Forest Research
Technical Report
Coast Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

TR-032 Hydrology March 2007

An operational method of assessing hydrologic recovery for Vancouver Island and south coastal BC

by

Robert Hudson and Glynnis Horel

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

Citation:
Hudson, R., and G. Horel. 2007. An operational method of assessing hydrologic recovery for Vancouver Island and south coastal BC. Res. Sec., Coast For. Reg., BC Min. For., Nanaimo, BC. Technical Report TR-032/2007.

Contact:
Robert Hudson, PGeo, PhD
Research Hydrologist
Coast Forest Region
BC Ministry of Forests
2100 Labieux Road
Nanaimo, British Columbia V9T 6E9
tel. 604-341-0135
email: Rob.Hudson@gov.bc.ca

Glynnis Horel, PEng
Geocoast Engineering Ltd.
2639 Barnes Road
Nanaimo, British Columbia V9X 1N3
tel. 250-722-7166
email: oesl@shaw.ca

website: http://www.for.gov.bc.ca/rco/research/index.htm

Cover photo: Satellite image of Koprino watershed on northern Vancouver Island. Copyright GoogleEarth™.

TABLE OF CONTENTS

SUMMARY

While streamflow in interior watersheds is dominated by radiation snowmelt producing a single annual peak flow event, coastal watersheds are subject to a mixture of processes with multiple peak flows, and the effect of forest harvesting on rainfall interception is at least as important as its effect on snow interception and melt. This report aims to integrate the results of coastal hydrologic recovery research into a unified method of determining hydrologic recovery of coastal forest stands. It describes an empirical model of stand level hydrologic recovery that is based on a standard set of recovery curves, and is capable of being applied in a distributed framework. The authors recognize that our understanding of this complex subject is incomplete, and the model has certain limitations. Nevertheless, the model framework represents the state of knowledge of post-disturbance coastal hydrologic recovery processes, it is simple to apply and amenable to integrate with a numerical hydrology simulator, and it is flexible enough to be easily updated as new information becomes available through ongoing research.

KEYWORDS

Forest harvesting, forest management, hydrology, hydrologic recovery, snowmelt, streamflow, rainfall interception, clearcuts, watershed, watershed assessment, Coast Forest region

ACKNOWLEDGEMENTS

We would like to thank various people who have reviewed and contributed to this work over the last three years, in particular Brian Roberts, David Campbell and Shelley Higman.

DEDICATION

This publication is dedicated to the memory of our dear friend, colleague and mentor: Dr. Bob Willington. Bob was a great supporter of this work and we believe he would have approved of this report.

1. INTRODUCTION

Forest stands influence the hydrologic behavior of a site by creating a complex interaction between live tree cover and the water input-output balance. Because forest canopies modify the delivery of water to the soil, removal of the canopy by clearcut harvesting has been found to alter both the peak flow and the total volume of flow (in most cases increasing both). For purposes of this report, hydrologic recovery of forest stands has been defined as the process by which the hydrologic conditions of a harvested site are restored to near pre-harvest conditions with the re-growth of a new forest at the site. The focus of the report is on hydrologic processes which affect peak flows.

In a typical interior watershed, streamflow is dominated by radiation snowmelt to produce a single annual peak flow event. A typical coastal watershed responds to a mixture of processes. Multiple peak flows occur, mostly in the fall and early winter, driven by a series of rainfall and/or rain-on-snow (ROS) events. At upper elevations (above 1,000 metres), spring snowmelt is a dominant process.

Most hydrologic recovery research in Canada (e.g., Hudson, 2000, Winkler, 2001, Talbot and Plamondon, 2002, Buttle et al, 2005) has focused on recovery of snow interception and melt processes. For coastal watersheds, the effect of forest harvesting and regeneration on rainfall interception is at least as important as the effect on snow interception and melt. The concept of rainfall recovery of forest stands has been developed by Hudson (2003) based primarily on detailed rainfall interception studies conducted at low-elevation sites on Vancouver Island (McMinn, 1957, Spittlehouse, 1995), and at high elevation at Gray Creek (Hudson, 2003). The purpose of this report is to integrate the results of coastal hydrologic recovery research into a unified method of determining hydrologic recovery of forest stands suitable for either professional assessment work or for integration into a numerical hydrologic simulation model.

The preceding definition of hydrologic recovery is common to the Canadian literature on the effects of forest harvesting and regeneration on the water balance (e.g., Hudson, 2000, Talbot and Plamondon, 2002, Buttle et al, 2005). However, within the American "grey" literature, hydrologic recovery is defined as "a condition in which post-disturbance watershed response corresponds to pre-disturbance watershed response." (Schaffner and Reed, 2005) This is an important distinction, and is likely to cause confusion if not resolved. It would be more correct to use the term "forest stand hydrologic recovery" in place of hydrologic recovery as it is referred to in the Canadian literature, and "watershed hydrologic recovery" to describe hydrologic recovery as referred to in the American literature. As we have defined it, forest stand hydrologic recovery is not an index of a change in streamflow (specifically peak flow), it is an index of the degree to which a regenerating forest stand is similar to old growth in its interception characteristics and its influence over snowmelt. The linkage between ECA and its potential to alter streamflow will be the subject of future publications.

1.1 CONCEPTUAL DEVELOPMENT

The concept of hydrologic recovery as we have defined it is applied to individual forest stands. Hydrologic recovery tells us how much a regenerating stand is like the original (old growth) stand in terms of its capacity to intercept precipitation and modify snow distribution and melt. The degree to which a forest stand is hydrologically recovered is usually expressed as a proportion, where 1 = fully recovered or uncut, and 0 = clearcut or equivalent.

More simply, for an area of land with regenerating forest, its hydrologic recovery status tells us to what degree it is expected to act like old growth. However, the question more commonly asked by management is "what effect will forest harvesting activities in a watershed have on streamflow?" Thus, at the stand level, the more important management question is "to what degree is it expected to act like a clearcut?" In other words, what is its clearcut equivalence?

Intuitively, if a forest stand has interception characteristics that are not measurably different than those of a clearcut, then its hydrologic recovery status is 0 and it is equivalent to a clearcut. Therefore we can define the quantity clearcut equivalence as:

$$\textit{Clearcut Equivalence} = 1 - HR$$

where HR is hydrologic recovery expressed as a proportion.

In order to manage forested watersheds more effectively, a method of assessing the hydrologic condition of regenerating forests at the watershed scale is needed. To that end, the concept of Equivalent Clearcut Area (ECA) has been adopted in BC, which is defined as the degree to which a regenerating forest stand is hydrologically similar to a clearcut, relative to the hydrologic status of the original stand, expressed as the area of a hypothetical clearcut that would have the same hydrologic effect as the regenerating stand. For individual stands, it can be defined mathematically as:

$$ECA = \textit{Area} \times \textit{Clearcut Equivalence}, \text{ or,}$$

$$ECA_{stand} = A \cdot (1 - HR)$$

where A = harvested stand area.

While hydrologic recovery is determined for individual forest stands, ECA is generally applied at the watershed scale to represent the cumulative effect of all harvested and regenerating stands in the watershed. Mathematically, this can be expressed as:

$$ECA_{WS} = \frac{\sum ECA_{stand}}{A_{WS}} \quad (1\text{-}1)$$

The concept of ECA has been developed in BC, but is beginning to gain acceptance elsewhere in Canada (Talbot and Plamondon, 2002).

To account for the variability of conditions throughout the watershed, it is necessary to consider several factors that influence water balance at the site. These include:

1. Canopy condition, including:
   a. Stand height,
   b. Canopy density,
   c. Crown closure/canopy completeness,
   d. Patchiness;
2. The dominant species and the species mix of the regeneration,
3. The age or status of the stand that was there originally,
4. The dominance of rain, snowmelt or rain-on-snow (ROS) as runoff processes,
5. Regional hydrologic conditions, and
6. The influence of elevation on precipitation and evaporation.

This report will describe a forest stand hydrologic recovery model that integrates the above factors to determine stand-level recovery that is suitable for either watershed assessment purposes or for integration into a distributed hydrologic simulation model.

2. METHODOLOGY

2.1 BRIEF SUMMARY – DEVELOPMENT OF SNOWMELT AND RAINFALL RECOVERY CURVES

Full hydrologic recovery for coastal British Columbia consists of several distinct components, including rainfall interception recovery, snow accumulation and interception recovery, snowmelt recovery, ROS recovery, and evapotranspiration (ET) recovery. Snowmelt and rainfall are clearly different processes; the ROS component is a composite of the first two, but is by far the most complex and for practical purposes can be treated as a separate process.

We have not addressed ET recovery specifically for several reasons. During the fall and winter when peak flows in coastal watersheds tend to occur, ET is very low and is usually insignificant compared with precipitation. For many of our coastal watersheds there is no correlation between peak flow and antecedent moisture condition, which suggests that the moisture status of the soil is not the main factor that determines how much water is delivered to stream channels (Aotake and Alila, 2006). These observations both suggest that ET is only a minor contributor to hydrologic recovery in coastal watersheds, and given the difficulties in measuring actual ET directly, it is highly unlikely that we would be able to measure ET with sufficient accuracy or precision to define its role.

