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Towards an energy-based runoff generation theory for tundra landscapes

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Abstract

Runoff hydrology has a large historical context concerned with the mechanisms and pathways of how water is transferred to the stream network. Despite this, there has been relatively little application of runoff generation theory to cold regions, particularly the expansive treeless environments where tundra vegetation, permafrost, and organic soils predominate. Here, the hydrological cycle is heavily influenced by 1) snow storage and release, 2) permafrost and frozen ground that restricts drainage, and 3) the water holding capacity of organic soils. While previous research has adapted temperate runoff generation concepts such as variable source area, transmissivity feedback, and fill-and-spill, there has been no runoff generation concept developed explicitly for tundra environments. Here, we propose an energy-based framework for delineating runoff contributing areas for tundra environments. Aerodynamic energy and roughness height control the end-of-winter snow water equivalent, which varies orders of magnitude across the landscape. Radiant energy in turn controls snowmelt and ground thaw rates. The combined spatial pattern of aerodynamic and radiant energy control flow pathways and the runoff contributing areas of the catchment, which are persistent on a year-to-year basis. While ground surface topography obviously plays an important role in the assessment of contributing areas, the close coupling of energy to the hydrological cycles in arctic and alpine tundra environments dictates a new paradigm. Copyright © 2008 John Wiley & Sons, Ltd.

Key Words cold regions; runoff generation theory; surface energy balance; permafrost; organic soils

Introduction

Hillslope hydrology is largely concerned with the mechanisms and pathways of how water is transferred to stream networks. There is a rich historical context for hillslope hydrology, beginning with the works of Horton (1933) who introduced the concept of infiltration excess overland flow, and Sherman (1932) who employed this concept in his unit hydrograph theory. However, the Horton-Sherman assumptions that runoff is uniformly distributed and derived from an excess of infiltration (i.e. Hortonian runoff), could not be substantiated for most natural, vegetated hillslopes. Therefore, new mechanisms and pathways were proposed in subsequent theoretical developments. Betson (1964) suggested that the generation of surface runoff is limited to partial areas where hydrological inputs are sustained until the water table intersects the surface. Others stressed that partial areas are not fixed in space, but expand and contract in response to soil moisture variations (Hewlett and Hibbert, 1967; Dunne and Black, 1970), while the remainder of the basin was seen to act as a reservoir that maintains the wetness of runoff source areas and produces baseflow between storm events (Chorley, 1979). Underlying these new theories of hillslope hydrology was the recognition that exceedance of storage, rather than infiltration excess, controlled hillslope runoff, and a new set of models were introduced that reflected this in an explicit (Freeze, 1972) or a semi-explicit (Beven and Kirkby, 1979) manner. Subsequent to these seminal works, there has been an explosion of both conceptual and numerical models that have detailed more explicitly the mechanisms of runoff

generation, notably, preferential flow pathways (Weiler and McDonnell, 2004), transmissivity feedback (Bishop, 1991), fill-and-spill mechanisms (Spence and Woo, 2002; Tromp-van Meerveld and McDonnell, 2006) and a recognition of how catchment topography and topology combine to control streamflow at various scales (Buttle *et al.*, 2004).

Despite the large amount of research on the mechanisms of hillslope runoff generation, there has been relatively little application of these concepts to cold regions, particularly the expansive treeless environments where tundra vegetation, permafrost, and a continuous organic cover predominate. Arctic and alpine tundra, which is ubiquitous in much of Canada's northern and cordilleran regions and the circumpolar arctic (Bliss and Matveyeva, 1992), has a distinct hydrological cycle that is heavily influenced by 1) snow storage (Church, 1974), as the annual freshet can release more than half the annual precipitation (Woo, 1986); 2) permafrost (ground that remains below 0 C for two consecutive years or more), which severely restricts hydrological interaction between near-surface suprapermafrost water and deep sub-permafrost groundwater; and 3) the large water holding capacity of organic soils (Slaughter and Kane, 1979) with very high frozen and unfrozen infiltration rates that far exceed the rate of input from snowmelt or rainfall (Dingman, 1971).

