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A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider?

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Introduction

Clearly defined hydrologic response units (HRUs) that incorporate unifying concepts in hydrology—the complete hydrologic cycle and conservation of mass (Dooge, 1986)—are required to direct and integrate local, regional and continental scales of hydrologic research and management. The topographically defined watershed or catchment has been championed as the basic HRU (Dooge, 1968). However, catchment studies reveal large complexity and heterogeneity of runoff behaviour, resulting in a multitude of conceptual and numerical model structures. Recent reviews argue that a broad-scale classification of catchments is required to generalize dominant hydrologic processes, direct field methodologies, and apply hydrologic model structure (Sivapalan, 2003; McDonnell and Woods, 2004). However, protocols on defining such areas are presently lacking.

Traditionally, researchers have disregarded large portions of the landscape in favour of areas amenable to 'hydrologic study', by relying on catchments where hydrologic boundaries can be easily defined. These catchments are often small and homogeneous, to 'control' for climatic and geologic features, which may have misled non-catchment-hydrologists (or up-and-coming hydrologists and managers) to believe that the first variable to consider in predicting hydrologic response is topography. This approach may provide a false sense of security about the effectiveness of topographically defined catchments as an approach to conduct research, assess regional hydrology, and generalize results to broad landscape scales.

Recent reviews clearly illustrate the need for a thorough integration of surface water and groundwater processes (Winter, 2001a,b; Sophocleous, 2002), and current research has begun to challenge the assumptions of the dominance of topographic controls on soil moisture distribution and runoff responses (Rodriguez-Iturbe, 2000; Grayson and Western, 2001; McDonnell, 2003; Buttle *et al.*, 2005). Paradoxically, the principal hydrologic boundary of most watershed studies continues to be surface topography and/or channel networks (Winter, 2001a; Sivapalan, 2003; Woods, 2004). As a result, approaches to catchment delineation, and subsequent instrumentation and application of model structures, may not consider the validity of assumptions implied by using topography to define HRUs

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with respect to dominant hydrologic cycling and mass balance. We believe that asserting the topographically defined catchment as a standard hydrologic unit, or by assuming that the water table conforms to topography, is a methodological approach that has been overstated in importance for regional to national scales of water management.

Effective Delineation of a Catchment Using Dominant HRUs: a Boreal Plain Example

The impetus for this commentary comes from an interest in understanding hydrology on the subhumid glaciated plains of the western Boreal Forest, and our realization that traditional approaches for hydrologic research may actually serve to limit insights into hydrologic function in this region. Ongoing research at our Utikuma Research Study Area (URSA), Alberta, Canada, reveals that glaciated regions, such as the Boreal Plain, with deep glaciated substrates arguably result in some of the most complex surface and groundwater interactions (e.g. Winter, 1999, 2001a). In addition, wetlands are widely distributed across the landscape (NWWG, 1988), and the water table often does not mirror local topography (Meyboom, 1966; Ferone and Devito, 2004; Smerdon *et al.*, 2005).

The difference in a hydrologist's perception of the effective catchment area determined by first considering topography, rather than climate and geology, is illustrated in the example in Figure 1 (Mink Lake, Alberta). From the data provided and the scale of the example, similar runoff contribution per unit area would often be assumed, and the hydrologic response time of rainfall at Site 2 would be considerably less than Site 3. Catchment delineation and tracking of water flow described in Figure 1a may hold for some biogeoclimatic regions, but this assumes a lack of influence by, or homogeneity in, climate, geology and wetland distributions. Research in areas with a sub-humid climate and low relief shows that unsaturated zone storage, vegetation water demand or evapotranspiration (ET), and vertical flow dominate over lateral flow in hillslope water balances (Rodriguez-Iturbe, 2000; Winter, 2001a; Smerdon *et al.*, 2005). This results in dynamic thresholds in surface water regimes and hillslope water balances with low runoff ratios (<20%), especially when summer precipitation dominates annual water budgets (Carey and Woo, 1999; Yue and Gan, 2004; Devito *et al.*, 2005).

