Scale influences on the representation of crucial stores in a heterogeneous northern basin

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ABSTRACT
Hydrological connectivity controls runoff response in those northern landscapes that can be characterized as patchy or heterogeneous. This is problematic for catchment modeling because how to efficiently represent connectivity over space and time in a patchy landscape is not necessarily obvious. The pattern of hydrological elements over which a drainage network passes is considered in an attempt to understand how the landscape heterogeneity should be sampled in order to best represent it for the purposes of runoff modeling. The present study addresses how drainage density and sampling frequency influence the nature of the probability density function of hydrological elements along a drainage network in a typical heterogeneous subarctic Canadian Shield catchment. Upon generating fifty five sequences, the results imply that these two factors do influence sequence representation, and that the typical or representative sequence is one dominated by lakes. The gross variation in this sequence can be characterized into three phases. These phases were a function of the rate of change in drainage density with defined minimum contributing area. Since drainage density can be representative of the moisture state of a catchment, the results imply that parameterization of patchy landscapes for hydrological modelling needs to be dynamic and may need to be a function of the moisture state of the catchment.

KEYWORDS
Storage, Canadian Shield, Modelling, Hydrological elements, Streamflow

1. INTRODUCTION
Recent field studies (Carey and Woo, 2001; Hutchinson and Moore, 2000; Spence and Woo, 2003; Tromp van Meerveld and McDonnell, 2006) have highlighted the importance of basin heterogeneity, geometry, topology and dynamic hydrological connectivity in hillslope and catchment runoff generation. After studying hydrological and energy budget processes in the northern Canadian Shield physiographic region where connectivity has a profound influence on the runoff signal, Spence and Woo (2006) proposed an element threshold concept of runoff generation that perceives heterogeneous catchments as comprised of "hydrological elements". Hydrological elements are areas within a catchment that function hydrologically in a homogenous manner over time at a given scale of interest. Spence and Woo note the importance of the elemental geometry and topology of elements for runoff generation, which may need to be represented in model structures in order to correctly simulate when they contribute to downstream runoff.
The hydrologic response of a watershed to an impulse can be interpreted as a function of the probability density function, *pdf*, of travel times to the outlet along the drainage network. These *pdf's* have been equated to Strahler (1952) stream order (Wang et al., 1981), basin width function (Mesa and Mifflin, 1986), basin magnitude (Boyd, 1978) and basin area function (Robinson et al., 1995). Using a *pdf* of topographic index, Beven (1986) is one of the few works directly relating the landscape to the runoff response. The present study considers the pattern of hydrological elements (Spence and Woo, 2006) over which the drainage network passes in an attempt to understand how

the landscape patchiness should be sampled in order to best represent it for the purposes of hydrological modeling.

A literature review by the authors did not reveal any application deriving the probability density functions of the distribution of elements (or similar areal catchment components such as the hydrological response unit of Leavesley and Stannard (1990)) in a watershed. Similar questions about sampling effects on element *pdf's* (Becker and Braun, 1999) would apply to this activity as much as deriving the *pdf* of components of a drainage network. Melville and Martz (2004) and Helmlinger et al. (1993) show that arbitrarily assigned minimum contributing area thresholds do not necessarily change scaling properties. The effect of decreasing sampling on basin and drainage network delineation, and derived topographic variables has been found to be non-linear (Armstrong and Martz, 2003), but the persistence of symmetries is often observed (Marani et al., 1991). The present study addresses the following questions:

1) Does a) drainage density or b) sampling frequency influence the nature of the cumulative density function of hydrological elements along a drainage network?
2) Do changes in these two factors influence the eventual element sequence representation?
3) Is there a typical or representative sequence?

2. RESEARCH BASIN

Baker Creek is a water course characterized by lakes connected by short channels that drains ~150 km^2 into Great Slave Lake in Canada's Northwest Territories (Figure 1). The portion of the watershed that was investigated is upstream of the Baker Creek at the outlet of Lower Martin Lake Water Survey of Canada (WSC) hydrometric gauge (07SB013), draining a ~137 km^2 basin area.

In most years, the largest input of water to the basin is during the spring freshet (Spence, 2006) and the hydrological regime of Baker Creek is described best as subarctic nival (Church, 1974) as this melt dominates the annual hydrograph of Baker Creek. Baker Creek's drainage network is very dynamic with storage thresholds throughout the basin significantly controlling its extent. The extent is generally at its maximum during the spring freshet as snowmelt inputs easily overcome soil storage thresholds kept low by frozen conditions. Relatively high runoff from the uplands brings headwater lake levels above their outlet elevations, permitting flow to proceed to the main channel (Mielko and Woo, 2006). As spring gives way to summer, low intermittent rainfall-runoff from uplands and intermediate wetlands in the basin becomes disconnected from the main channel as evaporative and outflow losses drop levels in intervening lakes below their outlet elevations. By mid summer in a dry year only the three lowest lakes in the system can be hydrologically connected to the outlet of Lower Martin Lake. This equates to only 4% of the basin area (Spence, 2006).

