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Equivalent Clearcut Area as an Indicator of Hydrologic Change in Snow-dominated Watersheds of Southern British Columbia

R. Winkler
B.C. Ministry of Forests, Lands and Natural Resource Operations
Kamloops, B.C.

S. Boon
Creekside Communication
Cobble Hill, B.C.

Introduction

Forest disturbance, whether natural or as a result of timber harvesting, directly affects stand-scale hydrologic processes through changes in interception, evaporation, and transpiration. When disturbance occurs over a large enough area, hydrogeomorphic processes at the watershed scale can also be affected. In British Columbia, statistically significant shifts in the timing and magnitude of snowmelt-dominated streamflows and in the frequency of peak flow events of all magnitudes have been measured in watersheds where more than 25% of the area has been clearcut (Moore and Scott 2005; Zhang and Wei 2012; Winkler et al. 2015). Streamflow regimes may also be affected following less extensive changes in forest cover where disturbance location and watershed attributes synchronize melt runoff timing and delivery to stream channels (Schnorbus and Alila 2004, 2013; Green and Alila 2012). These increases may have subsequent downstream effects on channel morphology, aquatic habitat, alluvial fans, floodplains, infrastructure, and community water supplies.

The potential effects of forest disturbance on streamflow are often evaluated by examining the total area disturbed and the location(s) in a watershed where forest cover has been (or will be) altered. The assumption is that the greater the disturbed area, the greater the potential for hydrologic change. It is also assumed that these changes will diminish over time as the forest regrows (i.e., recovers). The extent of disturbance, accounting for regrowth, is referred to as the equivalent clearcut area (ECA). This note describes ECA, including its origin, development, and use, how it is calculated, and its applicability to forest development planning and watershed assessment. This note focusses on ECA in snow-dominated interior British Columbia watersheds where spring peak flows are a key hydrologic concern. However, the discussion applies wherever ECA is used, although the methods of calculation and seasons considered may vary.

Development of the Equivalent Clearcut Area Method

In 1974, the United States Department of Agriculture (USDA) Forest Service

British Columbia

developed a method to evaluate the cumulative watershed effects of timber harvesting for third- to fifth-order watersheds in Idaho and Montana. This method examined cumulative forest disturbance and forest regrowth to calculate ECA (the proportion of a watershed that responds hydrologically as a clearcut), and to assess the subsequent potential for channel destabilization. Forest disturbance included roads, clearcuts, partial cuts, and burned areas (King 1989). Empirical relationships between forest disturbance and water yield were estimated as a function of vegetation type, elevation, and time since disturbance (Reid 1993). However, since quantitative relationships between water yield and all disturbance and forest cover types were not known, these relationships were often defined using professional judgement.

Equivalent clearcut area was then compared to either legislated or expert opinion–defined harvest thresholds that were considered acceptable for the area (Reid 1993; Berg et al. 1996). If watershed-scale ECA exceeded the set threshold, downstream resources were assumed to be at risk either until adequate recovery occurred or until harvest plans were modified to result in a smaller ECA increase (Reid 2010). This approach assumed that by limiting streamflow increases in higher-order streams, lower-order stream channels would also be protected (King 1989).

Equivalent clearcut area was intended to be only one of many tools used by hydrologists to compare various watershed management options (King 1989; Ager and Clifton 2005). Equivalent clearcut area continues to be used in the United States as an indicator of changes in water yield (peak flow, timing, and total yield), and assumes that post-logging increases in water yield may have negative effects on a broad range of watershed values (Ager and Clifton 2005).

Application of the Equivalent Clearcut Area Method in Alberta and British Columbia

In Alberta, ECA is currently used in conjunction with the U.S. Environmental Protection Agency's Water Resources Evaluation of Non-point Silvicultural Sources (WRENSS) model to evaluate the effects of past and future forest harvesting and natural disturbance by simulating relative changes in annual water yield (USDA 1980). This approach relies heavily on the accuracy of both post-disturbance stand recovery information and regional streamflow and precipitation data (Silins 2003). The mitigating effects of forest regrowth on streamflow are based on the recovery of evapotranspiration losses to pre-disturbance levels, as represented by mature basal area (Watertight Solutions Ltd. 2008).