Spatial heterogeneity of surficial glacial deposits (e.g. sand outwash, clay–silt moraines, and peat-covered low-lying lacustrine clay) in the URSA (Figure 1b) (Fenton *et al.*, 2003; Paulen *et al.*, 2004) is associated with variations in vadose zone storage, runoff, and the scale of surface water and groundwater interactions. Hydrogeologic studies indicate minimal regional groundwater interaction with Mink Lake, due to 50 m of low-permeability till deposits overlying shale bedrock of low permeability (Vogwill, 1977; Ceroici, 1979). In the fine-grained moraine till landform (Site 2; Figure 1), groundwater is largely restricted to local flow that conforms to topographic divides (van der Kamp *et al.*, 2003; Ferone and Devito, 2004). The sub-humid climate and fine-grained deposits restrict infiltration of precipitation to the shallow soil zone (i.e. vadose storage), which is subsequently taken up by high vegetation water demands (Rodriguez-Iturbe, 2000; Devito *et al.*, 2005). Although Site 2 is geographically closest to Mink Lake, in most years the water table elevation in the uplands is below adjacent valley or wetland depressions. Consequently, runoff contributions from Site 2 are very small or, in some years, non-existent (Ferone and Devito, 2004; Devito *et al.*, 2005).

In contrast, coarse-grained deposits (Figure 1b) enhance both infiltration and subsurface flow, and in sub-humid climates the water table mirrors the underlying confining layer rather than surface topography (Smerdon *et al.*, 2005). Regional surveys indicate that the coarse-grained deposits are 20 m thick and that the underlying confining layer slopes from west to east, towards Mink Lake (Ceroici, 1979; Mendoza and Devito, unpublished data). Increased baseflow contribution to Mink Lake can be expected, compared with other fine-grained surficial geologic units (Winter, 2001a), from subsurface flow paths originating beyond local topographic divides (Winter *et al.*, 2003) at several areas of the Mink Lake catchment (Site 1; Figure 1). Some surface water systems are perched 15 to 20 m above the regional

