Incorporating hydrologic dynamics into buffer strip design on the sub-humid Boreal Plain of Alberta

I.F. Creed, G.Z. Sass, M.B. Wolniewicz, K.J. Devito

1. Introduction

The Canadian boreal forest is one of the world’s largest forest regions. Increasing demands for natural resources have resulted in about 50% of the Canadian boreal forest being allocated for timber harvesting and for oil and gas exploration (Global Forest Watch Canada, 2002). Such activities may have a range of impacts on aquatic systems including alteration of water, sediment, and nutrient fluxes from terrestrial to aquatic systems. This practice does not seem to be effective in the sub-humid boreal forest where climatic and physiographic variability produces complex hydrologic pathways not well protected by standard width buffers. We developed a remote sensing technique that forms a hydrologic basis for buffer strip design. Synthetic aperture radar (SAR) imagery was used to map, both inundated and saturated areas (herein called wet areas) amenable for surface transport of nutrients and sediments on a low relief landscape in northern Alberta, Canada. Wet areas coverage of the Moose Lake drainage basin showed a semi-logarithmic relationship with daily discharge ($r^2 = 0.72$, $p < 0.001$, $n = 18$). This relationship was used to define a flow-duration curve for wet areas that could be used as an aspatial assessment of what proportion of a drainage basin should be protected. A probability map of wet areas formation was calculated from the database of 18 images. We demonstrated how the probability map may be used to design adaptive buffer strips for the mitigation of increased nutrient loading to boreal lakes following timber harvesting.

Devito et al. (2000) presented a hierarchy of landscape features that control the range in natural variation in the nutrient status among boreal lakes and the potential susceptibility of the nutrient status of these lakes to disturbance. Sass et al. (2008) tested this hierarchy in a relatively undisturbed region of the Boreal Plain ecozone and found that indicators of surface and subsurface hydrologic connections between terrestrial and aquatic systems explained 72% of the natural variability in trophic status of 40 shallow lakes. One of the key surface hydrological indicators of lake trophic status was the percent of the drainage basin occupied by wet areas. Sass et al. (2008) defined wet areas as parts of the landscape that experience either saturation or inundation. He argued that wet areas provide effective surface pathways of water directly to lakes and/or streams, and thus influence the export of nutrients and ultimately the trophic status of lakes.

The effectiveness of wet areas in transporting matter differs based on their position within the landscape. Wet areas will act as sources of water and associated dissolved or particulate materials only if they are connected to receiving water bodies. On the Boreal Shield, which is characterized by a humid climate and/or rugged terrain, previous studies have observed strong positive relationships between the proportion of wet areas covering a drainage basin and the amount of surface and/or near-surface transport of...
water and water-soluble nutrients to lakes (e.g., Dillon and Molot, 1997, 2005). On the Boreal Plain, which is characterized by a sub-humid climate and flat terrain, a significant relationship was observed not between the proportion of wet areas covering a drainage basin and the nutrient status of lakes, but rather between the proportion of wet areas connected to the lake and nutrient status (Devito et al., 2000). On the Boreal Plain, wet areas located within topographic depressions and flats may not regularly connect through surface or near-surface hydrologic pathways to the lakes. The relatively well-organized hydrologic pathways that occur on the Boreal Shield, where wet areas connect directly to the lake or indirectly through streams to the lake (Creed et al., 2003), contrast with the relatively disorganized hydrologic pathways that occur on the Boreal Plain, where wet areas shift from a state of being ‘disconnected’ during dry periods to ‘connected’ during wet periods (Devito et al., 2005a; Sass and Creed, 2008). A large portion of Canada’s boreal forest is characterized by flat landscapes with poorly defined networks of wet areas, and yet, we know little of the importance and the implications of disruptions and/or enlargement in these hydrologically active areas on the structure and function of boreal ecosystems.