In British Columbia, the ECA approach was widely adopted in the 1990s to assess potential changes in peak flow following timber harvesting in watersheds ranging from 500 to 50 000 ha (5–500 km^2) (B.C. Ministry of Forests 1999). In 1992, the Okanagan timber harvesting guidelines (B.C. Ministry of Forests 1992) set ECA thresholds of 20% in community watersheds, 25% in fisheries-sensitive watersheds, and 30% in all other watersheds. Equivalent clearcut area was used in combination with variables such as road density, stream crossings, landslides, and length of stream channel logged to assess the effects of timber harvesting on downstream values. In community watersheds, provincial ECA thresholds were set at 30% in sub-basins that were > 250 ha and one stream order lower than at the most downstream point of interest, and at 20% for slopes above Class IV and V terrain (B.C. Ministry of Forests 1996).

Equivalent clearcut area continues to be used in British Columbia as (1) a forest stewardship plan threshold value for undertaking watershed assessments in community and fisheries-sensitive watersheds, (2) a forest certification target, (3) an indicator of the likelihood of increased snowmelt-generated peak flows in watershed assessments, and (4) a cumulative watershed effects indicator in regional GIS-based watershed risk assessments for the Southern Interior. In the latter approach, ECA is used in combination with biogeoclimatic ecosystem classifications, non-forested land area, presence of lakes and wetlands, drainage density, elevation range, and slope gradient to calculate a streamflow hazard rating (D. Lewis, pers. comm., July 2016). The influence of these watershed characteristics, as well as others such as roads, ditchlines, and soil compaction, on hydrologic response is described by Winkler et al. (2010a, 2010b).

Calculating Equivalent Clearcut Area

In British Columbia, the ECA of an individual cutblock or disturbed area (Figure 1) is computed as follows:

$$\mathrm{ECA} = A \times (1 - \mathrm{HR})$$

where ECA is the area in an individual cutblock or otherwise disturbed area (ha) that functions hydrologically as a clearcut, A is the original cutblock or disturbed area (ha), and HR is hydrologic recovery (decimal) (B.C. Ministry of Forests 1999). Where portions of a cutblock or disturbed area have differing levels of HR, ECA should be calculated for each portion of the block. Mainline roads, power lines, and permanent land conversion to non-forest uses have a permanent ECA of 100% ($\mathrm{HR} = 0$) and must be included in the total area disturbed. The percent ECA of a watershed is the sum of the individual ECA values for all disturbed areas, divided by the total watershed area above the element