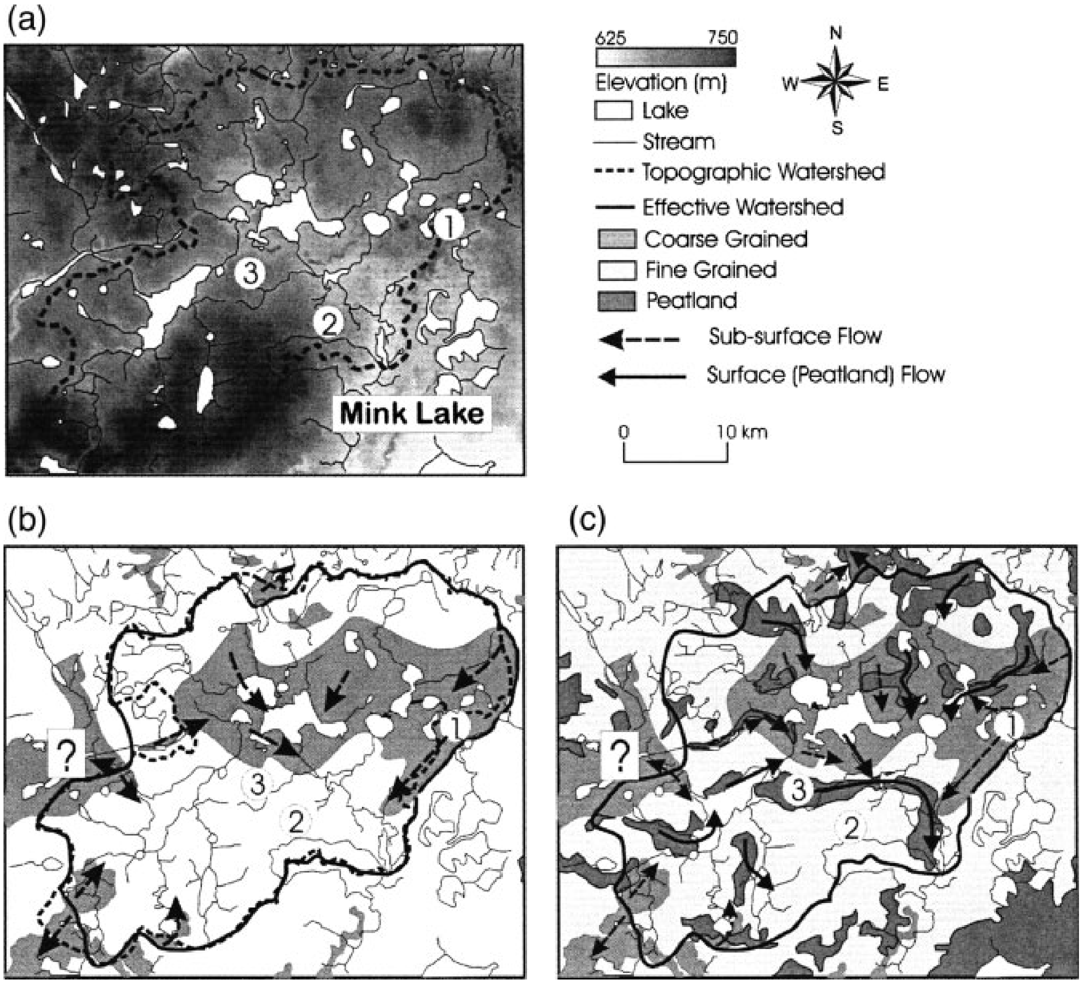

Figure 1. Comparison of the (a) topographically defined catchment (~700 km^2) and potential surface runoff area with HRUs incorporating (b) surficial geology and (c) peatland distribution for drainage contributing to Mink Lake, Alberta, Canada (115° 30′W, 56° 10′N). Average monthly temperature range is −14·6 to 15·6 °C, with annual *P* of 481 mm (Environment Canada, 2003) and annual PET of 517 mm (Bothe and Abraham, 1993). Topographic boundaries were defined using digital terrain analyses (Hutchinson, 1989; Hutchinson and Gallant, 2000). Three numbered sites illustrate hydrologic boundaries and scales of groundwater interaction and potential flow paths from contributing areas to Mink Lake. Assuming topographic control and humid climate, Site 1 is outside the topographic divide and does not contribute flow; Site 2 is adjacent to a stream directly feeding Mink Lake; Site 3 is near a tributary of a stream that feeds Mink Lake. Panel (b) shows the distribution of (1) coarse-grained sediments (depth 10–20 m) from aeolian and glacial–fluvial processes, and (2) fine-grained sediments from stagnant ice moraines (Fenton *et al*., 2003; Paulen *et al*., 2004). In contrast to panel (a), hydrologic boundaries differ in panel (b), and arrows on dashed lines show possible groundwater flow in permeable surficial aquifers. At Site 1 the surface water systems are perched and groundwater flows beneath topographic divides. Areas with question marks (eastern edge) indicate unknown groundwater divides. In this sub-humid climate, minimal runoff occurs from fine-grained materials (Ferone and Devito, 2004; Devito *et al*., 2005). Thus, Site 2 is not a major water source to Mink Lake. Panel (c) incorporates the distribution of peatlands, and arrows on solid lines indicate regions where surface runoff through peat dominates (Gibson *et al*., 2002; Devito *et al*., 2005). Consequently, there are larger surface water contributions from Site 3, compared with Site 2

water table at Site 1 (Mendoza and Devito, unpublished data). In this catchment the actual groundwater divide and the direction of flow within the coarse deposits result in an effective catchment area that is considerably different than topographically defined regions (Figure 1b).