Four land cover types dominate the basin. Exposed Precambrian bedrock is common throughout the basin (27%), particularly in the northeast portion. Open black spruce (*Picea mariana*) forest with an understory containing dwarf willow (*Salix* spp.), Labrador tea, and blueberry (*Vaccinium augustifolium*) occupies 24% of the basin. Bogs, fens and peat plateaus are all present as wetlands occupy 15% of the basin. Hummocky topographic surfaces formed by glacial erosion result in surface water accounting for 21% of the basin area. There are 349 perennial lakes in the basin with a median lake area of 5,400 m^2. The vast majority of lakes are smaller than 0.5 km^2 (97%), yet eight lakes larger than 1 km^2 skew the mean lake area to 88,800 m^2.

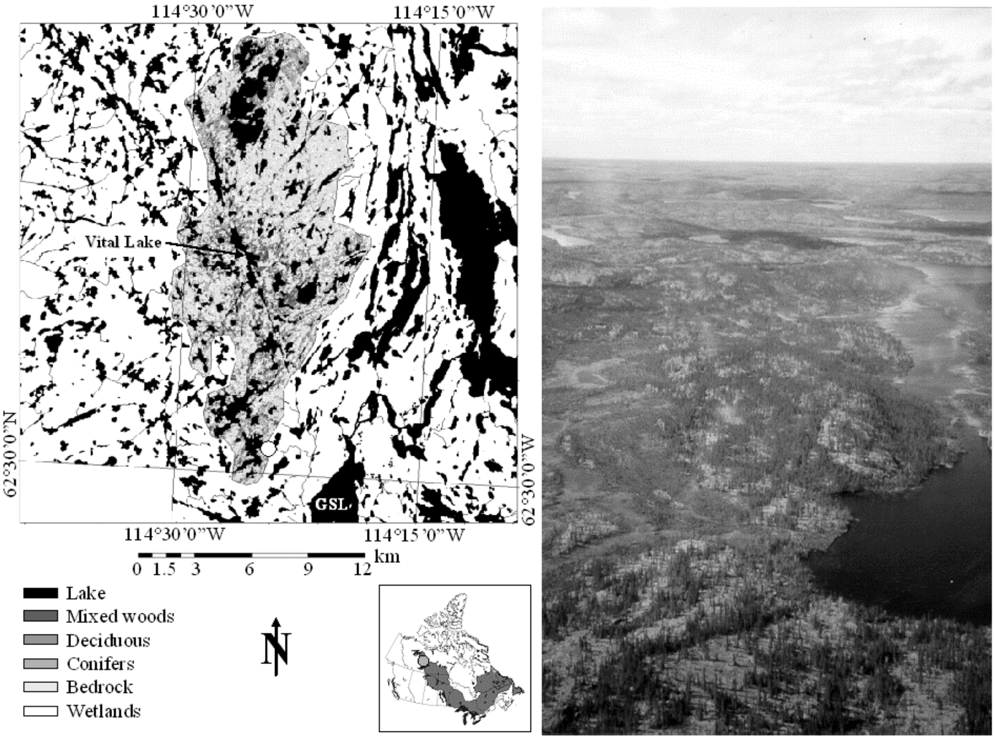

Figure 1: The location of the Baker Creek research catchment illustrating land cover, and notable lakes and a picture of the typical heterogeneous subarctic Canadian Shield landscape. The white circle on the map denotes the location of Water Survey of Canada hydrometric gauge 07SB013 Baker Creek at the outlet of Lower Martin Lake. GSL denotes Great Slave Lake. The shaded area of the reference map refers to the extent of Canadian Shield ecozones.

3. DATA SOURCES AND MANIPULATION

For the purpose of this study, it was assumed that the total range of hydrological elements in the Baker Creek catchment could be captured using land cover variation. This is not necessarily so. For instance, aspect can have an influence on the snowmelt processes that dictate hydrological functioning of exposed bedrock during the spring freshet (Spence and Woo, 2002). However, including aspect in the definition of a Baker Creek basin hydrological element, while more realistic, made the analyses more complicated than was felt necessary. The questions posed by the study could be answered without this added complexity.

Distributed land cover data was derived from Landsat TM satellite imagery. An unsupervised classification with channels 2,3,4,5 and 7 over representative terrain created sixteen classes. Ground truthing from air and ground surveys suggested that amalgamating these sixteen classes into six; coniferous forest, deciduous forest, mixed-wood forest, wetlands, bedrock and lake, would best represent the variation in land cover. Using the classified representative area, a supervised classification was implemented for the remainder of the catchment, resulting in the land cover distribution illustrated in Figure 1. The land cover raster map was imported into ArcInfo 9.0 and converted into a shapefile to permit interaction and analyses with the layers created with the catchment digital elevation model.

