction in North Central Idaho." *Water Resources Research* 20.8: 1159-1163. Web.

King, John G. (1989). Streamflow responses to road building and harvesting: A comparison with the equivalent clearcut area procedure. Res. Pap. INT-401. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p

Lewis, D., and Huggard, D. (2010). "A Model to Quantify Effects of Mountain Pine Beetle on Equivalent Clearcut Area." *Watershed Management Bulletin* 13.2: 42-51. Web.

Lynch, J. A., Corbett, E. S., and Mussalem, K. (1985). "Best Management Practices for Controlling Nonpoint-Source Pollution in Forested Watersheds." *Journal of Soil and Water Conservation* 40.1: 164-167. Web.

McDonald, L. H. (2000A). “Evaluating and Managing Cumulative Effects: Processes and Constraints.” *Environmental Management* 26.3: 299-315. Web

MacDonald, L. H. (2000B). Predicting and managing cumulative watershed effects. In *Watershed Management and Operations Management* 2000 (pp. 1-10). ASCE.

McGurk, B. J., and Fong, D. R. (1995). “Equivalent Roaded Area as a Measure of Cumulative Effect of Logging.” *Environmental Management.* 19.4: 609-621. Web.

Moore, R.D. and Wondzell, S. M. (2005). Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review.*Journal of the American Water Resources Association* 41:763-784.

Moore, R.D., Spittlehouse, D. and Story, A. (2005). Riparian microclimate and stream temperature response to forest harvesting: a review. *Journal of the American Water Resources Association* 41:813-834.

Moore, R.D., Sidle, R.C., Wilford, D., and Takahashi, G. (2016). *Water and Watersheds*. Unpublished manuscript.

Pike, R.G., T.E. Redding, D.J. Wilford, R.D. Moore, G. Ice, M.L. Reiter, and D.A.A. Toews. (2010). Detecting and predicting changes in watersheds. In: *Compendium of forest hydrology and geomorphology in British Columbia*. R.G. Pike, T.E. Redding, R.D. Moore, R.D. Winkler, and K.D. Bladon (editors). B.C. Ministry of Forests and Range, Forest Sciences Program, Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Management Handbook No. 66, pp. 527–552.

Reid, L. M. (1993). Research and cumulative watershed effects. Gen. Tech. Rep. PSW-GTR-141. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 118 p.

Schnorbus, M.A., R.D. Winkler, and Y. Alila. (2004). Modelling Forest Harvesting Effects on Maximum Daily Peak Flow at Upper Penticton Creek. B.C. Min. For., Res. Br., Victoria, B.C. Exten. Note 67. http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En67.htm

Spafford, M., and Devito, K. (2004). “*Boreal Conservation: Hydrology and Forestry in the Alberta-Pacific FMA Area*.” Retrieved from http://esrd.alberta.ca/lands-forests/forest-management/forest-management-plans/documents/AlPacForestProducts/ALPAC-FMP-Appendix3.pdf

Stednick, J. D. (1996).“Monitoring the Effects of Timber Harvest on Annual Water Yield” *Journal of Hydrology.* 176: 79-95. Web.

Wilford, D.J. (1987). *Watershed Workbook: Forest Hydrology Sensitivity Analysis for Coastal British Columbia Watersheds.* Smithers, British Columbia: BC Ministry of Forests and Lands