As a consequence of inadequate knowledge on how environmental changes in terrestrial and aquatic ecosystems affect wet areas and the surface hydrologic pathways that connect these hydrologic features to receiving water bodies, the governmental policies that try to address these potential impacts on the Boreal Plain are general and largely imported from other jurisdictions. For example, a common practice in forest management is to leave buffer strips of riparian forest between harvested areas and adjacent surface waters to trap dissolved and particulate nutrients in hydrologic flows, and thereby, reduce nutrient loading from harvested areas to surface waters (Castelle et al., 1994; Lee et al., 2004). Most jurisdictions apply a rule-based approach when it comes to assigning minimum buffer widths. Current guidelines on the Boreal Plain (Alberta) require that a standardized width of buffer strip be left around wet areas (20 m), streams (30 m), rivers (60 m) and lakes (100 m) (Alberta Environmental Protection, 1994). The guidelines exclude streams that are less than 0.5 m in width or lakes less than 4 ha in area and these guidelines assume that a uniform and diffuse hydrologic flow from contributing hillslopes dominates runoff. These guidelines fail to incorporate the spatial and temporal dynamics of the hydrologic system.

The failure to incorporate hydrologic dynamics in the design of buffer strips may explain conflicting results among studies that evaluated the effectiveness of standard widths of buffer strips on surface water quality in the boreal forest. The effectiveness (e.g., Carignan et al., 2000) versus ineffectiveness (e.g., Steedman, 2000; Prepas et al., 2001; Pinel-Alloul et al., 2002) of buffer strips in minimizing nutrient loading to surface waters may in part be attributed to the dynamics of hydrologic pathways within these boreal watersheds. For example, in the TROLS experiment on the Boreal Plain, an increase in total phosphorous (TP) observed in the experimental lakes following timber harvesting was not related to the width of riparian buffer strips (Prepas et al., 2001). The failure to find a significant relation between buffer strips and nutrient loading in the TROLS study may be attributed to the (1) heterogeneity in hydrologic pathways among the experimental drainage basins, and (2) variability in the climatic conditions for the duration of the study. Specifically, subsurface and surface connectivity (through wet areas) were implicated as important in identifying the susceptibility of receiving aquatic systems to disturbances and in determining the effectiveness of buffer strips in mitigating the impacts of disturbances (Devito et al., 2000). Prior to offering better guidelines for buffer strips, we need a better understanding of the spatial and temporal dynamics of wet areas and how these vary in different landscapes.

Although government policy and therefore most operational guidelines incorporate standard width buffers to protect water resources, there are increasing calls from the scientific community to incorporate hydrologic dynamics in designing management plans not only for buffer but also road and bridge placement (Smith et al., 2003; Lee and Barker, 2005). At its simplest, hydrologically informed buffer design has been based on the idea that different stream segments have differential loading potential based on their specific contributing areas (i.e., convergent areas have higher loading than divergent areas) and therefore, buffer widths have been recommended to be normalized to hydrologic loading potential (Bren, 1998, 2000). So far, to our knowledge, hydrologically informed buffer design has exclusively used topographic information to define wet areas of the landscape, which are prone to generate saturation overland flow. However, even in humid catchments where surface topography is a good replica of the water-table, the topographic index alone can not identify all runoff generating areas (Western et al., 2004). On the sub-humid Boreal Plain where there is a water deficit during most years, surface topography is a poor replica of the water table and therefore topographical information alone will not be very useful in identifying wet areas (Devito et al., 2005b). On the other hand, remote sensing techniques offer ways to detect areas of saturation and inundation over large geographic scales and independent of landscape position (Frazier et al., 2003; Moran et al., 2004).

Recent work on the Boreal Plain has indicated that radar imagery is useful at mapping wet areas at regional scales (Sass and Creed, 2008; Clark et al., 2008). Clark et al. (2008) used European Resources Satellite (ERS) imagery collected over an eleven year period to delineate wet areas in a regional drainage basin and subsequently to derive a map of probability of inundation and saturation. Similarly, Sass and Creed (2008) mapped wet areas using ERS imagery, however, their focus was on wet area dynamics in the context of climatic variability. Whereas both Clark et al. (2008) and Sass and Creed (2008) focused on wet area mapping in undisturbed drainage basins, we applied their mapping technique to another part of the Boreal Plain, one which has experienced significant amount of forest harvesting.

The focus of this paper was on using satellite-derived saturated and inundated areas as a basis for designing hydrologically meaningful buffers. The objectives were to: (1) map saturated and inundated areas (collectively termed wet areas) within a drainage basin; (2) establish links between wet area extent and hydro-climatic metrics; (3) generate probability of wet area formation aspatially and spatially; and (4) demonstrate how probability of wet area formation can be used to aid in the design of buffer strips that incorporates the natural range of variation in wet area cover. Future studies will examine the difference between standard width and hydrologically based buffer design in controlling the nutrient loading to lakes.