The one element common to all cases is the form of the recovery curve, on which the model is based. In all cases the relationship between recovery and stand descriptor (SD) is best described by a variant of the Chapman-Richards curve, an exponential-asymptotic function of the following form:

$$HR = A\left(1 - e^{-b(SD - T)}\right)^{c} \quad (2\text{-}1)$$

Where HR is the hydrologic recovery (as a proportion or a percent), A is the asymptote (for recovery A is usually 100%), b and c are curve fitting parameters, T is the recovery threshold (the value of the stand descriptor where recovery starts; below that level, HR=0), and SD is the stand descriptor.

2.2 STAND DESCRIPTOR

For snowpack recovery (i.e., combined snowmelt and snow interception recovery), stand height and canopy density were found to be equally good predictors, but combining them into a composite stand descriptor did not improve the predictive ability (Hudson, 2000). For snowmelt recovery the best stand descriptor is stand height (m), whereas for rainfall recovery a stand descriptor called Adjusted Stand Height (ASH) was developed to account for over-stocked or under-stocked stands (Hudson, 2003).

In the case of snowmelt recovery, there is a physical rationale for basing recovery on stand height:

- The shade that a tree casts on the snowpack influences radiation snowmelt, and
- Wind speed, the primary parameter controlling latent and sensible heat fluxes in ROS melt, is more closely related to

stand height than canopy density.

In the case of interception recovery (either snow or rainfall interception) some measure of canopy density or completeness is probably a more physically correct descriptor than stand height; however the latter is a better descriptor of recovery because:

- There is usually a close relationship between stand height and density, and
- Stand height is
  - o Routinely reported in inventory,
  - o A precision measurement, and
  - o Objective (i.e, there is no observer bias).

In contrast, canopy density can also be reported as crown closure, or crown or canopy completeness, all of which are subtly different from one another. There are several ways to measure it; however, they are somewhat unreliable as they all produce slightly different results—often canopy closure is just estimated from the air.

At the time of writing this report, stand height remains the principle stand descriptor used to estimate snowmelt recovery and ASH is used as the stand descriptor for rainfall recovery. ASH is defined as the sum of stand height and the residual derived from regression of stand height against canopy density.

The effect of this is that ASH is greater than stand height for overstocked stands, and less for understocked stands. Currently, snowmelt recovery is being reformulated as a function of ASH. When this has been done these methods will be updated accordingly.

2.3 SNOWMELT RECOVERY

2.3.1 DEVELOPMENT AND TESTING OF THE SNOWMELT RECOVERY CURVE

The snowmelt recovery curve was derived from eight separate events (including both radiation and ROS snowmelt) at 10 regenerating stands at Gray Creek. Curves were fitted to spring and ROS events separately but were not significantly different. Therefore, treating these as independent events, snowmelt recovery is described by the following:

$$HR_{snow} = 100\left(1 - e^{-0.22(Ht-T)}\right)^{0.70} \qquad (2\text{-}2)$$

When all events are lumped in this way the variability of the curve is ±40% (Figure 1). However, when the events are averaged and plotted against the five-year mean stand height, the error is reduced to ±10% with a mean recovery threshold of 1.2 m (Figure 2).

2.3.2 TESTING AND VALIDATING EQUATION 2-2

The recovery curve was validated at Chapman Creek under ROS conditions (1993-94) and at Gray Creek under extreme conditions due to ROS (February 1995) and spring snowmelt (1999). Curves fitted to these data sets were not significantly different from equation 2-2, assuming that the threshold could be adjusted to the snowpack conditions (Figure 3). In total, 11 scenarios were tested, including six spring melt and five ROS melt events. Using equation 2-2, the value of the recovery threshold for each scenario was derived statistically (Table 1). Average recovery thresholds for spring snowmelt conditions (T) were found to be equal to the average peak snowpack depth at open sites, and the threshold for ROS conditions (T_{ROS}) equal to the peak snowpack depth plus 0.5 metres. Therefore, in order to derive a regional method of determining a recovery threshold it was assumed that those values could be determined from the mean annual peak snow depth (D_{max}) for a given site in metres using the following simple formula:

$$T_{ROS} = D_{max} + 0.5 \qquad (2\text{-}3)$$

$$T = D_{max} \qquad (2\text{-}4)$$

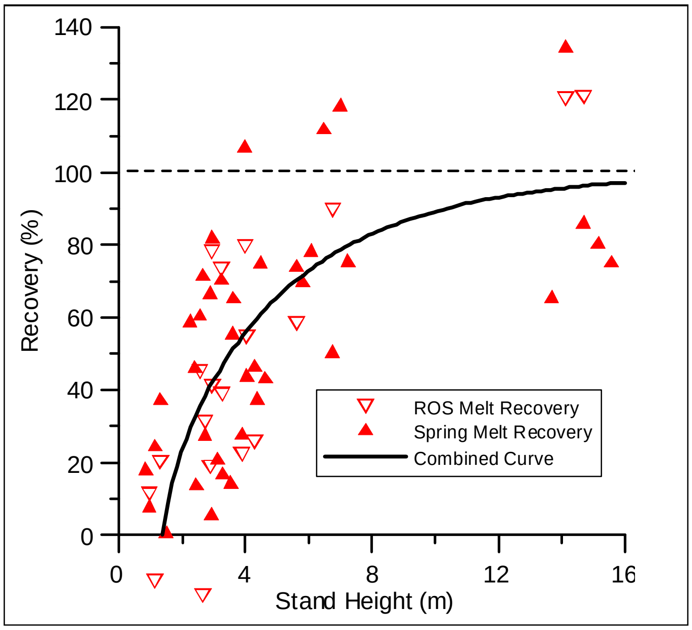

Figure 1. High variability in recovery among individual events (±40%).

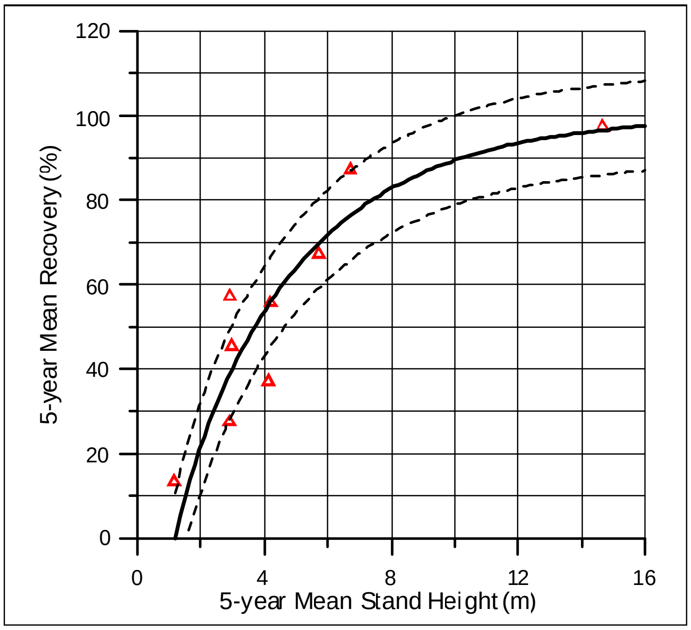

Figure 2. Averaging across all events reduces the error to ±10%.

An analysis of 50 years of regional snow course data revealed five "Snowpack Zones" as defined by D_{max} vs. elevation relationships (Figure 4). Based on these relationships, the recovery thresholds for any zone or elevation can be determined as follows:

$$T = Z_0 \cdot elev + Z_1 \text{ in the transient zone, and} \qquad (2\text{-}5)$$

$$T = 0.00353 \cdot elev + Z_2 \text{ in the snowpack zone.} \qquad (2\text{-}6)$$

The transient zone is usually 300 to 800 metres elevation and the snowpack zone 800 metres elevation and up. T refers to the threshold under spring snowmelt conditions. For ROS conditions, simply add 0.5 metres.

$$T_{ROS} = T + 0.5 \qquad (2\text{-}7)$$

2.3.3 RELATIVE CONTRIBUTION OF RAINFALL AND SNOWMELT TO PEAK RUNOFF

Full hydrologic recovery must include a rainfall component, as the relative contribution of rainfall to ROS runoff increases with storm size. Results obtained from Gray Creek suggest a "semi-exponential" relationship for warm (mean daily temperature greater than 1.5 °C) ROS events (Figure 5). Similarly, a limited number of small, cold ROS events suggested a relationship parallel to the linear portion of the warm ROS relationship. Although there were no large, cold ROS events to extend this relationship, it seemed reasonable to assume that for events larger than 40 mm the cold ROS relationship would continue parallel to the warm ROS curve. Thus the following set of equations can be used to determine the proportion of storm runoff supplied by snowmelt [$p(S)$]:

$$p(S) = X_0 - 1.7(PP_{basin}) \qquad (2\text{-}7)$$

for $PP_{basin} \leq 35$ mm., where PP_{basin} is the basin average total storm rainfall and

$$p(S) = X_2 + e^{\left(X_1 + \left\{47.4 / PP_{basin}\right\}\right)} \qquad (2\text{-}8)$$

Table 1. Coefficients for threshold calculation.

Snowpack Zone	Z_0	Z_1	Z_2
1	0.00564	-0.574	0.63
2	0.00414	-0.217	-0.28
3	0.00257	0.215	-1.03
4	0.00137	0.572	-1.82
5	0.00068	0.785	-3.02

Table 2. Coefficients to calculate proportional contributions of snowmelt to ROS runoff in equations 2-7 and 2-8.

	X_0	X_1	X_2
Cold (T<1.5 °C)	80	2.0	-5.8
Warm (T>1.5 °C)	97	2.32	0.0

for $PP_{basin} > 35$ mm. The coefficients X_0, X_1, and X_2 define the cold and warm versions of the relationship (Table 2).