The distribution of major wetland deposits (Figure 1c) represents distinct hydrologic units

within the defined HRU (McDonnell, 2003; Price *et al.*, 2005). As noted earlier, runoff contributions to adjacent wetlands are small in a sub-humid climate, although infrequent large runoff contributions via surface pathways can occur during extended wet periods (Devito *et al.*, 2005). Greater antecedent moisture is maintained in wetlands versus forested uplands, as a result of contrasts in vadose zone storage capacity, thermal properties, and vegetation cover (Price, 2003; Price *et al.*, 2005). Furthermore, near-surface moisture in organic soils is conserved during years of extended dry periods, due to rapid reduction in transmissivity of peat with depth, ice storage and reduction in actual ET (AET) to potential ET (PET) ratios due to shallow rooting zones, and low vertical unsaturated moisture transport (Silins and Rothwell, 1998; Petrone *et al.*, 2005). Counterintuitively, water table gradients often slope against topography (i.e. from peatlands to adjacent mineral uplands) in the Boreal Plain, and water may move into the hillslope to recharge groundwater or be transpired by upland vegetation (Mills and Zwarich, 1986; Hayashi *et al.*, 1998; Ferone and Devito, 2004). In the wetlands (Site 3; Figure 1c), the wetter surfaces generate larger surface water fluxes towards Mink Lake (Gibson *et al.*, 2002; Devito *et al.*, 2005). In the Boreal Plain, wetlands (which comprise 25 to 50% of the land area; NWWG, 1988) and low relief complicate traditional definitions of HRUs based on topography. The distribution and hydraulic connectivity of wetlands provide more practical insights into effective drainage networks and surface runoff contributing areas than topography within surficial geologic units (Devito *et al.*, 2000; Wolniewicz, 2002).

Finally, precipitation on large lake systems feeds depression storage and subsequently can either evaporate or recharge local coarse-grained surface aquifers. In coarse-grained areas, large lakes can act as evaporation windows to groundwater, exposing regional aquifers to significant water losses (Winter, 1999; Smerdon *et al.*, 2005).

Hierarchy of Factors to Define HRUs

The example demonstrates that we cannot assume topographic control *a priori* to explain the dominant components of the hydrologic cycle, groundwater conditions, or the type or scale of landscape hydrologic linkages across the Boreal Plain. We present a hierarchy of factors (Table I) that expands on work from URSA and other landscapes to define (a) regions of dominant hydrologic processes (i.e. HRUs) and (b) boundaries that incorporate the complete hydrologic cycle and mass balance of water for a specific region (Winter and Woo, 1990; Rodriguez-Iturbe, 2000; Winter, 2001a; McDonnell and Woods, 2004; Buttle *et al.*, 2005). We argue that, for broad-scale classification of an HRU, the order in which factors are considered is important, and that the factors should be considered in sequence of decreasing spatial scale to determine the relative influence on controlling hydrologic processes, scales of interaction and budgets.

Climate controls

Hydrologists should first consider broad-scale differences in climate, because it varies regionally with latitude and altitude, and locally with aspect (Table I) (Brutsaert, 1982; McDonnell and Woods, 2004). Climate governs the difference and seasonal synchronization between precipitation P and ET and defines broad limits, or constraints, on the relative roles of vadose zone storage and frost, vegetation water demand, and the dominant direction of water flow (e.g. vertical versus lateral) (Woo and Winter, 1993; Rodriguez-Iturbe, 2000; Grayson and Western, 2001; Winter, 2001a). Broad-scale frameworks based on indicators of dryness, such as the ratio of PET to P have been developed to generalize basic water balances of lakes, wetlands, and forests (Winter and Woo, 1990; Buttle *et al.*, 2000; Rodriguez-Iturbe, 2000; Yue and Gan, 2004) (Table I). In humid ($P >$ PET) eastern Boreal Canada, annual changes in soil storage are small, so annual P versus runoff R relationships and assumptions of unit area runoff models tend to hold, especially over longer periods (Buttle *et al.*, 2000, 2005; Yue and Gan, 2004). In contrast, in sub-humid climates ($P \leq$ PET), ET and changes in soil storage dominate water balances, which produce low runoff and poor relationships to annual P (e.g. Everson, 2001). This has been observed in a wide range of topographic and geologic settings, such as continental Boreal Canada