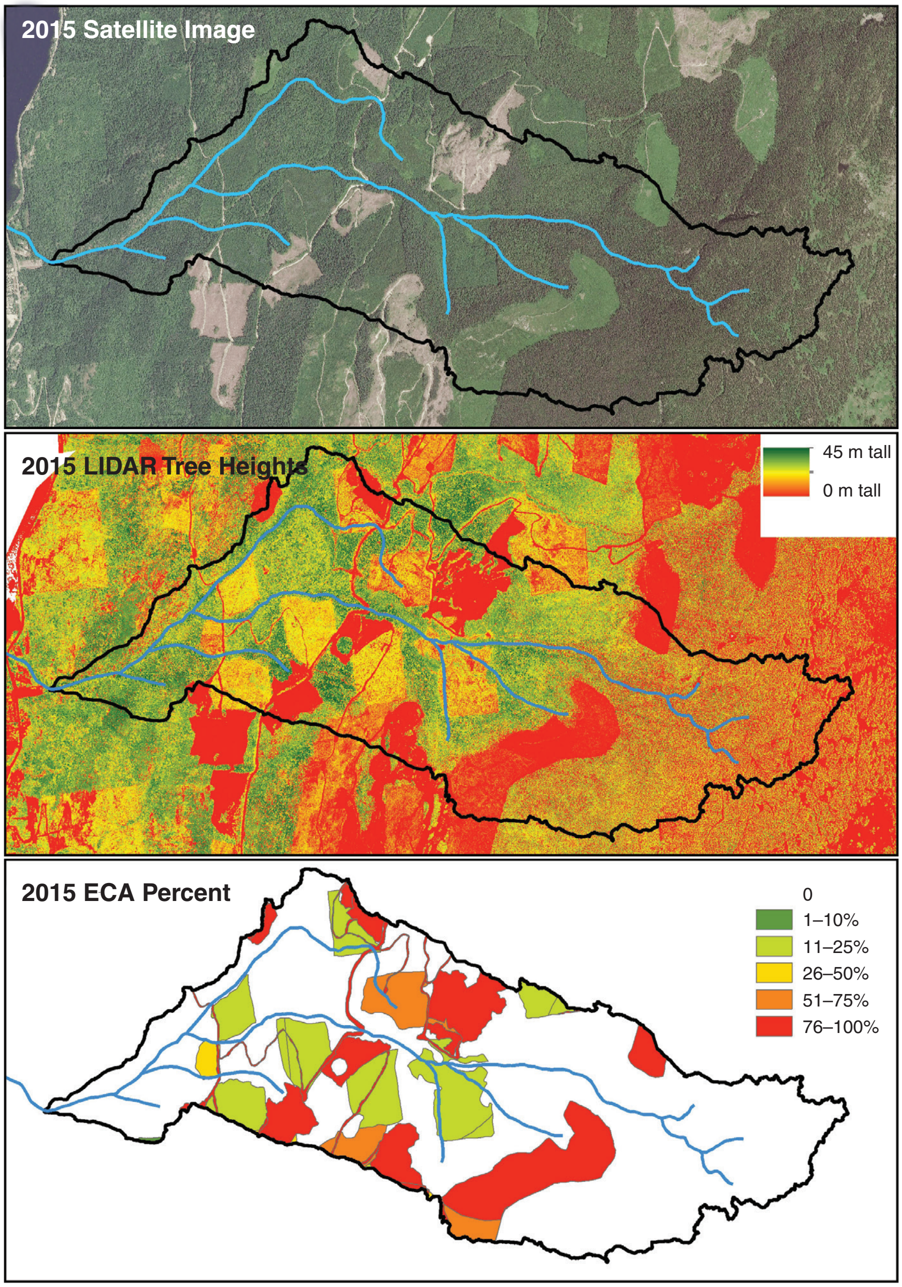

FIGURE 1 *A typical southern interior watershed over which equivalent clearcut area has been determined for each cutblock and disturbance.*

or value at risk (e.g., a water intake, bridge, or fish habitat). In watersheds with limited forest area, streamflow is driven by hydrologic processes on non-forested land (e.g., snowmelt from alpine areas and glaciers, runoff from open range or rock), and this non-forested area must also be included in the watershed total. Note, however, that these areas are not "clearcut" and therefore do not contribute to ECA.

Forest regrowth is accounted for in ECA calculation as hydrologic recovery. Hydrologic recovery is the restoration of stand-scale hydrologic characteristics to pre-disturbance, mature stand conditions with forest regrowth (Figure 2). In British Columbia, HR has most often been used in reference to snow accumulation and melt in a second-growth stand relative to both a clearcut and unlogged mature forest. Hydrologic recovery can also apply to rainfall, rain-on-snow, evapotranspiration, or seasonal water balances; however, these relationships have not been quantified in British Columbia. Hydrologic recovery is estimated using relationships between stand attributes (basal area, canopy cover, or tree height) and the hydrologic response indicator of interest—for example, snow water equivalent (SWE) and snowmelt. HR is estimated using readily available tree height data. While canopy cover and distribution also influence snow accumulation and melt, there is insufficient data available to quantify their relationship for all tree species and hydrologic regimes. Winkler and Boon (2015) provide a detailed discussion of hydrologic recovery based on snow accumulation and melt in Interior British Columbia, and an updated "recovery" curve to replace the original Interior Watershed Assessment Procedure approximation (B.C. Ministry of Forests 1999). For spruce–fir and lodgepole pine forests, 90% recovery is expected once regrowth is ≥ 60% of the original stand height at full stocking. Additional measurements are needed to quantify this relationship for other species, stand types, and hydrologic regimes.