2.4 "STANDARD RECOVERY" DUE TO RAINFALL INTERCEPTION

2.4.1 INTERCEPTION AND INTERCEPTION RECOVERY

Some of the rain or snow that falls on a forest canopy is caught and returned to the atmosphere by evaporation or sublimation; this is called interception. It is quantified by measuring throughfall and stemflow and subtracting those values from

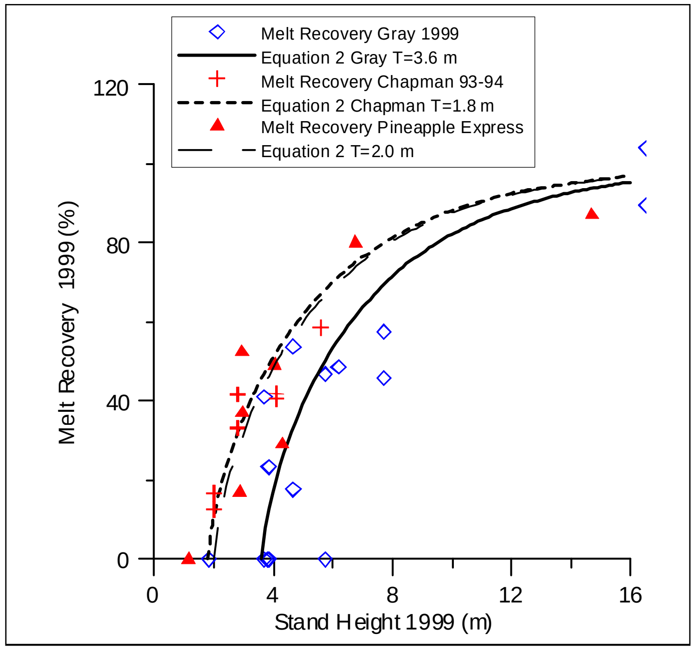

Figure 3. Validation trials of the recovery curve. Results indicate that the threshold can be adjusted to account for variability in snowpack conditions without altering the b or c parameter.

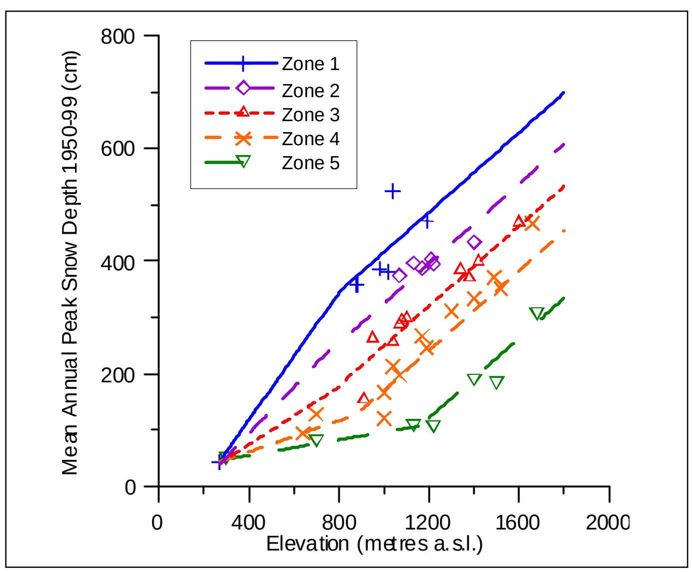

Figure 4. The basis of the snowpack zones.

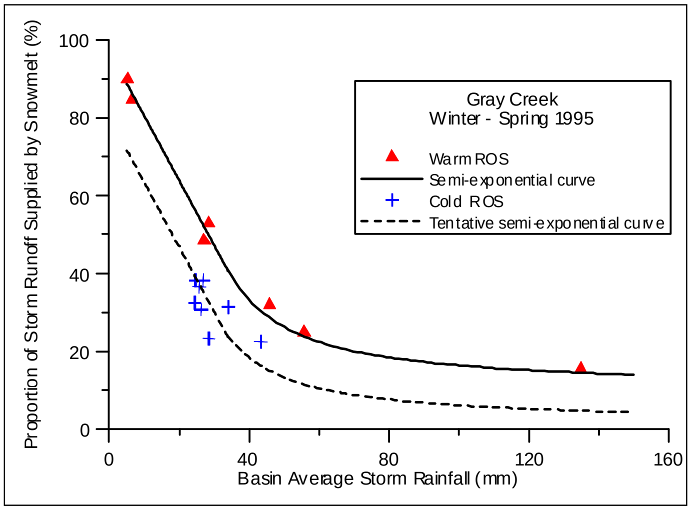

Figure 5. The effect of temperature and storm size on the relative contribution of rain and snowmelt to ROS peak flows.

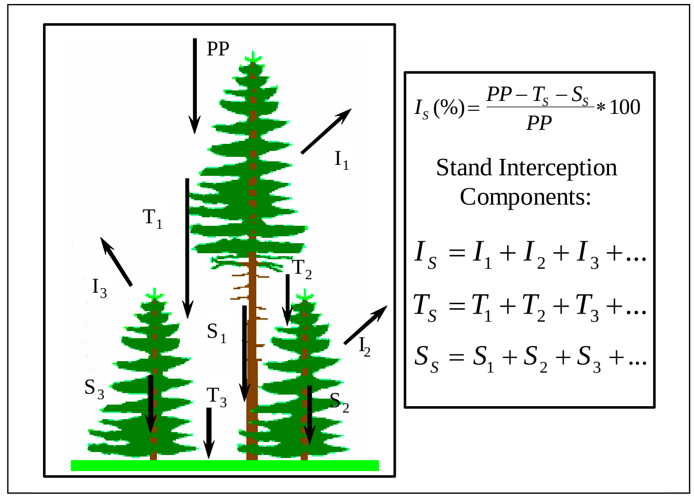

Figure 6. A schematic diagram showing the components of interception.

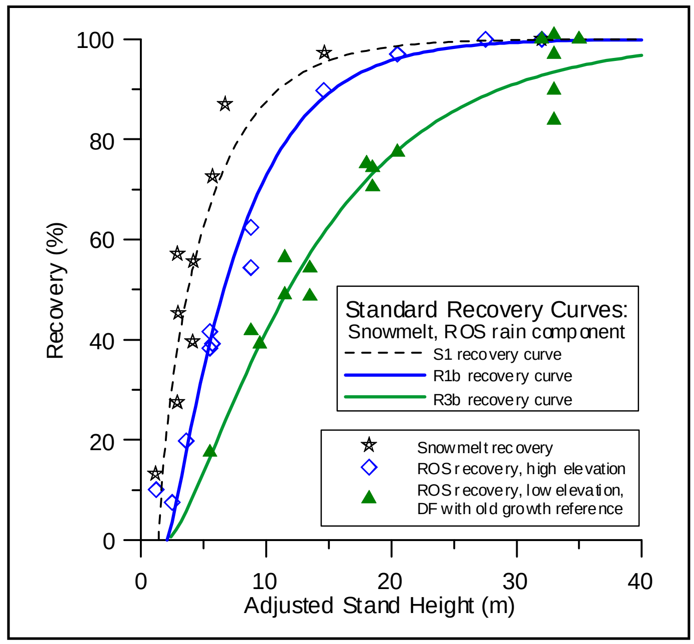

Figure 7. Standard recovery curves.

the total open-site rainfall (Figure 6).

Interception loss for a stand is determined as a percentage of open-site rain:

$$I_S(\%) = \frac{PP - T_S - S_S}{PP} * 100 \qquad (2\text{-}9)$$

Recovery for the stand is the ratio of stand interception to that of the reference stand:

$$HR_{rain,S} = \frac{I_S}{I_{\text{Ref}}} * 100 \qquad (2\text{-}10)$$

For measured stands, recovery was calculated for individual storms. There is high variability among storm interception recovery data. Variability is reduced by averaging across a large number of storms. Seasonal averaging of storm recovery data resulted in a set of "Standard Recovery Curves" describing snowmelt and rainfall interception recovery under average conditions (Figure 7).

2.4.2 FACTORS AFFECTING RAINFALL INTERCEPTION RECOVERY

Research clearly shows that rainfall recovery is affected by several factors other than regeneration status:

1. Rainfall regime, season

- Forest canopy has a finite holding capacity.
- If total precipitation increases, the percentage of interception loss decreases.
- Anything that affects precipitation (elevation, season, topography, etc.) affects interception recovery.

2. Temperature

- Affects evaporation from canopy: the higher the temperature, the greater the interception loss.
- Anything that affects temperature (elevation, season) affects interception recovery.

3. Tree species and stand structure

- Tree canopy development affects interception and hence recovery.
- Higher elevation stands have different structures than low elevation stands, which may contribute to elevational differences in recovery rates.

The curves integrate the above effects such that rainfall interception recovery under average conditions could be described by three standard curves. These were referred to as R1, R2, and R3 curves (Table 3):

- R1 describes high elevation (1000 m) fall–winter rainfall recovery.

- R2 describes low elevation (275 m) fall–winter rainfall recovery for Douglas-fir using mature second growth as a reference stand and for other species.
- R3 describes summer rainfall recovery for all elevations and species, and also includes fall–winter recovery for Douglas-fir with old growth as a reference stand.