2. Drainage basin description

The study area is centered on the Moose Lake drainage basin (55°07′58″N, 111°46′17″W), which is a sub-basin of the larger Logan River drainage basin. The drainage basin lies within the Mixed-Wood Boreal Forest ecoregion (Rowe, 1972), which is part of the Boreal Plain ecozone (Ecological Stratification Working Group, 1995) in northern Alberta, Canada (Fig. 1). The drainage basin is 22.5 km² in area and it is characterized by gentle topography ranging from approximately 570–650 m in elevation. The underlying glacial drift ranges from 20 to 200 m in thickness, with a stratigraphy that contains complex inter-beds of clays,
sands, and gravels (Tokarsky and Epp, 1987). The soils are highly variable ranging from well to poorly drained, with Gray Luvisols and Eutric Brunisols in uplands and Gleysols in lowlands (Tokarsky and Epp, 1987). Tree species such as jack pine (*Pinus banksiana* Lamb.) and balsam fir (*Abies balsamea* (L.) Mill.) are found in dry habitats (Rowe, 1972). Trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) are common in the mesic habitats, while balsam poplar (*Populus balsamifera* L.), paper birch (*Betula papyrifera* Marsh.), tamarack (*Larix laricina* (Du Roi) K. Koch), and black spruce (*Picea mariana* (Mill.) B.S.P.) are common in wet habitats (Rowe, 1972). Trembling aspen is the dominant species within the drainage basin (Rowe, 1972). The Boreal Plain ecozone contains numerous wetlands, including bog and fen peatlands, with marshes and swamps common along lake margins, adding to the complexity of the hydrology in the region.

### 3. Hydro-climatic context

The average annual precipitation (*P*) and mean-temperature (*T*) were 457 mm year$^{-1}$ and 1.6 °C, respectively, from 1970 to 2005. *P* and *T* were spatially interpolated using inverse distance weighting from the closest four meteorological recording stations. Average annual discharge (*Q*) was 98 mm year$^{-1}$ based on the available record from 1984 to 2005 measured at Logan River discharge recording station (55°44’N, 111°43’W) located 20 km from Moose Lake. The average runoff coefficient was 22% with a maximum of 45% reached in 1997. Inter-annual hydrologic variability did not show any significant trends based on average annual *P*, *T* or *Q* (Fig. 2). However, there were periodic peaks in both precipitation and discharge occurring at a frequency of 3–7 years (Fig. 2).

Intra-annual hydrologic activity was driven by spring rain-on-snow and rain events and summer convective storms (Fig. 3). On average, 60% of the annual precipitation fell between May and September (Fig. 3A). The period with above-freezing temperatures lasted on average from April 1 to October 31 (Fig. 3B). The spring discharge period (April 1–May 31) accounted for approximately

![Fig. 1](image1.png)

**Fig. 1.** Map of the Moose Lake drainage basin showing location of harvest blocks and significant hydrological features. Inset map showing the location of the drainage basin within the mixed-wood Boreal Forest ecoregion (Rowe, 1972) and the Boreal Plain ecozone (Ecological Stratification Working Group, 1995).

![Fig. 2](image2.png)

**Fig. 2.** Inter-annual variability of precipitation (**P**), discharge (**Q**), and mean temperature (**T**) for the Moose Lake drainage basin. For **P** and **T**, data were compiled using an inverse distance-weighted average of measurements taken at four meteorological recording stations that had a continuous record and that were closest to Moose Lake. For **Q**, the Logan River discharge recording station data were used which was the closest station to Moose Lake.
23% of annual discharge, whereas the summer discharge period (June 1–August 31) accounted for approximately 55% of annual discharge (Fig. 3C).

4. Methods

Moose Lake was one of 12 experimental lakes used in a multi-year study analyzing the efficacy of standard width buffer design on reducing nutrient loading following forest harvesting (Prepas et al., 2001). We chose this lake as the topography and vegetation cover in the drainage basin was representative of this region. We used a combination of ground and satellite-based data to characterize the dynamics of wet areas within the Moose Lake drainage basin. We calculated the probability of wet area formation, which was then used to provide a hydrologic basis for an alternative buffer design strategy.