Table I. Hierarchical classification to generalize the dominant controls on water cycling and indices to define effective HRUs. The specified order (i.e. A to E) should be followed to develop a conceptual framework to determine the dominance of specific components of the hydrologic cycle and to determine the scale of interaction (e.g. local to regional) that should be considered. R = runoff, P = precipitation

Factor	Range of factor		Scale
A Climate	Dry, arid to sub-humid ($P <$ PET)	Wet, humid ($P >$ PET)	Continental to local
	• R poorly correlated with P • storage or uptake dominates • tendency for vertical flow	• R closely correlated with P • runoff dominates • tendency for lateral flow	
B Bedrock geology	Permeable bedrock	Impermeable bedrock	Continental to regional
	• intermediate to regional flow systems • lack of topographic control on direction of local flow • vertical flow dominates in surface substrate	• characterized by local to intermediate flow systems • topographic control on direction of local flow • lateral flow dominates in surface substrate	
	Bedrock slope perpendicular to land surface • complex watershed boundaries • regional aquifer definition needed to determine flow direction	Bedrock slope parallel to land surface • simple watershed boundaries	
C Surficial geology	Deep substrates • intermediate to regional flow	Shallow substrates • local flow most probable (but see bedrock geology)	Regional to local
	Coarse texture • vertical flow • deeper subsurface flow	Finer texture • lateral flow • depression storage and/or surface and shallow subsurface flow	
	Spatially heterogeneous deposits • complex groundwater flow systems • groundwater flow modelling important	Spatially homogeneous deposits • simple groundwater flow systems • surface flow modelling important	
D Soil type and depth	Upland mineral soils	Lowland organic soils	Local to regional
	• subsurface flow dominates • slow flow generation (matrix flow)	• return flow and surface overland flow pathways dominate • quick flow generation (return flow saturation overland flow)	
	Storage • deeper soils with large water storage potential	Storage • shallower soils with small water storage potential • lower specific yield of organic soils and compression leads to surface saturation	
	Transpiration • deep roots access stored water • P $\approx$ AET during dry periods	Transpiration • shallower roots limit access to stored water • AET < PET during dry periods	

(continued overleaf)

Table I. (*Continued*)

Factor	Range of factor		Scale
E Topography and drainage network	Gentle slopes	Steep slopes	Local to regional
	• disorganized, inefficient drainage network • large groundwater recharge • small, variable runoff yield	• organized, efficient drainage network • small groundwater recharge • large, uniform runoff yield	

(Devito *et al*., 2005), Cordillera (Carey and Woo, 2001), and subarctic Precambrian Shield (Spence and Woo, 2003).

Hydrogeologic architecture (bedrock geology)

The bedrock geology (permeability and lithology) of each region establishes the regional hydrogeologic architecture upon which water table configuration and groundwater flow systems (local, intermediate, regional) are manifested (Table I) (Tóth 1963, 1999; Freeze and Witherspoon, 1967; Winter, 1999, 2001a). Differences in bedrock geology configuration across the Boreal Forest, and continentally (Back *et al*., 1988), must be recognized to determine the scale of interaction and to define effective HRUs that incorporate all water sources (Winter, 2001a). For example, watershed boundaries for streams on the Precambrian Shield are generally easy to define as recharge areas, and infiltrating water is restricted largely to localized, lateral flow due to thin or absent surficial deposits on relatively impervious crystalline bedrock (Farvolden *et al*., 1988), with the exception of fractures (Winter, 2001a) or thicker surficial deposits (Hinton *et al*., 1993) (Table I). Defining recharge areas for streams on the Boreal Plain is complex, with infiltrating water dominated by vertical flow that can develop into local, intermediate, and/or regional scales of groundwater flow due to thick surficial deposits on permeable and heterogeneous bedrock (Lennox *et al*., 1988; Winter, 2001a). Recharge areas for streams in the Cordillera are defined by the slope and extent of bedrock faults in anticline or syncline valleys, or thrust faces, which can slope in the opposite direction of local topography, and headwater streams may feed or receive water from within or beyond the topographic divide (Foxworthy *et al*., 1998; Stein *et al*., 2004).