The R1, R3, and S1 curves are well supported by data, and while it is acknowledged that the method requires further validation to be broadly applied, these curves provide a firm basis for an operational method of assessing hydrologic recovery. However, the R2 curve is less well supported by data and is considered somewhat conjectural. Also, old growth is widely accepted as the correct reference stand for hydrologic recovery. For this reason R2 is not considered a standard recovery curve and is therefore not included in Table 3.

The curve fitting was done using an iterative least squares procedure that identifies the b and c parameters that result in the minimum SSE for a range of thresholds. In the case of the rainfall recovery data, a plot of SSE vs. the threshold revealed a double minimum, one at T=0 and the second at the value of T reported in Table 3. This suggests two variants of each curve, which were interpreted as representing recovery of interception processes for rainfall onto bare ground and onto snowpack. This is most likely a result of the fact that the rainfall recovery curve at Gray Creek was found to be collinear with the snow accumulation/interception recovery curve, and consequently the rainfall and snow interception recovery data were combined to help define the lower end of the curve. The non-zero threshold is therefore based on actual ROS conditions, and the thresholds reported are the result of prevailing conditions at the time and location of the studies.

3. ALTERNATIVES TO STANDARD RECOVERY: THE EFFECTS OF STORM SIZE ON RECOVERY

In section 2 we used the standard approach of assessing hydrologic recovery in terms of the average meteorological conditions by lumping together all storms and melt events regardless of their relative size. In general, hydrologic recovery is an index of the efficiency of a regenerating forest stand at modifying precipitation inputs to soil, relative to that of old growth. Factors that affect that efficiency include not only the stand characteristics, but also those of the precipitation. "Standard recovery" was determined for average conditions and suggests that old growth has the greatest capacity to modify precipitation and/or snowmelt. However, this might not always be the case. The type of storm is known to influence the relative efficiency of a given stand at intercepting precipitation relative to old growth (Harr, 1986), and storm magnitude also influences the interception (Spittlehouse, 1998). As an alternative, if we look at recovery according to data that is averaged by storm size, then we begin to see an effect where immature stands become "over-recovered" relative to old growth—an effect that increases as we focus on larger storms. There are two ways of using storm size to average the data, each one yielding somewhat different results:

- Average all storms above a "design storm" threshold. This allows recovery to be weighted towards the larger, more important events. Under this scenario stands within a specific height range become progressively over-recovered as the design storm threshold is increased.
- Average by storm size class. When storms within a specific size class are examined, the effect is similar to that of the design storm approach above, but the relative over-recovery occurs at all stand heights.

3.1 OVER-RECOVERY: THE DESIGN STORM APPROACH

It has been shown that over-recovery occurs in second growth stands relative to old growth. At Gray Creek, the stand at site E is about 95% recovered under snowmelt or rainfall conditions when all storms are averaged to calculate interception. This stand is at a mean adjusted stand height of about 20 m. However, if instead we wish to define recovery in terms of a design storm, thereby limiting our estimate of recovery to the bigger storms, then site E is 100% recovered for storms above 10 mm, becoming increasingly over-recovered as the design storm threshold is increased. This occurs because mean interception as a percentage is steady at site E over the full range of storms, while at site F, interception drops from over 30% for small storms and levels off at about 22% for storms above a threshold of about 40 mm. Thus, over-recovery for second growth stands occurs between approximately 10 and 40 mm of rainfall; the 40 mm threshold corresponds to a return interval of about

Table 3. Coefficients of standard recovery curves: all curves have an asymptote of 100% (or 1.0 as a proportion). R1a and R1b are variants of the same curve, similarly R2a and R2b, R3 and R3b.

Curve	Application	Threshold**	b	c	R^2
S1 *	Snowmelt (both radiation melt and ROS melt)	1.4	0.22	0.70	
R1a	High elevation rainfall	0.0	0.226	2.83	99.0
R1b	High elevation ROS	2.1	0.189	1.25	99.0
R3a	Low elevation rainfall (DF referenced to old growth), general summer recovery, all elevations and species	0.0	0.107	2.11	98.1
R3b	Low elevation ROS (DF referenced to old growth)	2.1	0.100	1.45	97.9

* (from Hudson 2001b)
** Use equations 2-5 and 2-6 with Table 1 to determine thresholds.

one year. As the design storm threshold is increased, evidence shows that interception under both old growth and second growth levels off, thereby establishing an upper limit to over-recovery.

There are two factors that need to be considered when developing a method of assessing over-recovery: one is the over-recovery that occurs as a result of applying a design storm threshold, and the second is the range of stand heights for which over -recovery applies. We wanted a method of applying this factor within the existing framework of assessing overall mean hydrologic recovery; the simplest approach was to develop a factor that could be applied as a multiplier to existing rainfall recovery curves. We developed each factor as an index that when multiplied together would result in a unified index, correcting an existing curve to account for over-recovery as a function of stand height and the design storm threshold.

3.1.1 OVER-RECOVERY INDEX DERIVED FOR SITE 'E' AT GRAY CREEK

If we assume that the reason for this phenomenon is the difference in canopy density (CD) between the old growth and the second growth, then an index of over-recovery can be formulated from two variables: the canopy density ratio and the mean rainfall of storms above the design storm threshold. Logically, the over-recovery effect should be proportional to the ratio of canopy density under the reference old growth to that of the second growth canopies. Therefore these two factors can be combined into a design storm index as follows:

$$I_{DS} = \frac{\left(\overline{PP_{T_{DS}}}\right)}{CD_{OG}/CD_{SG}} \quad (3\text{-}1)$$

where I_{DS} is the design storm index for assessment of over-recovery, $\overline{PP_{T_{DS}}}$ is the average rainfall volume of storms above a selected design storm threshold (T_{DS}), and CD_{OG} and CD_{SG} are the canopy densities of the reference old growth and second growth stands respectively.

Over-recovery can be expressed as a ratio of recovery that results from the application of a design storm threshold (HR_{DS}) over the recovery that results from all storms regardless of their size (HR_0). This over-recovery ratio can then be used in the form of a multiplier that is applied to a standard recovery curve. Therefore, if the over-recovery effect is zero then the over-recovery multiplier will be equal to one. However, since it must be combined with the effect index which would equal zero for a stand where over-recovery does not apply, we must first calculate an over-recovery index as follows:

$$I_{OR} = \frac{HR_{DS}}{HR_0} - 1 \quad (3\text{-}2)$$

where I_{OR} is the over-recovery index. This index is the proportion by which the peak recovery exceeds the average recovery as determined by applying a standard rainfall recovery curve. This quantity was calculated for Site E at Gray Creek along with the design storm index (Table 4). The canopy density ratio (CD_{OG}/CD_{SG}) determined from canopy measurements collected at sites E and F in 2001 was equal to 0.62.

The plot of the over-recovery index as a function of the design storm index (Figure 8) suggests that the over-recovery index has a maximum value; the scatter plot shows a leveling off effect as the design storm index increases. Using a Chapman-Richards curve, the best fit curve is given by the following equation:

$$I_{OR} = 0.62\left(1 - e^{-0.04\,(I_{DS})}\right)^{19.52} \quad (3\text{-}3)$$

Note that the asymptote is 0.62, which is equal to the canopy density ratio that was determined for the Gray Creek study site. This asymptote was determined as a least-squares curve-fitting parameter and is therefore an independently derived quantity. Thus the index has a potential range from zero to the CD ratio. According to expert opinion at this time, in most

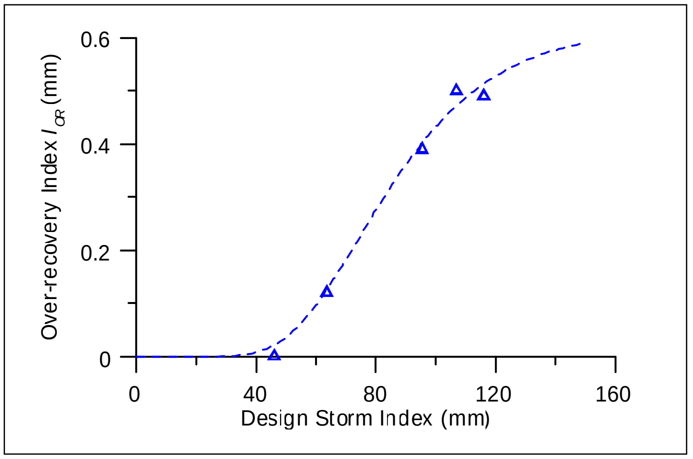

Figure 8. Over-recovery index as a function of Design Storm index.

Table 4. Derivation of the concept of over-recovery using a design storm index at Gray Creek.

T_{DS}	R_F	R_E	R_D	R_C	# storms	$\overline{PP_{T_{DS}}}$	I_{DS}	I_{OR}
0	100.0	92.1	57.6	31.1	25.0	28.5	46.0	0.00
15	100.0	102.8	59.8	36.5	16.0	39.4	63.6	0.12
30	100.0	128.1	55.0	41.5	8.0	59.2	95.5	0.39
45	100.0	137.9	51.4	32.0	6.0	66.3	106.9	0.50
60	100.0	137.1	42.8	29.9	4.0	72.0	116.1	0.49

cases the CD ratio may be anywhere between 0.6 and 0.7, and in lieu of specific information a default value of 0.65 is suggested.