During the snow accumulation period, which lasts eight to nine months, wind redistributes snow across tundra from areas of short vegetation and high wind exposure to sites sheltered from the wind, or with tall, dense vegetation (Pomeroy *et al.*, 1993), causing order of magnitude variations in snow water equivalent (SWE). At the end of winter, the timing and magnitude of runoff from tundra hillslopes is closely tied to aspect, owing to the latter's strong influence on the surface energy balance. North-facing slopes have relatively small snowmelt and active layer thaw rates, resulting in prolonged snowmelt periods and a relatively large proportion of runoff generated per snowmelt, or rainfall input to the hillslope (Slaughter and Kane, 1979; Carey and Woo, 1998). Melt water drains from hillslopes in daily pulses or waves (Dunne *et al.*, 1976) with a timing and magnitude controlled primarily by snowpack depth, and the angle and length of the hillslope (Ryden, 1977).

Melt water can percolate through the unsaturated, highly porous organic soil and move rapidly downslope, predominantly through shallow subsurface pathways (Soulis and Reid, 1978; Wright, 1979). Surface flow is virtually absent. Both matrix flow and preferential pathways such as inter-tussock flow (Dingman, 1973), inter-hummock flow (Quinton and Marsh, 1998), water tracks (Hinzman *et al.*, 1993) and soil pipes (Carey and Woo, 2000) contribute to flow, even when the surface is still snow covered (Woo, 1986) and before the soil moisture deficit is satisfied. These pathways are confined to the organic layer, which ranges typically from 0·1 to 0·4 m in thickness, and is further divided into a layer of living and lightly decomposed vegetation overlying a dense, compacted layer (Hinzman *et al.*, 1993). Typically, the water table remains within the organic soil throughout the thaw period (Hinzman *et al.*, 1993). Since the degree of decomposition increases with depth below the ground surface, so too does the proportion of small, closed and dead-end pores, and dry material per unit volume (Verry and Boelter, 1978). These depth variations in physical properties result in a decrease in the saturated, horizontal hydraulic conductivity by two to three orders of magnitude between the upper and lower organic layers (Quinton *et al.*, 2000; Carey and Woo, 2001).

Unlike temperate environments, subsurface fluxes of water and energy are closely coupled in tundra environments. During active layer thaw, the depth of the zero-degree isotherm (i.e. the frost table) coincides closely with that of the cryo-front, since the soil below the frost table is typically saturated with ice and a small amount of unfrozen water. The frost table is therefore relatively impermeable to water and represents the bottom of the subsurface flow zone—the thawed, saturated portion of the active layer that conducts the large majority of hillslope drainage. As the frost table and the water table perched above it descend through the thawing active layer, the horizontal hydraulic conductivity of the flow zone, therefore, decreases by orders of magnitude.

Despite the relatively deep frost table (extending to >0·5 m) in late summer, the hydraulic response of tundra hillslopes can be rapid due to the high rate of vertical infiltration to the zone of high water content above the water table (Hayashi *et al.*, 2007) and the relatively low drainable porosity at depth. In addition to the gradual reduction in subsurface runoff velocity with active layer thaw, abrupt changes to the subsurface flow rate and direction can occur in response to thaw-induced changes of the frost table topography that result in a sudden release, impoundment, or diversion of subsurface water (Woo and Steer, 1983).

Towards a New Hillslope Runoff Generation Theory for Tundra

Since the early 1970s, authors have related observations of runoff processes and pathways in arctic tundra to the aforementioned theories of runoff generation developed in more temperate locations. For example, Landils and Gill (1972) likened low-lying areas, where the water table is typically close to the ground surface prior to freeze-up and restricts meltwater infiltration during freshet, to the partial contributing areas described by Betson (1964). Several authors (e.g. Dingman, 1973; Quinton and Marsh, 1999; Carey and Woo, 2001) have noted that these areas expand and contract in response to subsurface inputs from adjacent hillslopes, and thus behave analogously to the variable source areas proposed by Hewlett and Hibbert (1967) and Dunne and Black (1970), with the distinction that flow is in the near-subsurface. In the high arctic, the spatial distribution of surface runoff generating areas can be governed by the disposition of snow drifts, which in turn is controlled by topography and the wind flow field (Lewkowicz and French, 1982; Lewkowicz and Young, 1990). Areas downslope of large drifts have been identified as partial contributing areas for runoff, which for a limited time (i.e. melt season) respond to rainfall input by lateral expansion. Obradovic and Sklash (1987) suggest that following snow cover removal, variable source areas diminish and deeper flowpaths become more important due to reduced water inputs, and lowering of the frost and water tables. Roulet and Woo (1988) reported a process whereby variable source areas coalesce as they expand, causing a spatial integration of runoff-producing areas, and a consequent abrupt increase in basin discharge.

