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The transformation of frequency distributions of winter precipitation to spring streamflow probabilities in cold regions; case studies from the Canadian Prairies

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SUMMARY

Hydrological processes alter the states and/or locations of water, and so they can be regarded as being transformations of the properties of the time series of input variables to those of output variables, such as the transformation of precipitation to streamflow. Semi-arid cold regions such as the Canadian Prairies have extremely low annual streamflow efficiencies because of high infiltration rates, large surface water storage capacities, high evaporation rates and strong climate seasonality. As a result snowfall produces the majority of streamflow. It is demonstrated that the probability distributions of Prairie spring streamflows are controlled by three frequency transformations. The first is the transformation of snowfall by wind redistribution and ablation over the winter to form the spring snowpack. The second transformation is the melt of the spring snowpack to produce runoff over frozen agricultural soils. The third is the transformation of runoff to streamflow by the filling and spilling of depressional storage by connecting fields, ponds, wetlands and lakes. Each transformation of the PDF of the input variable to that of the output variable is demonstrated at a number of locations in the Canadian Prairies and is explained in terms of the hydrological processes causing the transformation. The resulting distributions are highly modified from that of precipitation, and the modification depends on which processes dominate streamflow formation in each basin. The results demonstrate the need to consider the effect of the interplay among hydrological processes, climate and basin characteristics in transforming precipitation frequency distributions into those of streamflow for the design of infrastructure and for water management.

1. Introduction

Hydrological processes alter the state and/or location of matter and/or energy. Because matter and energy are conserved, a given hydrological process is also a transformation, whereby an input time series is transformed to that of an output, and the properties of the input time series (temporal distribution, probability density, autocorrelation) are transformed to those of the outputs. In temperate regions, streamflow can be regarded as the transformation of rainfall and the probability density function (PDF) of a given stream's flow could theoretically be computed analytically from that of the rainfall and from the transformations caused by the river basin (Eagleson, 1972), although the effects of heterogeneity, non-stationarity, and thresholding make this difficult in practice (Struthers and Sivapalan, 2007). Transformation of precipitation inputs to streamflow has been proposed as one approach for streamflow prediction in ungauged basins where streamflow statistical information is not available for design purposes (Sivapalan et al., 2003; Hrachowitz et al., 2013; Pomeroy et al., 2013).

In cold regions, an especially diverse set of hydrological processes is involved in the transformations of precipitation to streamflow (Kuchment and Gelfan, 1991). Cold region streamflows are the result of sequences of hydrological processes transforming the input time series (snowfall and rainfall) to the output (streamflow) through mass and/or energy transformation and storage functions. As shown in Table 1, these processes may share state variables, and the outputs of some processes are inputs to others because of temporal variations in energy inputs due to seasonality and diurnal fluctuations. Computing the PDF of streamflows analytically is more difficult in cold regions than in temperate regions because of the larger number of hydrological processes and the many ways in which they inter-relate, the importance of phase

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change and energy budgets, the memory effects due to storage in the state variables, the non-stationarity in the inputs and state variables of the processes and the effects of thresholds in governing many of the processes (Spence, 2010).

2. Study rationale and objectives

The rationale and objectives of this study are derived from its location in the Canadian Prairies (as shown in Fig. 1), the northern part of the prairie pothole region of the glaciated plains of North America (Shaw et al., 2012a). Most of the hydrological processes discussed are present in other cold regions of the world; others are unique to the prairie pothole region. The reasons for the study are connected to the requirement for estimating flows for the design and operation of hydraulic infrastructure in the region. Design flows are often determined by fitting historical peak annual flows to a frequency distribution which is extrapolated to the desired return period (WMO, 2009). On the Canadian Prairies, fitting frequency distributions to streamflows is made difficult by the relative scarcity of stream-gauges, by the region's unusual hydrography, and by the usual issue of nonstationarity in hydrological processes.

2.1. Prairie hydrography and hydrology

The Canadian Prairies are recently-glaciated, flat, cold, and semi-arid to sub-humid. The mean annual precipitation in the region is approximately 454 mm (McGinn and Shepherd, 2003), with about 70% falling as rain and 30% falling as snow (Akinremi et al., 1998).