Figure 3 provides two examples of changes in ECA with logging and regrowth of pine or spruce in a 15 000-ha (150-km^2) watershed with 10 000 ha (100 km^2) of operable forest and 4% road coverage. The site index (height of the largest-diameter tree at age 50 at breast height) was assumed to be 18 m, with a 60-year rotation length. In example 1, if ~2% of the operable pine is harvested each year, ECA increases gradually for approximately 60 years, at which point regrowth balances new logging and ECA remains at 34%. In example 2, if 20% of the operable pine forest is logged in each of three

FIGURE 2 *Hydrologic recovery (HR) of snow accumulation and melt is based on the height of the regenerating stand relative to mature forest. In this example, the young trees average <5 m tall relative to the 23 m tall mature forest, and HR is <10%.*

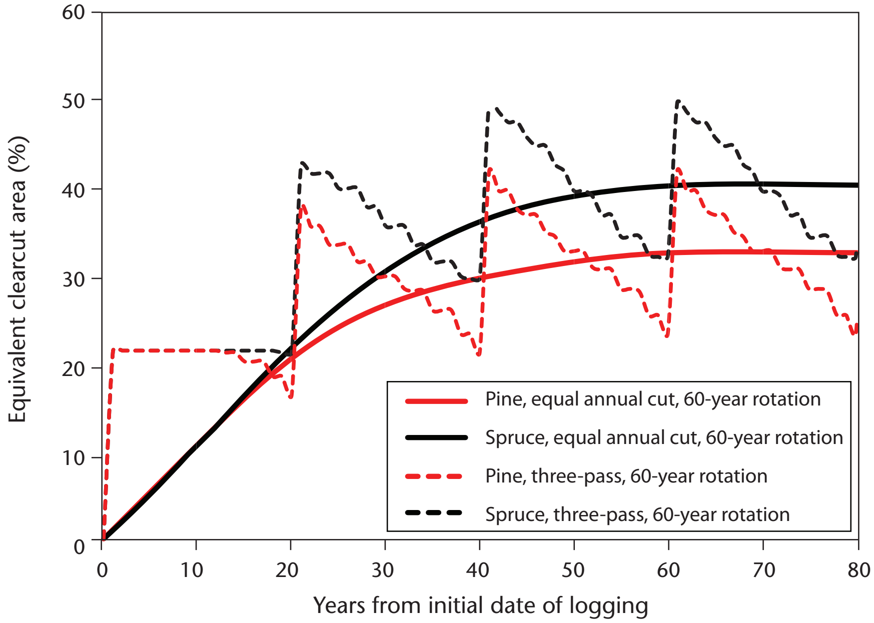

FIGURE 3 *Changes in equivalent clearcut area with logging and regrowth under two logging scenarios in a watershed over which two-thirds of the area is operable pine or spruce forest.*

passes (that is, once every 20 years), ECA reaches 43% following the second logging pass and does not drop below 24% over the entire rotation, even with recovery during the intervening years. If the tree species was spruce and the same recovery assumptions were applied, ECA would reach a long-term value of 42% if an equal area was logged annually, and a value of 50% under a three-pass system as a result of slower growth rates. Although the scenarios in Figure 3 are simplistic, they clearly illustrate that ECA limits based on hydrologic response thresholds affect rotation length and associated allowable annual cut levels. The average ECAs through time in these scenarios also suggest the need for long-term watershed-scale planning and consideration of multiple resource values prior to forest development.

Often ECAs are also calculated for specific elevation zones that represent the dominant form of precipitation that drives peak flow generation in a watershed: the snowmelt zone in the Interior, and the rain-dominated, transient snow and snowpack zones on the Coast. The relative hydrologic effects of ECA within these elevation zones are then determined largely by expert opinion.

Equivalent clearcut area should also be modified to account for areas that are not fully stocked with green coniferous trees (e.g., only a portion of the total stems has been removed or has died, regenerating stands are mixed deciduous/coniferous, non-clearcut silvicultural systems have been used, or stands have been spaced/thinned) (Figure 4). This is done by applying a disturbance coefficient to the ECA value. Currently, these estimates are largely unquantified by field measurements in British Columbia, but suggestions based on expert opinion are provided in the provincial watershed assessment guidebooks (B.C. Ministry of Forests 1999). For example, in partial cuts, ECA is based on the percent of the total basal area removed: that is, where 20–40% of the basal area is removed, ECA is 0.2 times the area disturbed; if >80% of the basal area is removed, this is assumed to be equivalent to a clearcut. Estimates are also provided for small openings and strip cuts (B.C. Ministry of Forests 1999). Additional research is necessary to quantify both HR and disturbance

FIGURE 4 *In stands that have been thinned (a), burned (b), or killed by insects (c), equivalent clearcut area must be modified to account for the partial or complete loss of green trees and the effects of standing dead trees. In British Columbia, disturbance coefficients generally remain unquantified.*

coefficient values for a broader range of forest covers, disturbance types, and silvicultural systems.