In recent years, there has been a demand for improved predictive models for runoff in arctic tundra given uncertainties regarding the future availability of northern freshwater resources, freshwater contributions to the Arctic Ocean, resource development, and climate warming (IPCC, 1996). Because the hydrological characteristics of arctic tundra are distinct from those of temperate environments from where traditional concepts of hillslope runoff have been adopted, new theories that apply specifically to tundra are needed. This will provide for a more robust model development, which in turn will improve runoff prediction for this region. To this end, we propose that the topographically based contributing area described by the partial and variable source area concepts be combined with, and where appropriate be superseded by, an energy-based contributing area.

When the spatial pattern of SWE due to variations in aerodynamic energy is aligned with the topographic-controlled variation in surface radiation balance which governs the spatial pattern of snowmelt and ground thaw, stark variation in the volume and timing of hillslope runoff can result. For example, deep snowpacks on north-facing exposures will melt later and over a more prolonged period compared with shallow snowpacks on south-facing slopes. Carey and Woo (1998) report complete loss of snowcover on a south-facing slope one month prior to the onset of melt at an adjacent north-facing slope. Similarly, Pomeroy *et al.* (2003) detail large differences in surface energy balance for adjacent north- and south-facing slopes.

Differences in energy not only affect the disposition of snowpacks and the volume and timing of snowmelt and soil thaw, but also affect the nature of the subsurface flowpaths through which water is conveyed from hillslopes to stream channels. Shallow thaw depths and suppressed evapotranspiration on north-facing slopes result in greater near-surface wetness, shallower frost and water tables, and hence, greater volumes and more rapid runoff of water in highly conductive near-surface soil horizons (Carey and Woo, 2001). Conversely, slopes that receive greater amounts of energy manifest deeper thaw depth, an enhanced storage capacity, and deeper, slower flow pathways.

The end-of-winter snow accumulation pattern, despite some inter-annual variability, is remarkably similar from year to year in tundra catchments, owing to the persistent interplay between topography and the aerodynamic energy distribution (Marsh, 1999). Likewise, the influence of topography on the distribution of radiant energy enables spatial patterns of snowmelt and soil thaw to persist from year to year. While traditional theories of runoff generation may apply to flat, homogeneous tundra, any degree of topographic complexity coupled with high latitude introduces stark variations in radiation and aerodynamic energy, which in turn affects the accumulation and melt of snow, active layer thaw, soil moisture, evapotranspiration, and therefore, the volume and timing of runoff.

Defining the spatial distribution of energy as it affects runoff is an important first step towards identifying energy-based contributing areas. High-resolution digital elevation models (DEMs) provide the necessary topographic information to distribute wind flow and model the spatial distribution of SWE. They are also needed to distribute solar and terrestrial radiation for different aspects and solar angles to compute the energy available for snowmelt and ground thaw (Pomeroy *et al.*, 2003, Hayashi *et al.*, 2007). The depth of the relatively impermeable frost table can be computed from the cumulative ground heat flux (Quinton *et al.*, 2005). If the amount of meltwater delivered to the ground surface is also known, the depth and thickness of the subsurface flow zone can be derived. This, in turn, can be related to the transmissivity of the soil profile to predict the volume and timing of runoff (Quinton *et al.*, 2004). Since the ground surface of arctic tundra is so highly permeable, the topography of the frost table strongly influences both the rate and direction of hillslope runoff. Defining frost table topography as it evolves throughout the thaw season is therefore necessary for proper routing of subsurface drainage from tundra hillslopes. Recent studies (e.g. Quinton *et al.*, 2005) suggest that maps of frost table topography can be achieved by recording the spatial distribution of the cumulative ground heat flux over a hillslope as its surface becomes snow-free.

