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Towards an improved land surface scheme for prairie landscapes

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SUMMARY

The prairie region of Canada and the United States is characterized by millions of small depressions of glacial origin called prairie potholes. The transfer of surface runoff in this landscape is mainly through a "fill and spill" mechanism among neighboring potholes. While non-contributing areas, that is small internally drained basins, are common on this landscape, during wet periods these areas can become hydrologically connected to larger regional drainage systems. Accurate prediction of prairie surface runoff generation and streamflow thus requires realistic representation of the dynamic threshold-mediated nature of these contributing areas. This paper presents a new prairie surface runoff generation algorithm for land surface schemes and large scale hydrological models that conceptualizes a hydrologic unit as a combination of variable and interacting storage elements. The proposed surface runoff generation algorithm uses a probability density function to represent the spatial variation of pothole storages and assumes a unique relationship between storage and the fractional contributing area for runoff (and hence amount of direct runoff generated) within a grid cell. In this paper the parameters that define this relationship are obtained by calibration against streamflow. The model was compared to an existing hydrology-land surface scheme (HLSS) applied to a typical Canadian prairie catchment, the Assiniboine River. The existing configuration is based on the Canadian Land Surface Scheme (CLASS) and WATROF (a physically-based overland and interflow scheme). The new configuration consists of CLASS coupled with the new PDMROF model. Results showed that the proposed surface runoff generation algorithm performed better at simulating streamflow, and appears to capture the dynamic nature of contributing areas in an effective and parsimonious manner. A pilot evaluation based on 1 m LiDAR data from a small (10 km^2) experimental area suggests that the shape of the modeled storage-contributing area relationship is broadly consistent with that inferred from terrain analysis, under certain simplifying assumptions. The direct identification of storage–runoff parameters from terrain analysis is an outstanding challenge, and a promising area for future research.

1. Introduction

The prairie provinces of Canada, and parts of North and South Dakota, Minnesota, Montana, and Iowa, in the United States, contain millions of small depressions of glacial origin called prairie potholes that provide important wildlife habitats (van der Valk, 1989; Johnson et al., 2004, 2005). The wetlands that form in these depressions are also hydrologically important due to their surface storage capacity (van der Kamp and Hayashi, 2009). Many of these wetlands are often the terminus in internally-drained closed basins, which under normal conditions are considered as non-contributing areas to the larger external drainage system in which they are located (Leibowitz and Vining, 2003; Pomeroy et al., 2010). However, connectivity is dynamic, leading to variable contributions to major river systems, particularly under extreme flood events. Substantial efforts have been made to investigate the hydrological processes governing prairie wetlands in terms of surface and subsurface hydrological processes, dynamics of wetland storage, and surface runoff (Woo and Rowsell, 1993; Winter and Rosenberry, 1995; Hayashi et al., 1998; Parkhurst et al., 1998; Johnson et al., 2004; Rosenberry et al., 2004; Susann et al., 2004; Spence, 2007; van der Kamp and Hayashi, 2009; Rains, 2011). The water balance of individual potholes in the prairie pothole region can be summarized as follows. During winter, windblown snow tends to be redistributed from areas of sparse vegetation and accumulates in the potholes (Fang and Pomeroy, 2008). Snowmelt runoff from upland areas into potholes can be high due to the reduced infiltration capacity of frozen soils (Gray et al., 2001; van der Kamp et al., 2003). Overland runoff can also occur during

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intense rainfall events (Woo and Rowsell, 1993; Hayashi et al., 1998; van der Kamp and Hayashi, 2009). During summer, overland flow events from upland areas are not common due to higher infiltration and storage capacities of unfrozen soils (Hayashi et al., 1998; van der Kamp and Hayashi, 2009; Pomeroy et al., 2010). Water leaves the ponds through direct evaporation and infiltration (Woo and Rowsell, 1993; Hayashi et al., 1998; van der Kamp and Hayashi, 2009). Infiltrated water moves laterally and then upward to satisfy evaporation and root uptake (Hayashi et al., 1998). The effect of deep groundwater flow exchanges on the water balance can be minimal when underlying tills have low hydraulic conductivity (van der Kamp and Hayashi, 2009).

For similar hydrometeorological conditions, runoff volumes can change dramatically from year to year depending on the available storage in the basin prior to a runoff event (antecedent conditions) (Stichling and Blackwell, 1957). Ephemeral streams can connect depressional wetlands to one another during wet conditions through a “fill and spill” mechanism (Winter and Rosenberry, 1998; Shaw et al., 2012). Gleason et al. (2007) suggested a method whereby runoff at the basin outlet is computed as net precipitation minus the available storage in the basin. However, depending on the topography and topology of the potholes, some potholes can contribute to the drainage outlet before the available storage in the basin is satisfied. Hence, a methodology that simply calculates runoff volume at the outlet as net precipitation minus available storage in the basin has important limitations (Shaw et al., 2012).