4.1. Satellite-based detection of wet areas

We used Radarsat Standard Beam Mode 1 (S1) images acquired during the growing season to capture surface hydrological dynamics (i.e., post-snowpack; early to late growing season; and pre-snowpack). This radar sensor operates in C-band (5.66 cm wavelength), which means that the microwave can penetrate the top 5 cm of soils. The acquired signal, taken at incidence angles between 20° and 27° from nadir, is HH polarized (the signal is horizontally transmitted and received), which investigators have found to better penetrate vegetation and therefore detect wetness than VV polarized ERS images (van der Sanden et al., 2001). All images were acquired in ascending orbit, at 18:00 h local time.

A total of 18 images were available for analysis (1 each from 1996 and 2003, 5 from 1999 and 11 from 2000). The goal was to capture both within-year hydrologic variability and inter-annual hydrologic variability of the past >30 years. Three of the images captured the spring period, 11 images captured the summer period and 4 images captured the fall period. Overall, we found no statistical difference between the hydro-climatic conditions captured by the 18 images and the 36-year record (Table 1), suggesting that our images were representative of spring-to-fall hydrologic conditions of this region.

We followed the methodology of Sass and Creed (2008) to delineate wet areas (areas of both saturation and inundation). First, images were geo-registered and rectified to the geographic coordinates on the digital elevation model (DEM) of the drainage basin. Following these geometric corrections, the images were processed for the reduction of noise (i.e., speckle filtering) using a gamma filter (Lopes et al., 1993).

The radar backscatter images (units of decibels) were converted to volumetric soil moisture (%) based on a regression model, which was generated from ground-based volumetric soil moisture and coincident backscatter signal. For the regression model, ground-based soil moisture measurements and coincident satellite-based radar imagery were collected during three sampling dates in 2000 (May 8, July 19, and October 16). Ground-based soil moisture was measured using a portable soil moisture meter (TH2O) (Dynamax Inc., Houston, TX), which measures the dielectric permittivity (units of millivolts) of the soil. Dielectric permittivity was converted to volumetric soil moisture using conversions given

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<th>Days (current + preceding)</th>
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Note: p < 0.05 indicates statistically different distributions.
by the manufacturer for mineral and organic soils. Soil moisture measurements were made at 7 plots representing the full range in canopy cover, including wetlands and uplands. Each plot was located within a larger homogenous area (minimum area of 1 ha) with respect to vegetation cover to ensure that coincident backscatter signal would be minimally influenced by mixed-pixel effects (Griffiths and Wooding, 1996). At each plot, soil moisture measurements were taken at the center (0 m) and at 3, 6, 9, 12, and 15 m along transects radiating out from the center in the N, E, S, W, NE, SE, NW, and SW compass directions, resulting in a total of 41 samples. At each sampling point, the surface cover was removed, and the TH2O meter was inserted horizontally into a litter-fibric-hemis (LFH) layer in the uplands or into the 0–10 cm layer in the organic rich lowlands. Satellite-based radar images that were acquired coincident to the ground-based sampling were used to derive an average backscatter coefficient for each plot sampled on the ground. Backscatter coefficients were extracted from homogenous polygons with respect to vegetation cover, which ranged in size from 1 to 3 ha.

Regression models explained between 74 and 94% of the variance in backscatter coefficient. Analysis of covariance showed the three regression models to be statistically similar (no difference in slopes, \( p = 0.84 \), or intercepts, \( p = 0.58 \)) and the data were therefore pooled. The regression model based on pooled data (\( r^2 = 0.81 \), S.E. = 0.89; \( p < 0.01 \); \( n = 21 \)) was used to convert backscatter coefficients to volumetric soil moisture for all 18 images.