A Digital Elevation Model (DEM) of the catchment was obtained by clipping Canadian Digital Elevation Data (CDED) (Natural Resources Canada, 1999). Systemic errors due to the contour map data source and the relatively coarse 25m grid size were removed manually with PCI Geomatics software. Corrections were based on field observations and mapping of the drainage network and catchment boundaries as part of previous studies in the catchment (Spence, 2006).

Drainage networks were derived from the corrected DEM using the Arc Hydro Tools extension software to ArcInfo 9.0 (Maidment, 2002). Flow direction and accumulation were defined with the D-8 method

(Fairchild and Leymarie, 1991). Drainage networks, including stream heads and confluence points representing different wetness conditions were defined with eleven stream definition thresholds, or minimum contributing areas, ranging from 5 ha to 50 km^2. The land cover layer attributes were added to the attribute table of each network's stream head and confluence attribute table, which already included distance from the catchment outlet. This permitted each point to be analysed with respect to its land cover and placement along the drainage network. The outlet was defind as the location of the Water Survey of Canada hydrometric station gauge at the outlet of Lower Martin Lake described above.

Probability and cumulative density functions (*cdf's*) of distances from the outlet for each land cover type were derived for each of the eleven defined drainage networks. Probabilistically derived element sequences were derived by selecting the land cover that had the maximum value of:

$$P(L_i | D_j) \qquad (1)$$

where L is land cover of type i and D is a distance j in kilometres from the outlet.

This approach assumes that the most representative land cover at a specific distance from the outlet is the one with the highest probability of occurring at that distance. These distances were defined at five different frequencies (1, 2, 4, 6, and 10 km from the outlet).

The efficiency with which individual hydrological elements will transfer runoff downslope or downstream is a function of not only topology but also the relative size of adjacent elements (Spence and Woo, 2006; Spence, 2006; Woo and Mielko, 2007). If it is assumed that area is a good surrogate for the actual storage capacity of an element, flow will be transmitted through an element i if:

$$R_T = \frac{A_i}{A_{i-1}} < 1 \qquad (2)$$

where R_T is the transfer ratio, and A_i is the area of element i and A_{i-1} is the area of the element immediately upslope of A_i. This approach assumes that the storage capacity per unit area between the two elements is identical, so Eq. 2 needs a weighting factor based upon the relative nature of the elements i and $i-1$ such that flow will be transmitted through an element i if:

$$R_T = (\frac{A_i}{A_{i-1}}) \cdot F_{i,i-1} < 1 \qquad (3)$$

where $F_{i,i-1}$ is a factor defined as the relative storage capacities of elements i and $i-1$. There is local evidence that exposed bedrock storage capacities can be defined as 16 mm (Spence and Woo, 2002; Landals and Gill, 1972). The average storage capacity of a lake could be resolved as its average depth below its outlet elevation, assumed to be 2000 mm for this study. Soil depths are 2 m on average in the Yellowknife region (Wolfe, 1998). Accounting for an average porosity of 40%, storage capacities per unit area in soil covered elements (i.e., conifers, mixed woods, wetlands and deciduous stands) could be 800 mm. Actual storage capacity values of lakes and soil columns will change with lake level, snow, ice and ground frost conditions. For this exercise, all three values were assumed constant over time and among elements.

$$R_T = (\frac{A_i}{A_{i-1}}) \cdot F_{i,i-1} > 250 \qquad (4)$$

is a special case of R_T. In these instances, element i tends to be so large that it contains enough storage to maintain outflow in between runoff events. The transfer of water from element i is controlled by storage within element i rather than the relative volume of runoff from element $i-1$. They tend to be very large lakes relative to the contributions that they receive and tend not to intercept and halt the lateral transfer of runoff (Spence, 2006).

Element area applied in Eqs. 2-4 was estimated as the average patch area of the predominant land cover type patch at each sampling interval identified with Eq 1. Eqs. 2-4 were used to amalgamate the probabilistically derived sequences derived using Eq. 1 into sets of geometrically adjusted sequences that included only those elements that tended to intercept and store streamflow from upstream. Both the geometrically adjusted and probabilistically derived sequences were analyzed to determine if either drainage density or sampling frequency has an influence on the sequence representation. Commonalities were searched for in an effort to resolve the typical or representative sequence of elements in the Baker Creek basin.

4. RESULTS

4.1 Cumulative density functions

The drainage networks defined with the eleven defined minimum contributing areas are illustrated in Figure 2. Minimum contributing areas of 5 ha reflect wet conditions and drainage densities of ~145 km/km^2, typical of those that occur during spring snowmelt. A negative power function related both drainage density and sample size to minimum contributing area (Figure 3). At the largest minimum contributing area of 50 km^2, the drainage density was 0.09 km/km^2. This density has been observed in the Baker Creek catchment at the end of dry summers (Spence, 2006).