It should be noted that the effects of fire- and insect-related forest mortality on watershed-scale hydrology may or may not be measureable during the initial post-disturbance years. They may affect only hydrologic response once significant canopy material has been lost—often more than 3–5 years post-disturbance (Winkler et al. 2015). Lewis and Huggard (2010) provide ECA curves for stands in which trees have been killed by mountain pine beetle and snags have fallen over time. Their curves are based on canopy loss over time plus data provided in five studies that relate tree height or crown closure to snow accumulation and melt in British Columbia, eastern Canada, and Montana. The authors also use reduction factors to account for the effects of understorey vegetation on snow processes in different biogeoclimatic units. They caution that these stand-scale estimates are based on only a few field studies that link stand-scale hydrologic processes to forest cover, and on modelled forest growth under average stand conditions. The influence of stand structure on stand-scale hydrologic response to disturbance is demonstrated at Mayson Lake, British Columbia, where 53% of the trees forming the main canopy in a mixed-species, mature stand died following attack by mountain pine beetle. In this stand, canopy transmittance at the snow surface did not change because of the remaining green non-pine species and the well-developed understorey; thus, there was no significant increase in snow accumulation or melt rate (Winkler et al. 2015).

Equivalent Clearcut Area and Hydrologic Change

Numerous summaries of watershed research, whether globally inclusive or restricted to a specific hydroclimatic regime, have shown that vegetation removal generally results in increased water yield and peak flows. However, the magnitude of the hydrologic response to any given level of disturbance is highly variable depending on hydroclimatic regime, watershed characteristics, forest cover, disturbance type, and disturbance distribution (Bosch and Hewlett 1982; Stednick 1996; Scherer and Pike 2003; Brown et al. 2005). For example, areas with high mean annual precipitation (> 400–500 mm/yr) generally have the largest increases in water yield with forest cover loss (Bosch and Hewlett 1982), as do wet versus dry years (MacDonald and Stednick 2003). However, the largest increases in yield do not necessarily correspond to the largest area cut, but rather are influenced by the distribution of disturbances with elevation and aspect, as well as post-disturbance stand retention (Green and Alila 2012; Pomeroy et al. 2012; Winkler et al. 2015). Watersheds in relatively dry, temperate hydroclimatic regimes often experience a change in the timing and magnitude of snowmelt-generated peak flows as a result of earlier snowmelt, but little or no change in total annual yield due to high vegetation demand for limited soil moisture during the growing season (Biederman et al. 2015; Winkler et al. 2015).

This large variability in hydrologic response to disturbance among watersheds precludes the development of a single "global" relationship between disturbance and streamflow. For example, in northern Idaho, two comparisons of measured and ECA-predicted changes in water yield showed that the ECA approach underestimated flow by 38–44% depending on watershed size (King 1989). The combined results of studies in Interior British Columbia indicated that only 49% of the variability in annual water yield and < 25% of the variability in peak flows was explained by ECA alone (Winkler et al. 2015). Similar results were obtained in a review of simulated hydrologic effects of harvesting in 35 Alberta watersheds, where percent watershed harvested explained 46% of the variability in post-harvest water yield (Watertight Solutions Ltd. 2008).

However, when forest disturbance within a single watershed is

FIGURE 5 *Aerial view of the Upper Penticton Creek watershed experiment and surrounding area.*

considered, the effects of increasing ECA on hydrologic response are clear. Analysis of streamflow data from Upper Penticton Creek (Figure 5), measured over a 7-year period at 47% ECA, showed a significant increase in May water yield (19%) followed by a significant reduction in June (23%), as well as a significant increase in maximum daily flows (21%) (Winkler et al. 2015). Streamflow modelling in a small (5 km^2), gently sloping, south-facing, upland watershed at Upper Penticton Creek suggested that average post-disturbance daily peak flows with a 10-year return period increased at ECAs < 20% (Figure 6). At 50% ECA, with cutblocks distributed throughout the watershed, the model suggested that peak flows may increase by 15–20% and become twice as frequent, regardless of magnitude (Kuraś et al. 2012).