We classified the images into three classes: inundated, saturated, and unsaturated. We defined unsaturated as 0–60% VSM and saturated as 60% > VSM. Inundated parts of the landscape corresponded to anything less than −15.1 dB. In order to account for uncertainty in the classification we allowed a fuzzy transition between classes (Sass and Creed, 2008). We determined the degree of overlap based on frequency distributions of backscatter coefficients separated based on the ground-based volumetric soil moisture measurements (Fig. 4). The final classified maps were reduced to a binary non-wet/wet classification by combining the saturated and inundated classes. We masked out open water areas using a provincial hydrography layer in order to reduce noise by wind (Sass and Creed, 2008). For each image, we computed the percent wet area cover (WET) of the Moose Lake drainage basin (open-lake areas were masked out), as well as the connected wet area cover (WET\text{con}). Connectivity was based on connections to all lakes greater than 4 ha as well as to connections to permanent streams.

### 4.2. Wet areas and the probability of their formation

The correlations between climatic and hydrologic variables and WET were computed, in order to understand the hydro-climatic controls on the formation of wet areas (inundated and saturated areas). Besides \( P \) and \( Q \), we also computed effective precipitation (P-PET) (Hamon, 1964) and an antecedent precipitation index (after Linsley et al., 1958). The influence of the hydro-climatic variables was tested by using the daily and the previous 7-, 14-, and 30-day totals. For P-PET, we also summed values from current day to beginning of growing season (Sass and Creed, 2008). We selected the variable-pair with the highest correlation coefficient for regression modeling.

To predict the probability of wet area formation aspatially, we derived a flow-duration curve based on all daily discharge measurements (1984–2005). Based on the statistically significant relationship between discharge and wet area cover, we assigned the exceedence probabilities of daily discharge observed on the image acquisition dates to the wet area extent derived from the images. We also mapped the probability of wet area formation across the Moose Lake drainage basin. We calculated the pixel-based probability surface by summing the 18 wet area maps and scaling to 0–100%. The binary wet area maps were each weighted based on their exceedence probabilities. While the intent of generating a spatial probability layer was to create something analogous to the aspatial wet area–duration curve, the two were not the same (i.e., the total wet area coverage at a given probability from the spatial layer was different from the total wet area coverage at the same exceedence probability from Fig. 7). In our discussion we refer to the spatial probability as “probability of wet area formation”. Finally, we used the wet area probability map to suggest an alternative buffer design.

### 5. Results and discussion

#### 5.1. Wet area dynamics: establishing the range of natural variation

The incorporation of a long hydrologic time-series that captures the range of natural variation is important when considering hydrologic dynamics since shorter periods (i.e., <5 years) may miss hydrologic extremes that are important in influencing the hydro-ecological behavior of drainage basins. We considered a multi-decadal time-frame for our study (1970–2005 for \( P \) and \( T \); 1984–2005 for \( Q \)) and used it as the reference condition to which we compared our wet area characterization. Overall, the satellite-image database captured the long-term hydro-climatic characteristics of the Moose Lake region (Table 1). There was substantial temporal variation in WET, ranging from a low of 5–26%. This range of wet area coverage was similar to what other studies have found in a regional drainage basin on the Boreal Plain (Sass and Creed, 2008) and a subcatchment of the Moose Lake drainage basin (Devito et al., 2005a). The spatial organization of wet areas also showed large variability (Fig. 5). Early in the growing season (post-snowpack), about 22% of the drainage basin was covered by wet areas, many of them connected to lakes and streams (9%). During the middle part of the growing season before the summer rains, WET decreased to 12%. This decrease most likely reflected the substantial increase in evapotranspiration due to leaf growth by end of May (Hogg et al., 2000). Summer rains substantially spiked the discharge, which was reflected in increased...
WET (25%). Summer convective storms are the primary hydrologic input into this system (Devito et al., 2005a), which translate into the highest discharge period (Fig. 3C). It was during this wet period when connectivity increased to its highest level (13%). Late in the growing season (pre-snowpack), WET contracted again (16%) but they were more connected than during the pre-rain drier period. Hydrologic inputs were minimal during this fall period.

We investigated the relationship between WET and hydro-climatic variables, in order to build a model that could be used to forecast wet area behavior based on commonly measured variables such as discharge and precipitation. WET was significantly and positively correlated to short term $P$, seasonal P-PET, and short term $Q$ (Table 2). One-day $Q$ showed the highest correlation with WET ($\rho = 0.81$, $p < 0.001$). $Q$, like WET, is an integrative variable, reflecting cumulative system behavior. The high correlation between WET and P-PET (cumulated at least 30 days) showed that WET reflects long-term memory of hydrologic inputs. Correlation analysis between 1-day $Q$ and P-PET cumulated over different time-periods also revealed that 1-day $Q$ reflects long-term behavior in the system.