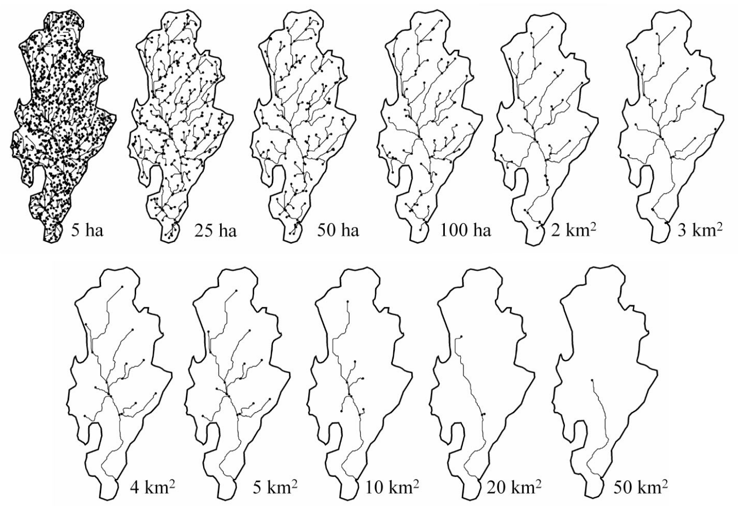

Figure 2: Drainage networks defined with each of the eleven minimum contributing areas, including the locations of land cover sample points.

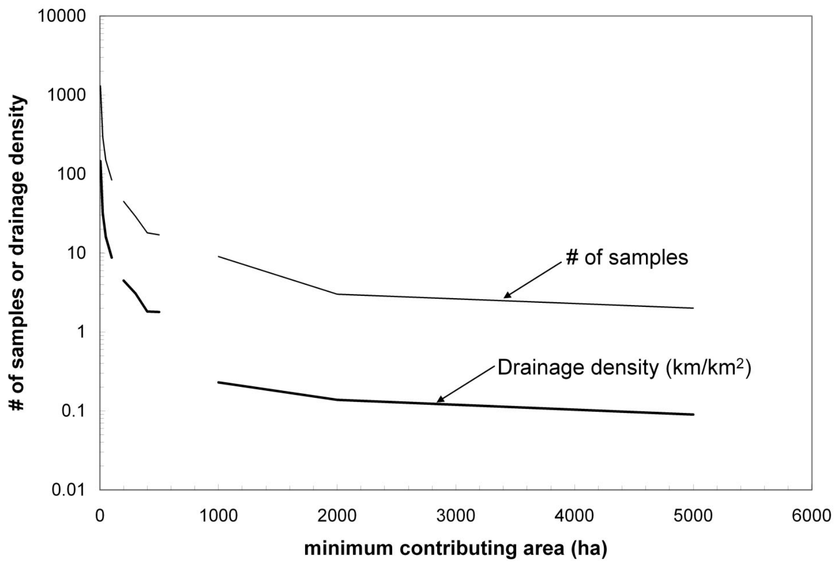

Figure 3: The non linear relationship between minimum contributing area, drainage density and the number of samples of land cover.

The eleven drainage networks each sampled at five frequencies produced 55 sets of cumulative distribution functions (cdf's) of distance from the outlet. All land cover types experienced a similar effect to their cumulative distribution functions when drainage density was changed. In general, the cdf tended to shift up and to the left of the 5 ha curve with decreasing drainage density. For example, beyond a 5 ha minimum contributing area the probability increased that a lake would occur closer to the outlet. This pattern changed to one which saw a higher probability of the lake occurring near the middle of the basin once minimum contributing areas were increased beyond 2 km^2. At the three largest minimum contributing areas (i.e., above 10 km^2) there is significant departure and variability from the rest of the curves (Figure 4). Only subtle changes in the shapes of cdf's derived from dense drainage networks were observed when sampling frequency changed (Figure 5a). The response of less dense networks to changes in sampling frequence was more variable (Figure 5b) and showed little consistent pattern.

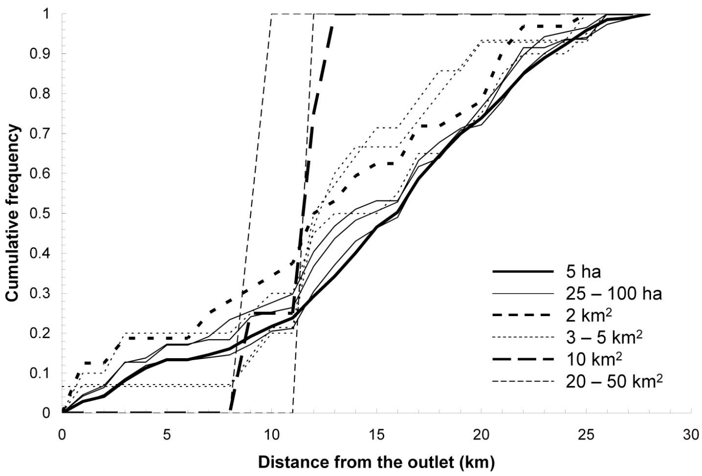

Figure 4: Variation in cumulative distribution functions of the water land cover type with minimum contributing area.