Model scenarios of clearcutting in distinct elevation bands at Redfish Creek, also a south-facing but larger (26 km^2), steeper watershed with 60% forest cover and 40% alpine, suggested that the largest increases in daily peak flows would occur in response to clearcutting in the upper third of the forested area (i.e., 20% of total area in the upper 60% of the watershed). Daily peak flows with a 10-year return period increased by 13% when a simulated 50% of the forested area was logged, a change that was partly mitigated by snowmelt processes in the alpine area that was unaffected by disturbance (Schnorbus and Alila 2004).

At both Upper Penticton Creek and Redfish Creek, the hydrologic response to clearcutting was predominantly a result of post-disturbance melt runoff synchronization between elevation bands. Green and Alila (2012) expanded on previous modelling work to suggest that, at 33–40% ECA, the average and variability in post-disturbance peak flows increases, which affects floods of all magnitudes, and the largest increases occur during the largest flood events. Based on their results, Green and Alila (2012) present a conceptual model of linkages between peak flow response to disturbance and watershed characteristics. They indicate that disturbance should have the greatest effect in small watersheds with steep slopes, uniform aspect, minimal alpine area, dense forest cover, and high drainage density. Their results clearly show that forest disturbance, even over < 20% of a highly responsive watershed, can substantially change the hydrologic regime. These changes may generate an associated channel response, varying from increases in the frequency of geomorphically effective floods to increases in the frequency of channel-forming floods,

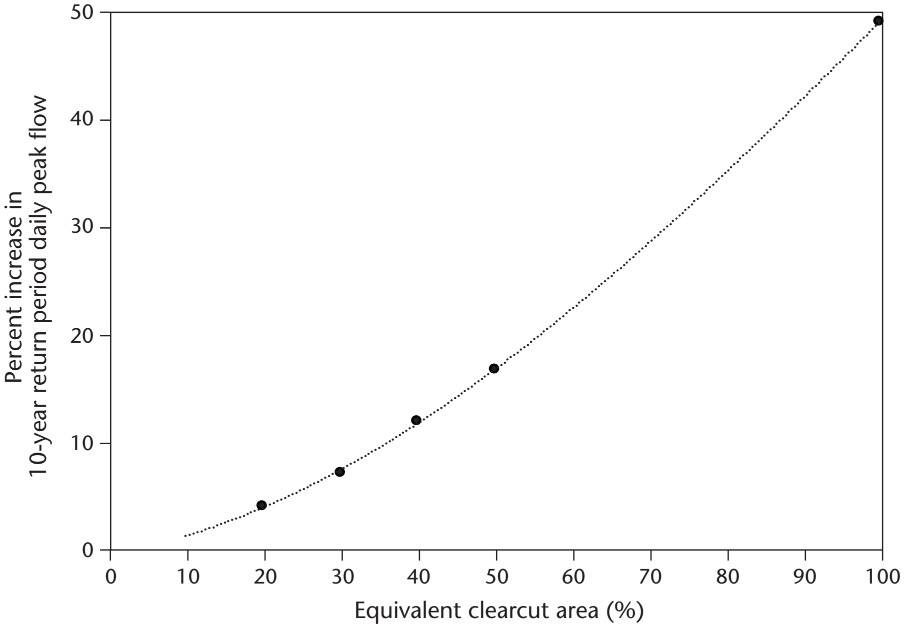

FIGURE 6 *Average predicted increases in 10-year return period daily peak flows from 240 and 241 Creeks at Upper Penticton Creek with increasing equivalent clearcut area (Schnorbus and Alila 2004; Kuraś et al. 2012).*

depending on channel morphology (bed texture, channel gradient and form, and presence of woody debris), with potentially significant downstream consequences (Green 2013).

Advantages and Disadvantages of the Equivalent Clearcut Area Approach

Simple index values such as ECA are often useful as consistent thresholds or precautionary targets to guide management decisions, to compare the potential relative effects of different management scenarios, and as communication tools (Price et al. 2009). The ECA approach requires no specialized expertise, can be completed in the office, and will provide the same value for anyone carrying out the analysis with the same input data using the same hydrologic recovery and partial cover loss assumptions. It is a useful indicator of the relative amount of disturbance to forest cover minus regrowth for comparing watersheds and forest development options.