Surficial geology

Within regions of similar bedrock geology, the depth, texture, lithology, and heterogeneity of surficial geologic deposits vary from local to regional scales in definable units associated with coarse- to fine-grained glacial–fluvial and glacial–lacustrine surficial deposits (Table I, Figure 1) (e.g. Klassen, 1989; Halsey *et al*., 1997; Winter, 2001a). Each distinct landform has characteristic vadose zone storage, infiltration, and recharge capacities, with generally larger values in coarser sediments (Hendry, 1983; Saxton *et al*., 1986; Haldersen and Kruger, 1990). Potential for lateral redirection of vertical water fluxes and modification of groundwater flow systems, or development of perched wetland and lake systems, will increase in surficial deposits with layering of fine and coarse textures (Freeze and Witherspoon, 1967; Stein *et al*., 2004). The depth and texture of surficial deposits influence the extent, ephemeral nature and type of flow path connecting slopes to streams, wetlands, and lakes in a wide range of geologic settings (Devito *et al*., 1996; Buttle *et al*., 2000). Furthermore, the depth and texture of distinct landforms influence the scale of groundwater interactions, water table configuration, and the distribution of losing and gaining functions for streams, wetlands or lake margins (LaBaugh *et al*., 1997; van der Kamp and Hayashi, 1998; Tóth, 1999; Winter, 1999).

Soil and vegetation (including wetland)

At a finer scale, wetlands, particularly peatlands, and mineral uplands reflect differences in soil organic content and soil depth (Table I). This governs compressibility, hydrologic and thermal properties, which influence frost regimes, water storage, and transmissivity (Table I) (Woo and Winter, 1993; Comer *et al*., 2000; Grayson and Western, 2001; Price 2003). Such a distinction represents fine-scale changes in the AET-to-PET ratio as the availability of water, depth of roots, and plant water demand vary with soil and vegetation type (Rodriguez-Iturbe, 2000; Grayson and Western, 2001; Price *et al*., 2005). Furthermore, near-surface moisture in organic soils is conserved relative to mineral uplands during extended dry periods, due to adaptation of peat transmissivity, ice storage, reduction in AET, and low vertical unsaturated moisture transport (Ingram, 1983; Silins and Rothwell, 1998; Petrone *et al*., 2004). In regions where P < PET, fine-scale spatial changes in AET can have a large influence on vadose zone water storage thresholds and water table gradients (Mills and Zwarich, 1986; Hayashi *et al*., 1998; Petrone *et al*., 2005).

Flow paths and runoff responses of peatlands and riparian wetlands can vary greatly due to contrast in antecedent conditions and vadose zone storage capacity, and often behave independently of adjacent hillslopes. Thus, these must be considered key runoff-generating areas (HRUs) that dominate regional water balances in a wide range of climates and can occur at spatial scales finer than HRUs defined only by geology (Gibson *et al*., 2002; McDonnell, 2003; Devito *et al*., 2005; Price *et al*., 2005).

Topographic control of drainage networks

Clearly, topography will influence recharge and discharge areas (Tóth, 1963), detention and depression storage (Buttle *et al*., 2005), and flow rate and direction across spatial scales in many landscapes (Sivapalan, 2003; Woods, 2004). In general, increasing surface water flows are expected with an increase in relief and efficiency or connectivity of drainage networks (Table I). However, the assumptions underlying the use of a topographic or channel framework for modelling water cycling should be examined carefully and limited to landscape units of similar climate, bedrock and surficial geology, and wetland distribution (Table I). There is growing evidence, particularly in the climatic and geologic setting of the Boreal Plain, that elevation differences among geologic surface features at coarse scales, or riparian wetlands and upland features at fine scales, do not provide adequate information about the hydraulic gradient and the flow of water, or the scale of interaction among units (Meyboom, 1966; Rodriguez-Iturbe, 2000; Grayson and Western, 2001, McDonnell and Woods, 2004; Ferone and Devito, 2004; Smerdon *et al*., 2005).