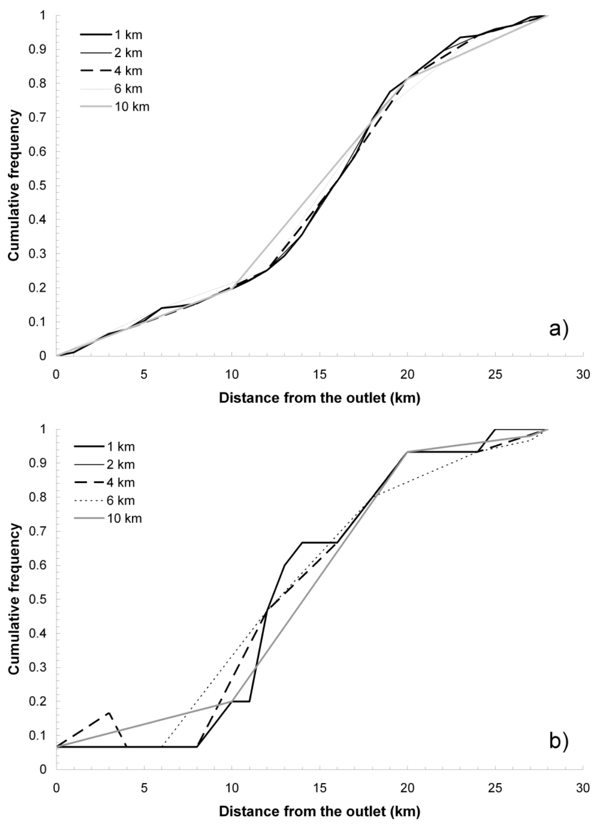

Figure 5: Variation in the cumulative distribution function of the conifers land cover type with sampling frequencies when minimum contributing area is defined as 5 ha (a) and the variation in the cumulative distribution function of the lake cover type with sampling frequency when minimum contributing area is defined as 5 km^2 (b).

4.2 Probabilistically derived sequences

Element sequences derived from the 5 ha minimum contributing area drainage network contained only lakes and conifers (Table 1). As sampling frequency diminished, conifers became even less common and lakes were the only selected elements at the largest sampling intervals when 5 ha was the defined minimum contributing area. There was convergence towards a sequence of three lakes among all the denser networks with decreased sampling (Tables 1-5). Nil samples in the frequent sampling sets began to appear when the minimum contributing area reached 2 km^2. Element variability along the sequence was at its highest among all 55 sets at the frequent sampling intervals (1-2 km) of these intermediately sized drainage networks (2-5 km^2) (Tables 1-5). A third group of sequence sets at minimum contributing areas of 20 and 50 km^2 were characterized by a lack of samples to define a complete sequence at the coarsest sampling interval of 10 km (Tables 1-5).

Table 1: Probability sequences with a sampling frequency of one kilometer. W denotes a lake; C, conifers; B, exposed bedrock, D, deciduous forest; T, wetlands; M, mixed woods. Bolded values denote storing elements identified using Eqs. 2-4.

	Minimum contributing area										
DFO (km)	5 ha	25 ha	50 ha	100 ha	2 km^2	3 km^2	4 km^2	5 km^2	10 km^2	20 km^2	50 km^2
0-0.9	***W***	***W***	***W***	W	W	W	***W***				
1-1.9	C	W/C	W	W							
2-2.9	W	***W***	***W***	W	***W***	***W***					
3-3.9	W	W	W/D	B/T							
4-4.9	***W***	W	W	W							
5-5.9	W	C	C								
6-6.9	***W***	***W/B***	W	***W***	***W***						
7-7.9	***W***	***W/C***	C	***W***	***W/C***						
8-8.9	***W***	***W***	***W***	W	W	W	W	W	***W***	W	
9-9.9	W	W	***W***	W	W	W	W	W	C	***W***	
10-10.9	W	W/C	W/C	W	W						
11-11.9	W	***W***	***W***	***W***	***W***	***W***	W	***W***	W		
12-12.9	***W***	W	W	W	W/C	***W/M***	***W***	***W***	W		W
13-13.9	***C***	***W***	***W***	W	***W***		***W***	***W***	T		
14-14.9	W/C	C	***W***	***C***	*W/D*	D/T	***W/D***	D	***D***		
15-15.9	C	C	C	B/D	C/B/D	W/B	C/D	C/D	***C***		
16-16.9	***C***	W	***W***	W	W	W	***W***	***W***			
17-17.9	W	***W***	W	C	C/T		W	W			
18-18.9	W	***W***	W	W	***W***	***W***		***W***		T	
19-19.9	W	C	W	***W***	W/C	W/B	W/C	W			
20-20.9	***W***	***W***	***W***	***W***	W	W					
21-21.9	W	W	***W***	W	W	W					
22-22.9	W	***W***	W	M/T	M	M			M		
23-23.9	***W***	***W***	***W***	***W***							
24-24.9	W	C	W	C	W	W		W			
25-25.9	***W***	***W***	***W***	***W***	C	W	W				
26-26.9	***C***	***W***	***C***	***C***							
27-27.9	W	W	C								

Table 2: Probability sequences with a sampling frequency of two kilometers.