3.1.2 OVER-RECOVERY AS A FUNCTION OF STAND HEIGHT

Over–recovery can be best formulated as a multiplier to be applied to the standard recovery curve for rainfall or ROS (i.e., R1 or R3). Because the over-recovery index was quantified for one second growth stand at Gray Creek, it is assumed that it can be applied to stands within a range of stand heights for which over-recovery could reasonably be expected to apply. As shown in Figure 9, interception under old growth and under 9-metre second growth declines throughout the T_{DS} range of 0 – 40 mm, while it remains relatively constant under 18-metre second growth throughout the same range. Table 5 confirms that over-recovery reaches a maximum at a design storm threshold somewhere between 30 and 45 mm at Site E, while, by varying the threshold, it remains relatively unchanged at Site D. Site E has a stand height of 18 m (adjusted stand height of 20 m). Therefore, assuming that site E represents more or less the peak of the over-recovery effect, and that the effect is zero under 9-metre second growth, we can use these limits to estimate the relationship between the effect of the over-recovery index and stand height.

Similarly, over-recovery also occurs among Vancouver Island stands when the rainfall interception of the stand in question is greater than that of the reference old-growth stand. The effect of varying the old growth reference stand was noted in Hudson (2003), including the fact that below a certain reference stand height, over-recovery became more common. Since the reference stands for Vancouver Island Douglas-fir were all simulated, any scenario is equally valid, and as a result different reference stands imply different recovery curves, as well as varied occurrences of over-recovery.

To assess the relationships between over-recovery and stand height as it applies to the different recovery curves, composite data sets were assembled from a combination of different design storm thresholds at Gray Creek and recovery data under different reference scenarios on Vancouver Island (Table 6). If the recovery data from each of these composite scenarios are plotted against stand height, the resultant graph suggests that the over-recovery effect reaches a peak at a stand height of 25 m (Figure 10). The curves that were fit to these data were parallel polynomials as follows:

$$HR_{OR_S} = 0.604 \cdot Ht^2 - 0.0158 \cdot Ht^3 + 21S \quad (3\text{-}4)$$

where Ht is the stand height in metres and HR_{OR_S} is the apparent recovery where S=0 for the R3 curve and S=1 for the R1/R2 curves.

The assumption made here is that the peak over-recovery can be predicted by the polynomial curve fit. Although there is no data to validate this, the data points suggest that the peak over-recovery occurs at a stand height greater than the stand height

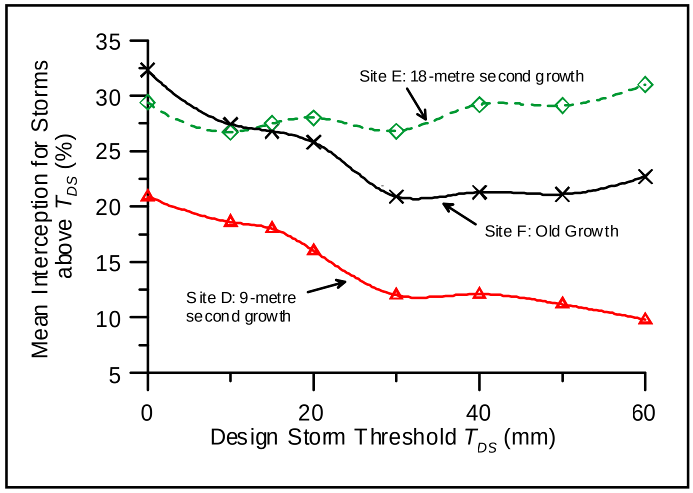

Figure 9. Interception vs. storm size for three stands at Gray Creek.

Table 5. Design storm and over-recovery indices for Site E at Gray Creek: simulated mean rainfall.

PP (mm)	I_{DS}	I_{OR}
30	46.2	0.022
31	47.7	0.027
32	49.2	0.033
34	52.3	0.047
36	55.4	0.065
38	58.5	0.086
40	61.5	0.109
42	64.6	0.134
44	67.7	0.161
46	70.8	0.189
48	73.8	0.218
50	76.9	0.247
52	80.0	0.275
54	83.1	0.303
56	86.2	0.329
58	89.2	0.355
60	92.3	0.379
62	95.4	0.401
64	98.5	0.422
66	101.5	0.442
68	104.6	0.460
70	107.7	0.476
72	110.8	0.491
74	113.8	0.504
76	116.9	0.517
78	120.0	0.528
80	123.1	0.538
82	126.2	0.547
84	129.2	0.555
86	132.3	0.562
88	135.4	0.568
90	138.5	0.574
92	141.5	0.579

at Site E, and likely represents a stand of 100% canopy density. This is supported by the fact that there is an asymptote of 0.62, although the maximum measured over-recovery index was 0.5. As the stand grows beyond that level of maturity one would expect the canopy to begin taking on the characteristics of old growth with gaps that develop over time, leading to an uneven aged structure. This is likely a gradual process, accompanied by a greatly reduced growth rate. Thus the decline in the over-recovery effect is also expected to occur in a manner similar to that which the curve suggests.

Since the over-recovery index was developed for a second growth stand of 20 m at Gray Creek, the effect of that index can be derived from applying the over-recovery index at that effect level. Over-recovery can then be determined by using a multiplier derived from a combination of the over-recovery and effect indices.

Because the over-recovery index was based on the behavior of one advanced second growth stand in relation to old growth, it was assumed that this stand would represent close-to-peak over-recovery, The design storm index becomes less certain as the design storm threshold increases, because the index is based on only four storms (for a threshold of 60 mm). Therefore, the peak over-recovery index might be higher than the reported value. The effect index is determined from the application of equation 3-4 in relation to the standard recovery curves (R1 and R3); this is given in Table 7. The effect index is 0 at a stand height that is unaffected by over-recovery and 1 at the stand height where over-recovery is at a maximum. Thus, the stand height index I_{SH} can be calculated with equation 3-5:

$$\left(I_{SH}\right)_i = \frac{\left(HR_{OR} - HR_X\right)_i}{\left(HR_{OR} - HR_X\right)_{\max}} \qquad (3\text{-}5)$$

Where I_{SHi} is the stand height index for a stand of height i, HR_{OR} and HR_X refer to the over-recovery and standard recovery. It is implied that the over-recovery is calculated for the appropriate recovery curve (R1/2 or R3 curve using equation 3-4). The development of the stand height index is given in Table 7. Note that if the calculation yields a negative answer the index defaults to zero.

3.1.3 OVER-RECOVERY FACTOR

As discussed above, the over-recovery factor calculated by applying a design storm threshold can be determined from the peak over-recovery index and the stand height effect index as follows:

$$F_{DS} = \left(I_{OR} \cdot I_{SH}\right) + 1 \qquad (3\text{-}6)$$

The over-recovery multiplier F_{DS} can be applied to any curve, either rainfall or ROS under design storm conditions, by multiplying the value of F_{DS} by the recovery as given by the appropriate rainfall/ROS recovery curve to give the corrected recovery values for large storms. The over-recovery results in a negative ECA of the opening for which the assessment is being done. However, since ECA normally implies average

Table 6. The over-recovery effect as a function of stand height. (Over-recovery refers to recovery greater than 100%; however, the data set comprises all data points that result from the given scenario. It is based on composite data assumed to represent over-recovery applicable to curves R1 and R2 (OR1) and to curve R3 (OR2).)

ASH	OR1	OR0
18.0	128.1	
8.8	55.0	
16.0	114.0	
13.5	91.6	
20.5	141.9	
8.8	57.3	
5.5	33.0	
33.0	107.5	
35.0	100.0	
13.5	85.3	
33.0	104.1	
13.5	91.6	
33.0	107.5	
32.0		100.0
11.5		56.4
13.5		72.2
13.5		67.3
17.0		93.8
18.5		114.0
13.5		72.2
33.0		83.8
33.0		86.6
18.0		106.2

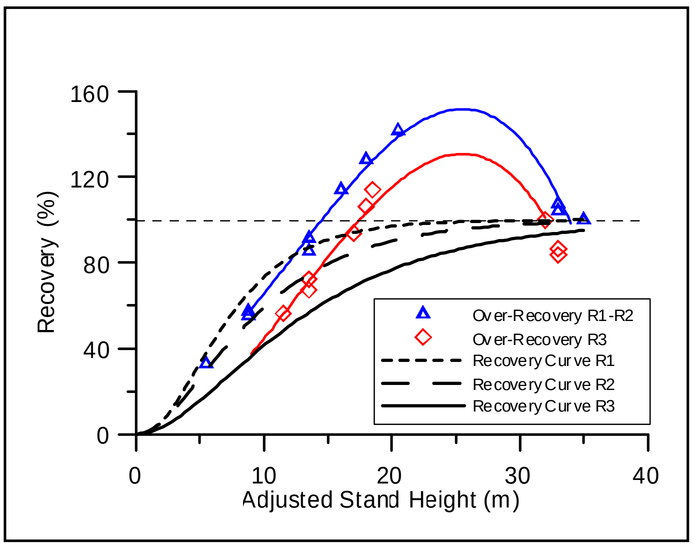

Figure 10. The over-recovery phenomenon.

Table 7. Effect of stand height on over-recovery: synthesis of the stand height effect index from equation 3-4 and rainfall recovery curves.