Physically-based models integrating cold regions hydrological processes have been assembled to simulate hydrological processes for individual closed wetland basins (Su et al., 2000; Pomeroy et al., 2007; Fang and Pomeroy, 2008). Recent applications of simpler “fill and spill” type of models include the work by Shaw et al. (2012) and Shook and Pomeroy (2011). Shaw et al. (2012) introduced the concept of a topographically-controlled dynamic streamflow contributing area and proposed conceptual curves that represent the relationship between potential surface storage and streamflow contributing area for sub-threshold runoff events in the prairie pothole region. To examine the proposed conceptual curves, Shaw et al. (2013) presented a Simple Pothole terraIn anaLysis aLgorithm (SPILL) for the determination of contributing area based on the surface water connectivity that results from the “fill and spill” of prairie potholes. The algorithm was applied to two digital elevation models (DEM) representative of the prairie pothole region. In their field and small scale modeling work in the prairie pothole region, Shaw et al. (2013) emphasized that various attributes, such as antecedent conditions, hydrometeorological factors and size and intensity of snowmelt or runoff event, combine to affect the surface water connectivity between prairie potholes. The resulting connectivity varies spatially and temporally and results in dynamic streamflow contributing areas. Shook and Pomeroy (2011) used a high resolution LiDAR DEM to represent surface runoff processes and emphasized that storage and discharge relationships are highly hysteretic at the scale of their model application. Huang et al. (2013) used a simple model to simulate the water balance of a prairie pothole complex. The model was used to compute water storage in individual wetlands and a LiDAR DEM was used to compute the storage thresholds for spilling and the connectivity between adjacent wetlands and basins. Despite a failure to represent runoff volumes for the smaller wetlands, the modeled water balance for larger wetlands and the modeled wetland areas agreed quite well with observations.

Large-scale hydrological and land surface models do not currently incorporate such nuances as hysteresis in storage–discharge relationships and its effect on streamflow contributing area in the prairie pothole basins. Similarly, other recent modeling applications in the prairie pothole region exclude the explicit representation of dynamic streamflow contributing area (Whitfield et al., 2006; Shrestha et al., 2012). Recent large scale applications that consider the effect of the prairie wetlands are briefly reviewed here. Whitfield et al. (2006) compared vertical fluxes using a regional Common Land Model (CLM; Dai et al., 2003) and a field-scale Land Surface Process (LSP; Liou et al., 1999) model for a prairie wetland in Florida. According to their study CLM demonstrated considerable potential, but requires changes to model physics for practical application to wetlands at a subgrid scale. Wen et al. (2011) applied the Variable Infiltration Capacity (VIC; Wood et al., 1992) land surface macroscale hydrology model over the prairie region and showed that including static non-contributing areas delineated by the Prairie Farm Rehabilitation Administration (PFRA, Hydrology Division, 1983) in the runoff calculation improved model results. These non-contributing areas are based on gross and effective area concepts (Godwin and Martin, 1975) in which the effective drainage area is that portion of a drainage basin which might be expected to contribute runoff to the main stream during a flood with a return period of two years.

To improve hydrological models for the prairie pothole region, Leibowitz and Vining (2003) suggested that surface-water connections between wetlands should be thought of as a probability distribution over time and space. The runoff generation concept of the probability distribution model (PDM) (Moore, 2007) provides an alternative approach to represent the prairie hydrology in large-scale land-surface and hydrological models. In the PDM model a catchment is assumed to be composed of spatially distributed points with differing storage capacities that can be integrated over some area (a basin, sub-basin or grid cell) and described using a probability density function. The Xinanjiang model (Zhao, 1992) uses a similar procedure to relate rainfall-runoff to soil moisture conditions. The PDM and the Xinanjiang models have been used for large scale modeling applications (particularly for flood forecasting) in the United Kingdom and China respectively. Direct application of these models for the Canadian basins will be challenging due to the cold regions processes as well as the dominant vertical processes in the prairie pothole region that require an advanced land surface scheme. On the other hand, application of fully physically-based and distributed models like the MIKE SHE (DHI, 1998) in the prairie region to reproduce the “fill and spill” process requires high resolution DEM and a similar model grid size. Hence, with respect to large scale modeling, fully physically-based and distributed models have little practical application in the prairie pothole region. Another limitation of the above mentioned models is the absence of a direct link to atmospheric models.

This paper introduces the PDMROF (Probability Distribution Model based RunOFf generation) algorithm which is based on the PDM runoff generation concept (Moore, 2007). This uses the Pareto distribution function which, by varying the shape factor parameter, can parsimoniously represent dynamic contributing areas as a function of percentage basin volume storage. The hypothesis is that PDMROF will permit better simulations of streamflow than those using a physically-based runoff generation scheme (the WATROF algorithm; Soulis et al., 2000) that uses static contributing areas. Both were applied within the MESH modeling system (Modélisation Environmentale Communautaire – Surface and Hydrology, Pietroniro et al., 2007), that permits a direct link to atmospheric forcing data. The objective is to develop a better way to represent the dynamic contributing areas and associated runoff processes of the prairie pothole region within large scale modeling applications that have the capability to link to atmospheric models. PDM concepts have been applied in the VIC model (Wood et al., 1992) and in a number of land surface schemes used in weather and climate modeling (Dümenil and Todini, 1992; Blyth, 2001). However, this is the first attempt, to our knowledge, to represent the surface water connectivity that results from the “fill and spill” of prairie potholes as dynamic contributing areas within coupled hydrologic land-surface schemes.