	Minimum contributing area										
DFO (km)	5 ha	25 ha	50 ha	100 ha	2 km^2	3 km^2	4 km^2	5 km^2	10 km^2	20 km^2	50 km^2
0-2.9	***W***	***W***	***W***	W	W	***W***	***W***				
2-3.9	***W***	***W***	W	W	***W***	***W***					
4-5.9	C	C	***W***	***W***							
6-7.9	***W***	***W***	***W/C***	***W***	***W***			W			
8-9.9	W	W	W	W	W	W	W	W	W/C		
10-11.9	W	***W***	***W***	W	W	***W***	W	***W***	***W***	***W***	
12-13.9	***W***	***W***	***W***	***W***	***W***	***W/M***	***W***	***W***	***W/T***		***W***
14-15.9	C	C	C	C	D	W/C/D/T	D	D	***C/D***		
16-17.9	W	W	W	W	W	W	***W***	W			
18-19.9	W	W	W	***W***	W	W	W/C	W			
20-21.9	W	W	***W***	W	W	W				T	
22-23.9	***W***	***W***	W	***W***	M	M			M		
24-25.9	***W***	***W***	***W***	***W***	W/C	W	W	W			
26-27.9	C	W	C	C							

Table 3: Probability sequences with a sampling frequency of four kilometers.

	Minimum contributing area										
DFO (km)	5 ha	25 ha	50 ha	100 ha	2 km^2	3 km^2	4 km^2	5 km^2	10 km^2	20 km^2	50 km^2
0-3.9	***W***	***W***	***W***	***W***	***W***	***W***	***W***				
4-7.9	C	***W***	***W***	***W***	***W***						
8-11.9	W	***W***	***W***	***W***	W	***W***	***W***	***W***	***W***	***W***	
12-15.9	***W***	***W***	W	W/C	***W***	***W***	***W***	***W***	W/C/D/T		***W***
16-19.9	W	W	W	W	W	W	W	W		T	
20-23.9	***W***	***W***	W	W	***W***	W			M		
24-27.9	W	W	W	W	W/C	W	W	W			

Table 4: Probability sequences with a sampling frequency of six kilometers.

	Minimum contributing area										
DFO (km)	5 ha	25 ha	50 ha	100 ha	2 km^2	3 km^2	4 km^2	5 km^2	10 km^2	20 km^2	50 km^2
0-5.9	***W***	***W***	***W***	***W***	***W***	***W***	***W***				
6-11.9	***W***	***W***	***W***	***W***	W	***W***	***W***	***W***	***W***	***W***	
12-17.9	W	W	W	W	W	W	***W***	***W***	W/C/D/T		***W***
18-23.9	W	W	W	W	***W***	W	W/C	W	M	T	
24-27.9	W	W	W	W	W/C	W	W	W			

Table 5: Probability sequences with a sampling frequency of ten kilometers.

	Minimum contributing area										
DFO (km)	5 ha	25 ha	50 ha	100 ha	2 km^2	3 km^2	4 km^2	5 km^2	10 km^2	20 km^2	50 km^2
0-9.9	***W***	***W***	***W***	***W***	***W***	***W***	W	W	W/C	***W***	
10-19.9	W	W	W	W	***W***	W	W	W	W/C	T	***W***
20-27.9	W	W	W	W	W	W	W	W	M		

4.3 Element area

The densest drainage networks exhibited a bimodal patch area distribution with larger average elements near the outlet and at the top of the catchment (Figure 6). These values are likely skewed by the larger Martin and Duckfish Lakes in these locations. The distribution of patch area becomes unimodal towards the center of the catchment at minimum contributing areas of 10 km^2 and more. This effect, too, is a result of sampling over lakes in the smaller sets.

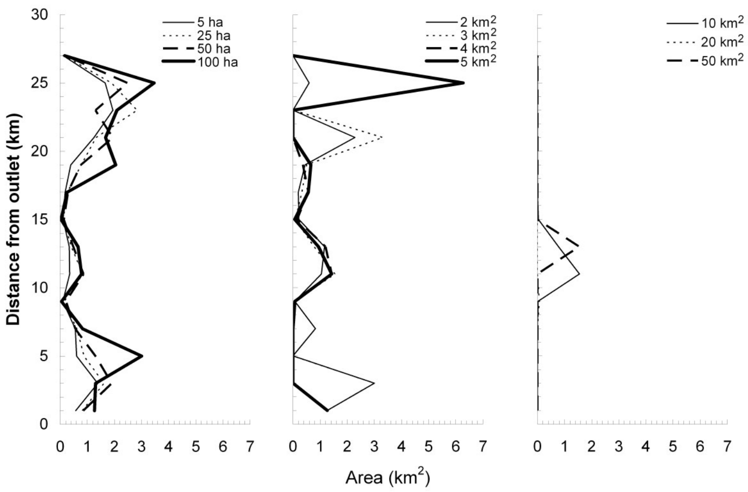

Figure 6: Distribution of average patch area as a function of distance from outlet for various minimum contributing areas, using a sampling frequency of 1 km.