	Over-recovery scenario		Standard recovery			Over-recovery effect		
ASH	Recovery (R1-2)	Recovery (R3)	R1	R2	R3	R1	R2	R3
8	51.6	30.6	60.2	47.3	31.1	0.00	0.08	0.00
9	58.4	37.4	67.3	53.5	36.3	0.00	0.09	0.03
10	65.6	44.6	73.2	59.1	41.2	0.00	0.12	0.08
11	73.1	52.1	78.2	64.2	46.0	0.00	0.16	0.14
12	80.7	59.7	82.3	68.7	50.5	0.00	0.21	0.21
13	88.4	67.4	85.7	72.8	54.7	0.05	0.28	0.28
14	96.0	75.0	88.5	76.3	58.6	0.14	0.35	0.37
15	103.6	82.6	90.8	79.5	62.3	0.24	0.43	0.45
16	110.9	89.9	92.6	82.2	65.7	0.35	0.51	0.54
17	117.9	96.9	94.0	84.6	68.8	0.45	0.59	0.63
18	124.6	103.6	95.2	86.7	71.7	0.56	0.67	0.71
19	130.7	109.7	96.2	88.5	74.4	0.66	0.75	0.79
20	136.2	115.2	96.9	90.1	76.8	0.75	0.82	0.86
21	141.0	120.0	97.6	91.5	79.0	0.83	0.88	0.92
22	145.1	124.1	98.1	92.6	81.0	0.89	0.93	0.97
23	148.3	127.3	98.4	93.7	82.8	0.95	0.97	1.00
24	150.5	129.5	98.8	94.5	84.5	0.98	0.99	1.01
25	151.6	130.6	99.0	95.3	86.0	1.00	1.00	1.00
26	151.6	130.6	99.2	96.0	87.4	1.00	0.99	0.97
27	150.3	129.3	99.4	96.5	88.6	0.97	0.96	0.91
28	147.7	126.7	99.5	97.0	89.7	0.92	0.90	0.83
29	143.6	122.6	99.6	97.4	90.8	0.84	0.82	0.71
30	138.0	117.0	99.7	97.8	91.7	0.73	0.71	0.57
31	130.7	109.7	99.7	98.1	92.5	0.59	0.58	0.39
32	121.8	100.8	99.8	98.4	93.2	0.42	0.42	0.17
33	111.0	90.0	99.8	98.6	93.9	0.21	0.22	0.00
34	98.2	77.2	99.9	98.8	94.5	0.00	0.00	0.00

conditions, this revised quantity should be called the "Runoff Enhancement Factor" to distinguish it from ECA.

3.2 OVER-RECOVERY FOR SPECIFIC STORM SIZE CLASSES.

The alternative approach is to divide the recovery data into classes according to storm size. Using the Gray Creek data set, storm size classes of 23 mm increments were used, thereby creating size classes with at least four data points in each one. The average storm size within each size class was then referenced to the mid point of the size class. When compared with the design storm approach, the storm size classes result in a greater degree of over-recovery over the full range of regenerating stand heights (Figure 11). The apparent recovery within each size class was expressed as a ratio of the standard recovery for each of the immature stands:

$$r_{SS} = \frac{HR_{SS}}{HR_{standard}} \quad (3\text{-}7)$$

where r_{SS} is the over-recovery ratio due to storm size and $HR_{standard}$ and HR_{SS} are standard recovery and recovery due to storm size respectively.

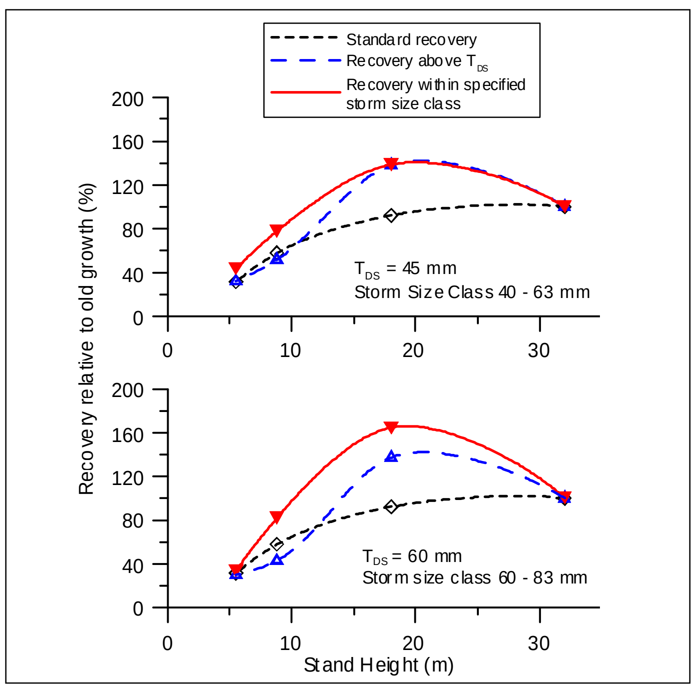

Figure 11. Over-recovery as a function of stand height for selected storms at Gray Creek.

Table 8 displays the coefficients of equations to predict r_{SS} as a function of storm size. Equations are of the form:

$$r_{SS} = 1 + A\left(1 - e^{(-b \cdot PP)}\right)^c \qquad (3\text{-}8)$$

The resulting storm size class midpoint and the average recovery ratio within those classes for 9- and 18-metre stands were then smoothed using a three-point moving average (Table 9), thereby creating a data set from which more or less continuous data on storm size recovery can be derived to assess recovery of regeneration during individual storms. Chapman-Richards curves were used to describe the relationship between the recovery ratios and storm size for each stand (Table 8, Figure 12). The curve coefficients were related to stand height by the following relationships:

$$A = 0.0012(Ht) + 1.029 \qquad (3\text{-}9)$$

$$c = 35.624e^{(-0.0508 \cdot Ht)} \qquad (3\text{-}10)$$

$$b = -0.0014 \cdot c + 0.0807 \qquad (3\text{-}11)$$

where A, b and c are the curve fitting parameters given in Table 10. For each of equations 3-8 to 3-10, the R^2 is 0.998 or better. These equations form a model that can be used to calculate an over-recovery ratio due to a combination of storm size and stand height, up to a height at which canopy density is at maximum and has a ratio of 0.62.

As with the design storm approach, this approach requires us to make some assumptions in order to fill in these missing pieces of the model:

1. The over-recovery phenomenon peaks at a stand height that corresponds to the maximum second growth canopy density (Ht_{CDmax}). At Gray Creek this was assumed to be between 22 and 25 m based on extrapolated stand data.
2. Past Ht_{CDmax}, the decline in over-recovery as the stand approaches old growth structure was achieved by reversing the stand height index back to zero for stand height equal to the reference stand height. This was done using a linear interpolation approach between Ht_{CDmax} and the reference stand height as follows:

a. For $I_{Ht} > Ht_{CDmax}$,

$$I_{Ht} = Ht_{CD\max} - (Ht - Ht_{CD\max})\frac{Ht_{CD\max}}{(Ht_{ref} - Ht_{CD\max})} \qquad (3\text{-}12)$$

b. For $I_{Ht} \leq Ht_{CDmax}$, $I_{Ht} = Ht$ (3-13)

The resultant model will calculate an over-recovery ratio for any storm size and stand height.

3.3 OVER-RECOVERY FACTOR DUE TO STORM SIZE

Because the over-recovery phenomenon is a result of a difference in canopy density between second growth and old growth, the effect of the over-recovery ratio can be scaled using the canopy density ratio. To apply the method it is necessary to assume that if the canopy density is equal to 1, there would be no over-recovery effect and the ratio would be 1.0. Assuming linear relationship between the effect and the CD ratio, the ratio can be scaled assuming that the equations as given represent a CD ratio of 0.62. These assumptions result in the following equation to adjust the storm size ratio, giving as a result the over-recovery factor due to storm size (F_{SS}):

$$F_{SS} = (r_{SS} - 1) \cdot (2.63 - 2.63 r_{CD}) + 1 \qquad (3\text{-}14)$$

Table 8. Coefficients of equation 3-8 by stand height (coefficients were derived from extrapolation of equations 3-9 to 3-11).

Stand Ht (m)	A	b	c
18.0	1.050	0.060	14.43
9.0	1.040	0.049	22.00
5.5	1.035	0.042	27.00
0.0*	1.029	0.029	36.00

Table 9. Over-recovery ratios due to storm size (r_{SS}).

Storm Size (mm)	Regeneration Stand Height		
	18m.	9m.	5.5m.
31.5	1.12	1.17	
41.5	1.27	1.20	
51.5	1.59	1.27	
61.5	1.76	1.37	
71.5	1.82	1.57	
81.5		1.70	
40.0	1.21		
43.8	1.31		
50.5	1.51	1.26	
52.2	1.52	1.18	
52.8	1.62		
58.5	1.75	1.25	
64.5	1.84	1.36	1.19
71.8	1.87	1.60	1.26
74.2	1.82	1.68	1.28
76.0	1.83		

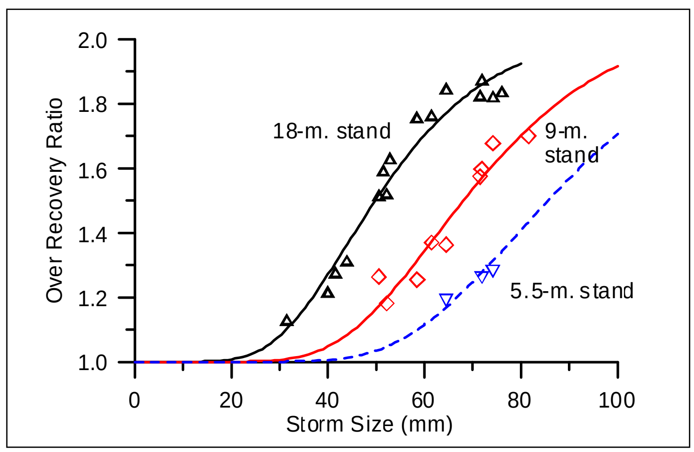

Figure 12. Over-recovery ratio as a function of storm size for three stands at Gray Creek.