The scatter-plot of $Q$ versus WET revealed a semi-logarithmic relationship (Fig. 6) with $Q$ explaining 72% of the variance in WET. This relationship signified that at high daily discharges, WET reached a maximum (near 25%) and no further increase in wet area size could be expected with increased discharge. It is likely that during these very wet periods, areas of saturation were beginning to get inundated and grow more in volume rather than area.

5.2. Predicting the probability of wet area formation

The flow–duration curve for all daily measurements of daily $Q$ from 1984 and 2005 showed the typical rotated S pattern with high flows having the lowest exceedence probabilities and low flows having the highest exceedence probabilities (Fig. 7). The wet area–duration curve showed a similar pattern, however, lack of data meant that the distribution extremes were not well defined. The exceedence probability of 5–10% WET of the drainage basin, reflective of dry conditions, was approximately 60%. For very wet conditions ($\approx 25\%$ WET), the exceedence probability was approximately 5%. From this we concluded that a majority of the time WET

Table 2

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Note: statistical significance * $p < 0.05$, ** $p < 0.01$. 

Fig. 5. A time-series of hydrologically classified images from 2000 showing within-year hydrological dynamics of wet areas from early to late growing season. The corresponding hyetograph and hydrograph are shown below the maps. (Note: same dataset as used in Fig. 2).
can be expected to fluctuate between 5 and 10%, only during infrequent wet periods can WET be expected to increase substantially.

The map of probability of wet area formation showed qualitatively a well-defined spatial structure (Fig. 8). Parts of the landscape with the highest probability of wet area formation were observed near lake and stream riparian zones, although there were other smaller pockets of high probability wet areas away from these bodies of receiving water (Fig. 8). Most of the existing cutblocks fell within parts of the landscape of low probability of wet area formation, however, there were some areas where they intersected wet areas and streams (Fig. 9). These are areas of concern, where the highest impacts could be expected as a result of increased nutrient or sediment loading.

5.3. Implications for design of buffer strips

Timber harvesting has the potential to alter wet area dynamics, either within or adjacent to these areas. Harvesting within and adjacent wet areas may lead to more frequent saturation and inundation because of decreased evapotranspiration after plant removal and enhanced channelization due to heavy equipment impacts and subsequently more efficient transfer of sediments and nutrients. To mitigate these impacts, the standard practice for forest companies is that they leave standard widths of riparian forest buffer strips around surface water bodies to serve as sinks for enhanced particulate and dissolved nutrients in hydrologic flows resulting from harvest activities (Castelle et al., 1994; Lee et al., 2004). Current forest management guidelines in Alberta require a standard width of buffer strip of 20 m around wetlands, 30 m around streams, 60 m around rivers, and 100 m around lakes (Alberta Environmental Protection, 1994) (Fig. 10A). In Alberta, the delineation of these hydrologic features is based on photo-interpretation of aerial photographs at cartographic scales of 1:20,000 to 1:50,000 (Alberta Vegetation Inventory, 2007). Logging planners use these hydrographic maps to allocate buffers and subsequently, in combination with maps of forest productivity, delineate areas that can be harvested. However, these standard buffer widths do not fully reflect the hydrologic characteristics of the landscape, especially in landscapes where the substrate has an important control on hydrologic fluxes (Buttle, 2002). Consequently, the standardized widths of buffer strips may offer too much or not enough protection for surface water quality (Belt and O’Laughlin, 1994).

An alternative to the standard width design of buffer strips that incorporates the range in natural variation of hydrologic pathways within the Moose Lake drainage basin is demonstrated in (Fig. 10B). Under this proposed system, the level of protection is based on the risk tolerance of the policy maker or resource manager. The riskiest approach would be to only protect wet areas that have a high probability of formation (e.g., 75% or higher) (Fig. 10B). This level of protection would only target a small area and would most likely lead to higher impacts as many wet areas would not be protected. In contrast, the safest approach would be to target wet areas that have a much lower probability of formation (e.g., 25% or higher) (Fig. 10B). At this probability level, a much larger area would be protected, similar in size to the area protected under the standard buffer width (Fig. 10A).