Summary

The enthusiastic and widespread use of digital elevation models to define catchments as basic management units for water resources appears partially driven by technological advancements and reduced costs in remote imaging. We echo Grayson and Western (2001), that measures of topography may be convenient, but that hydrologists and managers should not develop indices 'for ease of measure'. Hydrologists should determine which major features or indices can be generalized to explain collectively the greatest variation in dominant hydrologic processes, and the appropriate scale at which they interact (Sivapalan, 2003).

The key question is: which landscape feature should be considered first? A hydrologist must determine which feature, or factor, explains the greatest variation in the dominant hydrologic processes without masking the influence of factors lower in the order. Common catchment approaches predefine (or force) the scale of each hydrologic component into the scale of topographic control. However, if topography is considered prior to geology and climate, then the practitioner must be willing to perceive potential transfer of water across initially defined topographic divides, or accept that a hillslope contributes little or no runoff. This may provide one of the largest obstacles to scaling runoff behaviour, particularly in the Boreal Plains (see Winter *et al*. (2003), Sivapalan (2003) and McDonnell and Woods (2004)). The proposed framework provides the first step in a qualitative 'integrated, holistic description of heterogeneity' and a hierarchy of factors nested within each other to identify progressively the relative importance of different scales and types of hydrologic interaction or process to define hydrologic boundaries effectively (Sivapalan, 2003).

The actual scale of dominant hydrologic processes in water cycling may be much finer (e.g. evaporation and ET vary from open water, peatland and hillslope) or coarser (e.g. regional groundwater flow) than the 'ideal' size for most topographically defined catchment studies (Winter 2001a; McDonnell, 2003; Woods, 2004; Buttle *et al.*, 2005). Practitioners must appreciate the differences in the scale at which dominant hydrologic processes act to direct appropriate methodological and modelling strategies for any given region (see Sivapalan (2003) and McDonnell and Woods (2004)).

The availability or resolution of factors listed in Table I may be insufficient to define HRUs effectively at scales that are finer than possible using topographic indices. However, if topography does not exert the dominant control on hydrologic processes, than the increased precision in topography and the decreased cost of analyses may not compensate for the absence of spatially variable, subsurface information on the hydrologic properties of bedrock and surficial deposits. In most regions, data are available with sufficient detail on landform genesis and/or particle size distribution and can be used to conceptualize vadose zone or soil storage properties and potential dominance and scale of surface and groundwater interaction (Klassen, 1989; Haldersen and Kruger, 1990; Fenton *et al.*, 2004).

The heuristic, conceptual framework for defining HRUs will direct both hydrologists and resource managers without hydrologic backgrounds to identify appropriate indices and to make qualitative predictions of the dominant hydrologic processes influencing water resources at the local (i.e. within climatic and geologic zones) and regional scales for the complex glaciated western Boreal Forest of Canada, and potentially globally (see Sivapalan (2003)). These evaluations will lead to an improved understanding of natural systems, and will facilitate assessments of the potential susceptibility of aquatic systems to impacts from anthropogenic and natural environmental changes. Furthermore, our approach encourages the explicit determination of the scale at which water resources interact with the surrounding environment without any *a priori* assumptions about the 'catchment' area. This understanding will be necessary to assess cumulative environmental effects of multiple land-use impacts and to formulate appropriate adaptive management strategies. For example, managers could use indices of climate and surficial geology to determine whether a particular hillslope is likely to generate runoff, and thus to assess the susceptibility of associated aquatic systems to a disturbance such as logging. Indices of bedrock and surficial geology could also provide information about the likelihood that subsurface flow may dominate hydrologic processes, and at what scale. Managers could determine whether the hillslope above a stream defines the source area for the stream, and subsequently assess the degree of susceptibility to a particular disturbance, either inside or outside the 'topographic catchment'.

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