The formulation of an over-recovery factor due to specific storm size classes is similar to that of the over-recovery due to the design storm threshold (F_{DS}), except that over-recovery occurs over a broader range of regeneration stand heights, such that data are available for three sites at Gray Creek (Figure 11). The data shows that over-recovery begins to occur first in taller stands for storms of about 20 mm, and maxes out at a ratio of about two for storms of 80 – 100 mm. For shorter stands, the over-recovery begins at a progressively larger storm size.

4. APPLICATION OF HYDROLOGIC RECOVERY CURVES AS A BASIS FOR DISTRIBUTED MODELING.

This section describes a method of applying the standard hydrologic recovery curves to determine the recovery status of regenerating forest stands. The recovery status varies with elevation, precipitation regime and storm size and type. This method can be used to derive watershed scale ECA estimates in a modeling framework or as part of a CWAP. A step-by-step procedure is described as follows:

The initial requirements to calculate the recovery status for forest stands in a coastal watershed include a determination of the precipitation regime (snow accumulation zone as given on the attached map) and an inventory of forest openings including area, elevation and average stand height. From this information we can derive site specific recovery curves as follows:

1. Determine the snowpack accumulation zone (see Snow Accumulation Zone map).
2. Calculate recovery threshold using equations 5 or 6 for that zone.
3. Derive the standard recovery curves for specific elevations by substituting the appropriate threshold into equations S1, R1b and R3b.
4. Determine the form of the rainfall and/or ROS recovery curve by linear interpolation between the R1 and R3 curves:

$$R_{site} = \left(\frac{elev - 275}{725}\right)R1 + \left(\frac{1000 - elev}{725}\right)R3 \quad (4\text{-}1)$$

5. The resulting curves can be plotted or the above formula used to calculate recovery directly for a given stand height.

   The above procedure will yield three recovery curves (one each for snowmelt, rainfall and ROS rain component) for the specified elevation and precipitation regime. Hydrologic recovery can be estimated for different conditions by a linear combination of those curves. How to combine them depends on the desired application because a given stand interacts differently with the precipitation regime depending on the conditions under which the precipitation is delivered. That is, recovery is event based and how it is determined depends on whether a "long-term mean recovery" or an event specific recovery is needed. For snowmelt only, the recovery is based on a simple application of the S1 curve, and for rainfall recovery it is based on application of the site specific R(a) curve. If over-recovery is a consideration, then this should be factored into the R1 curve. For ROS events, the final recovery curve is made up of a linear combination of the S1 and R_{site} curves according to event size:

6. For overall mean recovery, the threshold-adjusted standard curves can be combined according to elevation band.
   a. Below 300 metres, use the R3a curve
   b. From 300 to 1000 metres (the ROS zone) recovery is a linear combination of the R_{site} and the S1 curve:
      i. Determine R_{site} for the specific elevation using equation 4-1 (step 4, above), and
      ii. Blend the R_{site} and S1 curves across the elevation band using the following equation:

$$HR = p \cdot S1 + (1 - p) \cdot R_{site} \quad (4\text{-}2)$$

where p varies from 0 at 300 metres to 1 at 1000 metres.

7. For event based determination of ROS recovery:
   a. Determine the storm magnitude R_S.
   b. Determine the over-recovery factor based on storm magnitude (or design storm threshold) and stand height and adjust the value of R1.
   c. Determine R_{site} using equation 4-1 above.
   d. Using equations 7 and 8, determine the proportion of recovery due to the snowmelt component p(S).
   e. Calculate recovery as follows:

$$HR = p(S) \cdot S1 + (1 - p(S)) \cdot R_{site} \quad (4\text{-}3)$$

Example: Russell Creek recovery curve for a site at 550 metres above sea level, for a rain-on-snow event with 35 mm of rain.

Russell Creek is a tributary of the Tsitika River on northeast Vancouver Island. It falls under zone 2 so the following equations can be used to determine the recovery thresholds:

$$T_{ROS} = 0.00414 \cdot elev - 0.717 + 0.5$$

For a 550 metre site equations 2-5 and 2-7 apply. The above equation is a combination of those equations for a threshold of T_{ROS}=2.06. Therefore the recovery equations are:

$$T_{ROS} = 0.00414 \cdot elev - 0.717 + 0.5$$

for the snowmelt component and

$$HR_{R1} = 100\left(1 - e^{-0.19(ASH - 2.06)}\right)^{1.25}$$

and

$$HR_{R3} = 100\left(1 - e^{-0.10(ASH - 2.06)}\right)^{1.45}$$

for the R1 and R3 components respectively (Figure 13). To resolve the rain component of the event into a single curve we then interpolate between the R1 and R3 curves above by elevation:

$$HR_{R550m} = \left(\frac{550-275}{725}\right)HR_{R1} + \left(\frac{1000-550}{725}\right)HR_{R3} = 0.379R1 + 0.621R3$$

The event in question is 35 mm ROS which implies a blending of the HRS1 and R550m equations where the proportion of the recovery due to snowmelt is:

$$p(S) = 97 - 1.7(PP) = 37.5\%$$

Therefore:

$$HR = 0.375\left(HR_{S1}\right) + 0.625\left(HR_{R550m}\right) \text{ (Figure 14).}$$

This method has been applied at Russell Creek and the results of that application found to be in close agreement with measurements made in the field using snowmelt lysimeters (Hudson and Floyd, 2006). In this case it was found that over-recovery did not apply because the old growth stands that were represented all had closed canopies.

5. DISCUSSION

In this report we have described an empirical model of stand level hydrologic recovery that is capable of being applied in a distributed framework. It is based on a standard set of recovery curves describing specific components of recovery at two reference elevations. The development of these curves into a general hydrologic recovery model involves several assumptions:

- The recovery threshold is related to the mean annual peak snow depth, which varies with elevation and hydrologic zone defined by the precipitation regime.
- The determination of recovery threshold is applicable to all recovery curves.
- Elevation-specific recovery curves can be derived by linear interpolation between reference curves.

The first assumption above was partially validated, but only with new data from the same site where the research was carried out. The second assumption remains unverified. The third assumption has been validated in a preliminary sense by Hudson and Floyd (2006), and remains the only reasonable solution when original recovery curves are available for only two reference elevations. To achieve full validation of the model (or modification as needed) ongoing research at Russell Creek should include younger sites to help define the interception characteristics of stands in the 0 – 5 metre range of stand heights.

While stand height remains the best variable to predict recovery from a statistical standpoint, and given that it is theoretically reasonable to predict snowmelt recovery on the basis of stand height, recovery of interception processes should theoretically be based on canopy density, LAI or some similar measure of canopy completeness. Radiation snowmelt is regulated by shade cast onto the snowpack by trees, and ROS melt is regulated by wind speed; both processes are directly related to stand height. However, interception processes are more closely related to canopy completeness since in an average sense, precipitation acts in the vertical plane as opposed to shade and wind, which act essentially horizontally. The only reason that stand height is a better predictor of interception recovery statistically is because of the relationship between stand height and canopy density and the fact that height is an objective, precision measurement while canopy density is essentially an estimate with strong user bias.

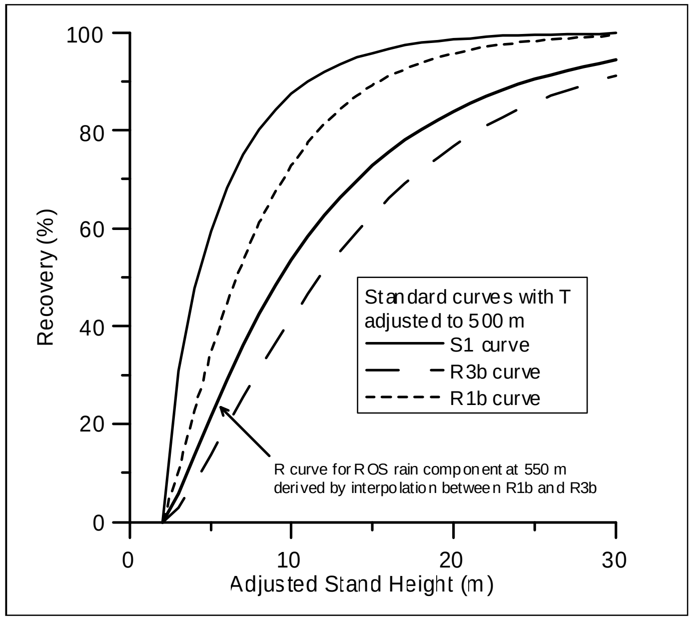

Figure 13. Model application example part 1.