For the Moose Lake drainage basin, a buffer based on a probability of wet area formation of 25% would protect an area of similar size to one with the standard approach (approximately 15% of the drainage basin). However, the spatial distribution of the wet areas and associated buffers would be somewhat different under the two approaches (63% of the probability based wet area was contained within the standard approach). The differences could most likely be attributed to the inability of photo-interpretive methods to capture hydrological dynamics, in ephemeral channels.
for example, that were not reflected by hydric vegetation or by mapping wet areas that do not wet-up at a probability level of 25%. Some of the differences could also be attributed to misclassification of the radar images from which the probability layer of wet areas was calculated. Sass and Creed (2008) reported a classification accuracy of 88% in differentiating saturated from nonsaturated parts of the landscape.

The selection of specific probabilities to form a basis of a hydrologically based design for buffer strips should consider a number of factors including the specific goals of the buffer such as nutrient or sediment reduction and economics. For example, if sediment movement is the concern than wet areas with a low probability of formation (e.g., >1%) would be selected. If nutrient transfer was the concern, the probability could perhaps be set between 20 and 30%. For example, Walter et al. (2000) advocated using a probability of 30% in identifying wet areas for protection in a nutrient loading context. Eventually this probability level could be quantified based on field-experiments although the difficulty in controlling for climate and landscape differences, as shown by (Prepas et al., 2001), would be significant. Research is also needed in determining how the timing of harvesting operations (e.g., winter or dry season harvesting) influences the probability level chosen for minimizing impacts. Harvesting during hydrologically inactive parts of the year will minimize impacts (e.g. rutting) and facilitate quicker recovery rates.

From an economic perspective, forest managers would also be interested in how much of the productive land-base (for timber) do the different levels of buffer designs prevent from being harvested. In the Moose Lake drainage basin, the total productive land area (loggable resource) was 13.9 km² or 62% of the total drainage basin area (Alberta Vegetation Inventory). Of this productive land-base, 92.5% would have been available for logging under the standard buffer width buffer design. Under the probability approach, the available productive land area would have decreased from near 97% at a probability of 99% to about 37% at a probability of 1% (Fig. 11). At a probability of 25%, the productive land base would have decreased to 87.1% (Fig. 11). By combining the hydrological and economic perspectives, the optimum probability of wet area formation would minimize the 'loss' of loggable resource and maximize the wet areas protection. In our example, this optimum probability would be approximately 20% (Fig. 11).

The general application of a remote sensing derived probability based way of selecting buffers will face two important considerations: (1) the hydrologic relevance of assessing hydrological dynamics by capturing a time-series of radar images; and (2) technical feasibility of deriving hydrodynamics from a time-series...
of radar images. With respect to relevance, in humid landscapes where there are well formed drainage networks and topography is the main control on water flow, knowledge of the stream networks and identification of wet areas using terrain analysis will suffice (e.g., Chappell et al., 2006). Therefore, the problem of omitting hydrologically active areas when using standard width buffer zones would be less acute. However, even in topographically controlled landscapes, the temporal dynamics of the system should be incorporated into selecting the appropriate protection for wet areas. For example, a wetness index could be calibrated using soil moisture information to reflect something akin to a probability of wet area formation. More complex hydrological models might also form a useful basis to predict the temporal variability in wet areas (e.g., Agnew et al., 2006). In landscapes where geology and soils supersede topography in controlling the movement of water, radar imagery offers an excellent way to derive a probability layer of wet area formation. However, this involves technical and financial considerations. On the technical side, dense forest canopies make it difficult for the radar signal to penetrate to the ground. In deciduous forests, this could be circumvented by imaging during leaf-off conditions. A new generation of satellites, including RADARSAT-2, will offer much improved vegetation penetration as a result of multi-polarized and multi-frequency imaging. In terms of finances, the total commercial cost of 18 archived RADARSAT-1 images would be US$ 65,000.

Fig. 10. Identification of riparian buffers based on (A) standard width approach and (B) probability of wet area formation. For B, a narrow definition of buffers might only protect areas that have at least 75% probability of being wet. A broader definition of buffers would target all areas of the drainage basin that have a probability of being wet 25% of the time or more.

Fig. 11. Trade-off between wet areas protection and available loggable resource at different levels of probability of wet area formation.


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