4.4 Geometrically adjusted sequences

Lakes dominated the selections even more once the element sequences were adjusted for geometric effects (Tables 1-5). In the 5 ha drainage network, there were fewer storing elements relative to the total in the probabilistic sequence. This ratio initially increased when 25 ha or 50 ha defined networks were applied, then decreased through networks defined with minimum contributing areas from 100 ha to 4 km^2 and to a stable level in the sparse networks. Some of this effect was due to a reduction in the number of selected elements overall, but not in the middle range of network densities, where no storing elements were selected among the upper reaches of the drainage networks. A series of t-tests revealed that the mean number of storing elements in networks defined with minimum contributing areas of 5 ha – 100 ha, 2 km^2 – 10 km^2, and 20 – 50 km^2 were each significantly different, assuming constant sampling frequency.

5. IS THERE A TYPICAL SEQUENCE?

The different sequences derived from different drainage network densities (Tables 1-5) suggest that the number and location of crucial stores along the drainage sequence of Baker Creek will change with wetness conditions. In an abstract sense, when conditions are very wet the influence of lakes as stores in a catchment is reduced; just as the number of key stores relative to the total number of elements. The number of stores increases when vertical hydrological processes such as evaporation begin to predominate in elements when contributing areas and incoming runoff decrease. When conditions are very dry, fewer elements remain connected to the stream so those elements in the upper reaches become irrelevant to the direct delivery of stream water to the outlet.

The results suggest that this dynamic of changing sequences and storages is non linear. Physically, this is a necessity because the creation and dissolution of stores along a drainage sequence is a threshold process. Upscaling of this threshold process to the catchment scale produces a curve, as different portions of the catchment contribute under different conditions. The dynamics of this curve can be deduced from that expressed in Figure 3. It illustrates how the minimum contributing area influences the resultant drainage density and number of samples. The breaks in the curve coincide with changes in the nature of the defined sequence of elements along the Baker Creek drainage network. There are three distinct phases. When minimum contributing area is small, conditions are wet, and drainage density in the catchment is high, the sequence is controlled by several lakes along the system. When minimum contributing area is of a magnitude of square kilometres, the watershed is in a state of flux as it could be drying or wetting. As the moisture state of the watershed dries, the storing elements located high in the system remain important in the sense that they continue to prevent headwater runoff from proceeding to the active water course, but they are themselves disconnected by degrees of separation. The watercourse becomes concentrated along a main trunk of a less than a dozen lakes, of which only some can act as stores. The number of stores in the watershed decreases to a few key locations.

This result is partially a sampling effect. The larger lakes in the catchment are longer than 1 km and can contain wholly several "headwater" basins when the minimum contributing area is defined as 5 ha. The effect is a sequence where individual lakes are partitioned into more than one reservoir. These reservoirs are merged when the sequence is adjusted for geometry, reducing the number of stores in the new sequence. In this sense the watershed is initially oversampled by a drainage network defined with a minimum contributing area of 5 ha.

It is conjecture, but the nature of the curves illustrated in Figure 3 and density of key storage elements in Tables 1-5 should vary among catchments and especially among landscapes due to the influence of relief and slope length on drainage density (Selby, 1985). They may be indicative of how quickly a given watershed can wet or dry up. The information provided by such curves and tables could suggest how susceptible a watershed is to rapid changes in contributing area. Such information would be of importance to flood forecasters that need to predict the response of disconnected watersheds that are strong threshold systems.

6. CONCLUSIONS

The results show that the drainage density has an influence on the shape of the cumulative distribution function of elements along a stream network. The slope of the cumulative distribution function continually steepens as density decreases. The likelihood that a given element will appear closer to the outlet increases as density decreases. However, at the smallest densities, there is convergence towards the centre of the watershed. This location is a function of the methodology chosen and the scale of this particular catchment. In contrast, changes in sampling frequency produced only subtle changes in the shapes of the cumulative distribution functions.

Lakes dominated all 55 sequence sets. This result, too, was a function of the methodology and landscape. Tributaries of Baker Creek tend to meet at lakes. Using confluences as sample points resulted in an oversampling of lakes at each distance from the outlet, especially in the denser networks. This was exacerbated because many of the confluential lakes are larger than the smallest selected minimum contributing areas, which increased sampling at edges within lakes.

The three typical sequence classifications were a function of sampling and drainage density. Change in the drainage density is indicative of change in basin moisture state. When the catchment is wet, drainage density is high and there are fewer key stores in the sequence than when the drainage is relatively less dense. As drainage density decreases, the irrelevance of storing elements in the upper portions of the watershed to the direct delivery of runoff to the catchment outlet is represented by the lack of sampling. The results imply that parameterization of key storages along disconnected stream networks for runoff modelling needs to be dynamic and may need to be a function of the moisture state of the catchment. Testing of hydrological models with different parameterizations of sequences during different known moisture states may reveal when crucial stores in disconnected stream networks need to be addressed for improved representation of catchment water fluxes.