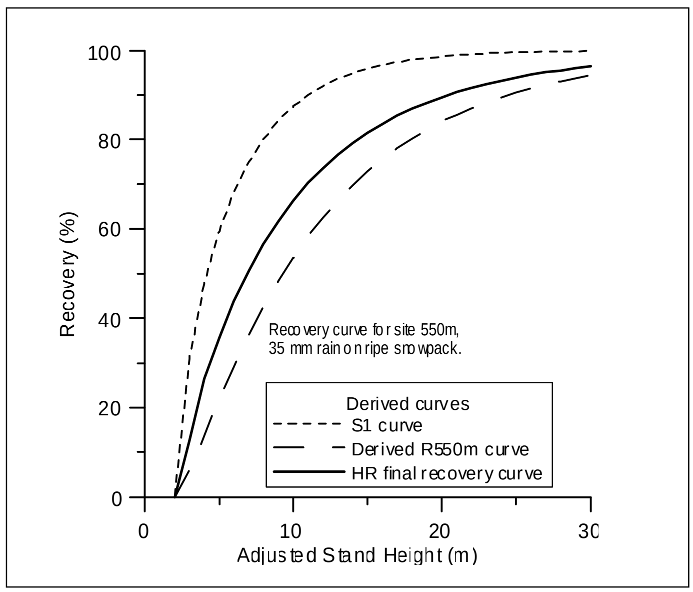

Figure 14. Model application example part 2.

For the reasons given above, it was found that while stand height and canopy density were equally good predictors of snowpack recovery (Hudson, 2000), rainfall recovery could not be adequately predicted without considering both stand descriptors. Therefore, since the Chapman-Richards Curve is univariate, *ASH* was developed as a combination of stand height and canopy density. Normally principal components analysis (PCA) would be used to derive a single predictor variable from a list of potential predictors, however PCA requires at least three predictors. To derive a combined predictor from stand height and canopy density, a linear relationship between stand height as the dependent variable and canopy density as independent variable was derived by simple linear regression, and *ASH* was then defined as the sum of stand height and the regression residuals. The regression relationship used for the adjustment was derived from inventory data for Chapman and Grey Creek watersheds. For regional application a set of standard Height vs CD relationships should be developed to act as a common basis for determining *ASH* for watershed assessment purposes.

The problem discussed above is immediately apparent in formulating the over-recovery factor. The form of the over-recovery curve mimics the relationship between canopy density and stand height for upper Gray Creek. Using stand height as a predictor, the formulation was somewhat convoluted and several assumptions were made due to the limited range of stand data available at the site (Figure 15). Either a precision measurement of canopy completeness that can be routinely collected is needed, or a relationship between canopy completeness and stand height should be developed to account for interception recovery. A general relationship would account for site index as well as whether or not the stand was managed as in Figure 15, and should be derived from a much larger inventory database.

The regional differences in the use of the term "hydrologic recovery" are important. Hydrologic recovery of forest stands as we have described is not the same as watershed hydrologic recovery, although as noted, in the Canadian forest hydrology literature, hydrologic recovery is usually taken to mean the former while in international literature it is taken to mean the latter. The commonly used approach is to use a paired catchment or watershed modeling procedure to assess hydrologic recovery following forest harvesting at the watershed scale according to changes in streamflow derived from a catchment area above a gauging point (e.g., Kochenderfer and Wendel, 1983, Schaffner and Reed, 2005). This lumped approach is limited in its applicability since hydrologic recovery can only be assessed at the watershed scale without allowance for differences in stand structure or runoff characteristics within the watershed. The approach we and others have taken, to begin studying hydrologic recovery at the stand level, reveals far more about processes and how they are altered by changes in canopy structure, and will allow for a distributed approach that can be applied at any scale equal to or larger than a forest stand. However, it must be clearly understood that the model we have described does not provide an index of peak flow change.

The water balance of any given site is also controlled by a host of other factors including soil properties (such as hydraulic conductivity, porosity, and macropore behavior), land slope gradient, and the position of the site on a slope in relation to other sites and the stream channel. These factors are collectively referred to as morphological factors. The hydrology of a watershed is controlled by the interplay between the cumulative interaction of all sites (whether forested or non-forested) and the stream channel network. For this study, we set out to integrate only those factors that control the effects of the forest canopy on hydrology into a set of hydrologic recovery curves. The distributed approach allows us to determine meaningful

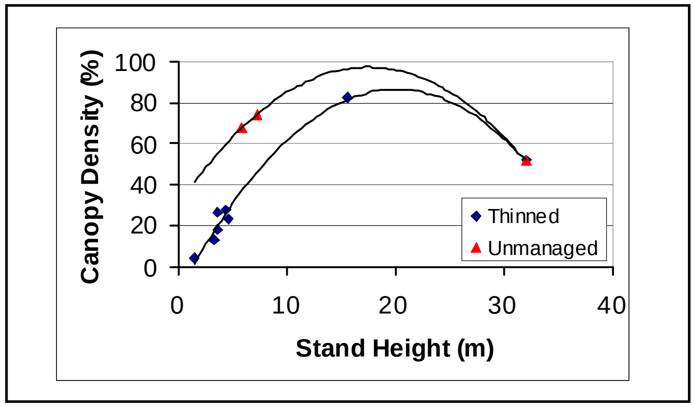

Figure 15. Apparent relationships between stand height and canopy density, upper Gray Creek.

ECA values with the greatest possible accuracy. Thus the resulting ECA provides us with an index of the hydrologic function of the post-disturbance canopy relative to that of the original canopy. The next step will be to formulate a peak flow index once the ECA concept has been integrated with other factors that influence streamflow, including morphological factors discussed above, proportion of the watershed under forest, the presence of lakes, glaciers etc. This integration will likely be achieved using a sophisticated model simulation platform and the methods presented in this report were developed with that goal in mind.

This method is put forward as a standard model framework for the determination of hydrologic recovery of coastal forest stands based on our current science-based understanding of the processes and principles that control the hydrologic behavior of those stands. These methods are not applicable to interior forests; the recovery curves were developed using data collected in coastal forests which are subject to different precipitation processes, climatic conditions and species composition than interior stands. We recognize that our understanding of this complex subject is far from complete; therefore, we have designed it with sufficient flexibility as to be easily updated when new information becomes available.

6. CONCLUSIONS

In spite of the limitations stated, we believe that this model framework represents the state of knowledge of post-disturbance coastal hydrologic recovery processes. The model is simple to apply and is amenable to integrate with a numerical hydrology simulator. It can also be easily updated as new information becomes available. It has passed a preliminary validation (Hudson & Floyd, 2006) and will be subjected to ongoing tests as more data are collected. The research into hydrologic recovery is not complete and therefore any person who wishes to apply it must understand its limitations, and use professional judgment.

REFERENCES

BC Ministry of Forests. 2001. Watershed assessment procedure guidebook. 2nd ed., Version 2.1. For. Prac. Br., Min. For., Victoria, BC. Forest Practices Code of British Columbia Guidebook

Berris, S.N. and Harr, R.D. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. Water Res. Res. 23(1): 135-142.

Bosch, J.M. and J.D Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55: 3-23.

Buttle, J.M., C.J. Oswald and D.T. Woods. 2005. Hydrologic Recovery of Snow Accumulation and Melt Following Harvesting in Northeastern Ontario. 62nd EASTERN SNOW CONFERENCE Waterloo, ON, Canada 2005

Hudson, R.O. 2000a. Snowpack recovery in regenerating coastal British Columbia clear-cuts. Canadian Journal of Forest Research 30(4): 548-556.

Hudson, R.O. 2000b. Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region. Forest Research Technical Report TR-004: Hydrology. Vancouver Forest Region, Nanaimo BC, November 2000.

Hudson, R.O. 2003. Using Combined Snowpack and Rainfall Interception Components to Assess Hydrologic Recovery of a Timber-Harvested Site: Working Towards an Operational Method. Research Section, Vancouver Forest Region, BC Ministry of Forests. Nanaimo, BC. Technical Report TR-027. 38 pp.

Hudson, R. and W. Floyd. 2006. Development and testing of an empirical hydrologic recovery model for coastal watersheds. Hydrologic Processes, in review.

Kochenderfer, J.N. and G. W. Wendel. 1983. Plant Succession and Hydrologic Recovery on a Deforested and Herbicided Watershed. Forest Science Vol. 29, No. 3. 1983. pp. 545-558

Marks, D., J. Kimball, D. Tingey and T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. Hydrol. Processes, 12, 1569-1587.

McMinn, R.G. 1960. Water relations and forest distribution in the Douglas-fir region on Vancouver Island. Publ. 1091, Div. For. Biol., Can. Dept. Agric., Victoria, BC.

Schaffner, W. and M. Reed. 2005. Evaluation of Post-Burn Hydrologic Recovery of a Small Mountainous Watershed: Upper Campo Bonito Wash in Southern Arizona. Western Region Technical Attachment #05-06. NOAA/NWS, Tucson AZ.

Sit, V. 1994. Catalog of curves for Curve Fitting. Biometrics Information Handbook series, ISSN 1183-9759; #4. British Columbia Ministry of Forests.

Spittlehouse, D. 1998. "Rainfall Interception in Young and Mature Conifer Forests in British Columbia" pp. 171–74 in Weather Data Requirements for Integrated Pest Management: 23rd Conference on Agricultural and Forest Meteorology, 2–6 Nov 1998, Albuquerque, N.M. American Meteorological Society. http://www.for.gov.bc.ca/research/pubs/pubs/0182.htm.

Talbot, J. and A.P. Plamondon. 2002. The Diminution of Snowmelt Rate with Forest Regrowth as an Index of Peak Flow Hydrologic Recovery, Montmorency Forest, Quebec

Winkler, R.D. 2001. Forest influences on snow: preliminary results on effects of regrowth. *In* Toews DDA, Chatwin S (eds), Watershed Assessment in the Southern Interior of British Columbia. Research Branch, BC Ministry of Forests, Victoria, BC. Working Paper 57/2001.