When using ECA as an indicator of potential hydrologic change, it must be understood that—although ECA assumptions are supported to some extent by field research at the stand and small watershed scale—there is no evidence that stand-scale ECAs are additive at the watershed scale, or that the total can be interpreted in the same way in all watersheds.

In a review of watershed indicators, Carver and Teti (1998) concluded that no single parameter—most notably ECA—was a sufficient indicator of the cumulative effects of disturbance in a watershed. The cumulative effects of disturbance at the watershed scale are also affected by local hydroclimatology, watershed characteristics, distribution of disturbance across elevation and aspect, and proximity of disturbances to streams. Furthermore, ECA is an unsuitable index for determining temporally cumulative effects because it considers only the recovery of the driving variable (e.g., increased streamflow or sedimentation) and not the time necessary for resulting downstream effects to recover (e.g., channel width or fish habitat) (Berg et al. 1996). The relative location of the disturbance to streams and the routing of water and sediment through space and time are not considered in the calculation of ECA, and the predicted physical changes are not related to fisheries, domestic water supplies, or other beneficial water uses (MacDonald 2000). Equivalent clearcut area also assumes a stationary climate, which may not be applicable over a typical rotation; thus, predicted future hydrologic response to disturbance may be different than under the current hydroclimatic regime (Moore et al. in press).

The key limitations of applying a single indicator such as ECA to quantify the potential hydrologic response to disturbance include the following (MacDonald 2000):

- the effects of a given management activity are highly variable and a function of site conditions;
- recovery rates are difficult to define;
- validation of empirical relationships is limited; and
- future events and indirect effects are largely unpredictable.

However, in the absence of quantified hydrologic response to increasing levels of disturbance and recovery at the watershed scale, ECA remains a useful tool for assessing the potential relative magnitude of hydrologic change associated with past and proposed forest development and natural disturbance. The limitations associated with ECA as an indicator of change do not preclude its use as one of a suite of indicators used in risk assessment or in management decisions but must be considered in its application.

Summary

Equivalent clearcut area describes the extent of forest disturbance while accounting for forest regrowth. Stand-scale ECA values are summed to provide a single value for a watershed. This value is then interpreted to describe the potential for disturbance-related, watershed-scale changes in hydrologic regime. When calculated consistently, ECA provides an easily communicated indicator of the potential relative hydrologic change resulting from forest cover loss. When used in combination with other indicators, ECA is most useful for evaluating the relative effects of different development plans and determining whether development is approaching a threshold value set by watershed assessments, forest stewardship plans, or government.

However, when using ECA, it is crucial to acknowledge that this approach is a highly simplified representation of the complex, likely non-linear, linkages between forest stands, hillslopes, topography, surficial geology, and the stream network. These linkages vary with weather and by watershed, and have at best been only partially quantified in long-term research on watersheds. Stand-scale effects may or may not be cumulative at the watershed scale, and the same ECA will not necessarily result in the same hydrologic response in all watersheds. Therefore, ECA must be considered in combination with other watershed attributes, such as watershed size, aspect, and elevation distribution, and environmental process variables in evaluating both the hydrologic response to disturbance and the relative effects of forest management options. Furthermore, ECA values must be interpreted both in light of differences in calculation methods (e.g., inclusion of “weighting factors” to represent the proportion of watershed affected and/or disturbance type), and in terms of the young stand information used to calculate HR.

Although ECA provides a relative indication of the potential hydrologic response to forest disturbance and regrowth, it should never be used as a stand-alone metric for watershed analysis, nor as a substitute for professional analysis and field assessment. Assumed linkages between ECA values and the hazard associated with potential changes in streamflow should be applied cautiously in watershed assessment and used only in combination with an understanding of the processes influencing hydrologic response, a knowledge of local conditions, and in consideration of the influence of weather. To better understand the effects of forest disturbance on hydrologic response, continued research is necessary to quantify HR across a broad range of forest and disturbance types and seasons, to determine linkages between ECA and hydrologic response across hydroclimatic regimes and watershed scales, and to define the potential changes in key hydrologic processes that affect the operational interpretation of ECA with climate change.

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