2.1.1. Prairie hydrography

Most of the land surface in the Canadian Prairies is not connected to a conventional fluvial drainage system. Instead, local runoff is often trapped in the multitudes of small, internally drained depressional storage ponds present in many Prairie basins. These depressions are a legacy of the relatively recent glaciation of the region where ice sheets left moraines, glacial lake beds, sand dunes and knob and kettle topography that was not subsequently eroded by fluvial processes into traditional drainage basins. The water bodies in the depressions vary in size from ephemeral puddles to large closed-basin lakes. The term 'wetland' is often used interchangeably with 'pond', but actually refers to specific depressions whose soils are saturated or nearly saturated for most of the year, include a dense ring of riparian vegetation, and which have fixed areas defined by their soils and vegetation (van der Kamp and Hayashi, 2008). A pond is the water in a depression, which may be a wetland or may simply be a temporary puddle. The area of a pond changes as the depth of water fluctuates. The upland which drains into the pond comprises its drainage basin.

As the soils of the region are predominantly underlain by glacial tills which have very low hydraulic conductivities, groundwater recharge rates are very low, with the little recharge that does occur generally being focused from underneath wetlands (van der Kamp and Hayashi, 1998). Consequently, baseflows are generally nonexistent on small streams arising from glacial till substrates within the region.

In Canada, drainage basins are designated as being comprised of the 'gross drainage area', which is the plane area enclosed by the divide, and the 'effective drainage area', which is defined as being the area which is expected to contribute flow to the stream one year in two (Godwin and Martin, 1975). That area which does not contribute flow with a return period of two years, i.e. the difference between the gross and effective areas, may be considered the 'non-effective' area within a basin.

Fig. 1 plots the non-effective areas of river basins in Western Canada, which generally coincides with the Prairie ecozone in Canada, 71% of the Prairie ecozone being non-effective. The effective fraction of each basin (the effective area divided by the gross area) is indicated by the color of the dots identifying the gauges plotted in Fig. 1 for streams having gross areas smaller than 1000 km^2 within the region. This maximum gross area value was selected to exclude large rivers (the Saskatchewan River and its tributaries) which are sourced in the Rocky Mountains and their foothills, rather than the Prairies. The means of the annual unit discharges of these streams over their periods of record, as computed from the gross and effective areas, are 19.5 and 29.3 mm, respectively. Despite the low mean annual flow depths, floods do occur on Prairie streams.

The fraction of the area of a Prairie basin which contributes flow to the stream (the contributing fraction) is dynamic and depends on the storage of water in the depressions (Stichling and Blackwell, 1957). Filled depressions allow additional water to spill overland to other depressions and may connect to a stream channel. This process, denoted 'fill and spill' (Spence and Woo, 2003) has been studied extensively by hydrologists in the Canadian and American Prairies (Spence, 2007; Shook and Pomeroy, 2011; Leibowitz and Vining, 2003; Zhang et al., 2009; Shaw et al., 2012b).

Declining water levels cause depressions to disconnect, reducing the fraction of the basin contributing flow to the stream channel. Because the connection and disconnection are controlled by differing processes, there can be hysteresis between the total quantity of water stored in depressions and the fraction of the basin contributing to flow from the basin (Shook and Pomeroy, 2011; Shook et al., 2013). The existence of hysteresis in the contributing fraction is evidence that the state of depressional storage (and therefore the contributing area) displays 'memory', being influenced by the history of prior inflows and outflows.

In a storage-dominated Prairie basin, the probability distribution of the discharge of a stream is the product of the distributions

Table 1
Important cold-regions hydrological processes responsible for the transformation of precipitation to streamflow.

Process	Mass input	Mass output	State variables governing process
Infiltration	Rainfall, melt water	Soil moisture	Soil moisture, ice content, soil temperature
Evaporation	Surface water, soil moisture	Water vapor	Depressional storage, soil moisture, state of plants
Snow accumulation	Snowfall	Snowpack water equivalent	Snow depth, density, vegetation states
Snow melt	Snowpack water equivalent	Melt water	Snowpack water equivalent, temperature
Detention	Direct precipitation, surface runoff	Detention, depressional storage	Soil saturation, surface water storage
Subsurface flow	Infiltration	Streamflow	Soil moisture, groundwater
Streamflow	Direct precipitation, surface runoff, subsurface flow, upstream flow	Downstream flow	Streamflow