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REFERENCES

Armstrong, R.N., Martz, L.W. (2003) Topographic parameterization in continental hydrology: a study in scale. *Hydrological Processes* **17**, 3763-3781.

Becker, A., Braun, P. (1999) Disaggregation, aggregation and spatial scaling in hydrological modeling. *Journal of Hydrology* **217**, 239-252

Beven K. (1986) Runoff production and flood frequency in catchments of order n: An alternative approach. In: Gupta, V.K. et al. (eds), *Scale Problems in Hydrology*. Reidel, pp 107 – 131.

Boyd, M.J. (1978) A storage routing model relating drainage basin hydrology and geomorphology, *Water Resources Research* **14**, 921-928.

Carey, S.K., Woo, M.K. (2001) Slope runoff processes and flow generation in a subarctic, subalpine catchment, *Journal of Hydrology* **253**, 110-129.

Church M. (1974) Hydrology and permafrost with reference to North America. Proc. *Permafrost Hydrology Workshop Seminar 1974*, Ottawa, pp 7 - 20.

Fairchild J., Laymarie P. (1991) Drainage networks from grid digital elevation models, *Water Resources Research* **27**, 29-61.

Helmlinger K.R., Kumar, P., Foufoula-Georgia, E. (1993) On the use of digital elevation model data for Horontian and Fractal Analyses of Channel networks. *Water Resources Research* **29**, 2599-2613.

Hutchinson, D.G., Moore, R.D. (2000) Throughflow variability on a forested hillslope underlain by compacted glacial till, *Hydrological Processes* **14**, 1751-1766.

Landals, A., Gill, D. (1972) Differences in volume of surface runoff during the snowmelt period: Yellowknife, NWT. In: *The Role of Snow and Ice in Hydrology*, IAHS Publication #107, pp 927-942.

Leavesley, G., Stannard, L. (1990) Application of remotely sensed data in a distributed parameter watershed. In: Kite, G. and A. Wankiewicz (eds.), Proc. *Applications of Remote Sensing in Hydrology*, NHRI Symposium #5, Saskatoon, pp 47 – 68.

Maidment, D.R. (2002) *Arc Hydro: GIS for Water Resources*. ESRI Press, Redlands.

Marani, A., Rigon, R., Rinaldo, A. (1991) A note on fractal channel networks, *Water Resources Research* **27**, 3041-3049.

Melville, J.K., Martz, L.W. (2004) A comparison of data sources for manual and automated hydrographical network delineation, *Canadian Water Resources Journal* **29**, 267-282.

Mesa, O.J., Mifflin, E.R. (1986) On the relative role of hillslope and network geometry in hydrologic response. In: Gupta V.K. et al. (eds.), *Scale problems in hydrology*, Reidel, pp 1-17.

Mielko C., Woo, M.K. (2006) Snowmelt runoff processes in a headwater lake and its catchment, subarctic Canadian Shield, *Hydrological Processes* **20**, 987-1000.

Natural Resources Canada (1999) Canadian Digital Elevation Data: Standards and Specifications, 13 pp.

Robinson, J.S., Sivapalan, M., Snell, D.J. (1995) On the relative roles of hillslope processes, channel routing, and network geomorphology in the hydrologic response of natural catchments, *Water Resources Research* **31**, 3089-3101.

Selby, M.J. (1985) *Earth's Changing Surface; An Introduction to Geomorpohology*. Clarendon Press, Oxford, 607 pp.

Spence C., Woo M.K. (2002) Hydrology of subarctic Canadian Shield: bedrock upland, *Journal of Hydrology* **262**, 111-127.

Spence C., Woo M.K.(2003) Hydrology of subarctic Canadian Shield: Soil-filled valleys, *Journal of Hydrology* **279**, 151 - 166.

Spence C., Woo M.K. (2006) Hydrology of subarctic Canadian Shield: Heterogeneous headwater basins, *Journal of Hydrology* **317**, 138-154.

Spence, C. (2006) Hydrological processes and streamflow in a lake dominated water course, *Hydrological Processes* **20**, 3665-3681.

Strahler, A.N. (1952) Dynamic basis of geomorphology, *Bulletin of the Geological Society of America* **63**, 923-938.

Tromp van Meerveld, H.J., McDonnell, J.J. (2006) Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, **42**: W02411, doi:10.1029/2004WR003800.

Wang, C.T., Gupta, V.K., Waymire, E.D. (1981) A geomorphologic synthesis of non-leariy in surface runoff, *Water Resources Research* **17**, 545-554.

Wolfe, S.A. (1998) *Living with Frozen Ground: A Field Guide to permafrost in Yellowknife, Northwest Territories*. Geological Survey of Canada Misc. Report 64. 71 pp.

Woo, M.K., Mielko, C. 2007. Flow connectivity of a lake-stream system in a semi-arid, Precambrian Shield environment. Hydrological Processes, (in press).