Representing the spatial distribution of energy as it affects runoff is necessary for the implementation of energy-based contributing areas in hydrological models. Hydrological Response Units (HRUs) are used in numerous models (e.g. Gurtz *et al.*, 2003; Pomeroy *et al.*, 2003; Zappa *et al.*, 2003) for mass and energy balance calculation of corresponding biophysical landscape units, such as north- or south-facing slopes, or portions thereof. HRUs are the smallest, sub-grid modelling unit that must be described to retain reasonable physical representation of runoff and other processes within models (Pomeroy *et al.*, 2007). They are presumed to have uniform internal hydrological characteristics, are sufficiently large to average out small-scale spatial variability, and are small enough that their response scales linearly with increased area. For the development of an energy-based runoff generation theory for tundra landscapes, such characteristics would be those that influence the aerodynamic and radiation regimes at the surface, including surface roughness, slope aspect and angle. Boundaries between HRUs can be approximated to topographic drainage divides, although it is recognized that the runoff contributing area within an HRU can expand beyond it to connect with adjacent HRUs. This is analogous to the spatial integration of source areas described by Roulet and Woo (1988), and in more temperate environments by McGlynn and McDonnell (2003). Such hydrological connectivity is controlled in part by the geometric distribution and sequence of HRUs in the landscape.

Summary

We propose an energy-based framework for delineating runoff contributing areas for arctic tundra environments. While ground surface topography obviously plays an important role in the assessment of contributing areas, the close coupling of energy to the hydrological cycle in arctic and alpine tundra dictates a new paradigm. Energy controls the disposition of snow, its melt, and the development of the active layer, all of which are critical in determining runoff contributing areas. The distribution of energy-based runoff contributing areas in catchments persist from year to year, since spatial variations in aerodynamic and radiant energy are strongly controlled by surface topography, namely aspect and slope angle. To date, there have been only a few process-based hydrological models explicitly developed and implemented for tundra environments (Zhang *et al.*, 1999; Quinton *et al.*, 2004). For this reason, schemes developed for temperate regions (such as TOPMODEL) are typically imported for tundra-applications to predict runoff and soil moisture patterns at smaller scales (i.e. Stieglitz *et al.*, 2003). New research priorities should include broadening the perspective on runoff models in organic-covered permafrost terrains. Recent research has demonstrated strong similarities in the thermal (Hayashi *et al.*, 2007) and hydraulic (Carey *et al.*, 2007; Quinton *et al.*, 2008) properties of the organic soils of arctic and alpine tundra, taiga boreal forest, and peat-lands. As discussed above, each of these cold region terrains manifests a similar close coupling of energy and water flows. It follows that a greater focus is needed from both field and modelling studies on coupled thaw and drainage processes. Research is needed on developing methods of combining high-resolution DEMs with energy distribution maps for the purpose of deriving the spatial distribution of: 1) end-of-winter SWE; 2) snowmelt energy; and 3) ground thaw energy. From these data layers, the frost table topography could be derived, which is a critical step toward predicting the rate and direction of flow. Updating the frost table topography throughout the thaw season is essential because, unlike the static bedrock surface, the frost table topography evolves as the active layer thaws with consequences for the rate and direction of subsurface drainage. Given the importance of the frost table topography to hillslope runoff, it is also recommended that the fill-and-spill hypothesis of Spence and Woo (2002) be modified for organic-covered permafrost terrain. Unlike water impounded by bedrock, water stored in frost table topographic depressions can be released (i.e. 'spilled') due to melt-out of the impounding ground ice without precipitation forcing. There is a pressing need for appropriate process-based models for tundra environments. As most tundra catchments (in Canada) are un-gauged, understanding the impact of observed climate warming and unprecedented resource extraction activities can only be achieved through improved conceptualization of hydrological processes. An energy-based framework of runoff generation may lead to improved predictions of streamflow in both the present and future.

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