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Reconstructing sixty year (1950-2009) daily soil moisture over the Canadian Prairies using the Variable Infiltration Capacity model

Lei Wen, Charles A. Lin, Zhiyong Wu, Guihua Lu, John Pomeroy, and Yufei Zhu

Abstract: The Variable Infiltration Capacity (VIC) land surface macroscale hydrology model was used to reconstruct 60 years (1950-2009) of daily soil moisture values for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) over the three Canadian Prairie Provinces with a total area of 1,964,000 km². VIC was applied over a grid of 4,393 points with a resolution of 0.25° × 0.25°, and was driven by observed daily maximum and minimum air temperature and precipitation from 1,167 meteorological stations. The model was first calibrated using observed hydrographs from seven catchments with drainage areas varying from 3,750 to 7,870 km². Special attention was given to modelling of rainfall-runoff processes over the non-contributing drainage area of the Prairies. VIC was then validated over these seven catchments at different periods and over an additional five catchments with drainage areas ranging from 36,500 to 131,000 km². An estimation procedure to determine model parameters was developed and applied to catchments where hydrographs are not available for the standard calibration process. In situ soil moisture measurements from six Alberta sites were also used for model validation. VIC performed well over both calibration and validation catchments. The results clearly demonstrate that incorporating non-contributing drainage areas into runoff calculations could substantially improve the ability of VIC to simulate surface and subsurface runoff in regions where poor drainage network development is a dominant feature of drainage basins. The VIC reconstructed 60-year average of the soil moisture in the top 1 m shows some expected climatological features of the Prairies. For example, the reconstructed soil moisture climatology portrays the dry Palliser Triangle region and the Prairie Dry Belt in the southern Prairies. The VIC simulated soil moisture was used to calculate the daily Soil Moisture Anomaly Percentage Index (SMAPI) for the three soil layers; SMAPI can be used as an index of agricultural drought severity taking into account climatology. The value of the calculated SMAPI in quantifying and documenting prairie drought events is demonstrated through an intensive examination of the April 2002 drought case.

Lei Wen1, Charles A. Lin1,2, Zhiyong Wu3, Guihua Lu3, John Pomeroy4, Yufei Zhu5

1 Department of Atmospheric and Oceanic Sciences, and Global Environmental and Climate Change Centre, McGill University, Montreal, Quebec, Canada; H3A 2K6; Tel: (514) 398-1035; lei.wen@mcgill.ca
2 Atmospheric Science and Technology Directorate, Environment Canada, Montreal, Canada
3 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China
4 Center for Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
5 Canadian Meteorological Centre, Environment Canada, Montreal, Canada

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Résumé: Le modèle hydrologique macroscopique de surface à capacité d’infiltration variable (VIC) a été utilisé pour reconstituer 60 ans (de 1950 à 2009) de valeurs quotidiennes d’humidité du sol pour trois couches de sol (de 0 à 20 cm, de 20 à 100 cm et de 0 à 100 cm) dans les trois provinces des Prairies, avec une superficie totale de 1 964 000 km². Le modèle VIC a été appliqué à une grille de 4 393 points avec une résolution de 0,25° × 0,25° et employé pour l’analyse de données de précipitations et de températures de l’air maximales et minimales quotidiennes observées, provenant de 1 167 stations météorologiques. Le modèle a d’abord été étalonné à l’aide d’hydrogrammes de sept bassins hydrographiques dont la superficie varie entre 3 750 et 7 870 km². Une attention toute particulière a été accordée à la modélisation des processus de précipitations/d’écoulement se rapportant aux bassins à contribution nulle des Prairies. Le modèle VIC a ensuite été validé pour ces sept bassins hydrographiques à différentes périodes et pour cinq autres bassins versants d’une superficie allant de 36 500 à 131 000 km². Une méthode d’estimation visant à déterminer les paramètres de modèle a été élaborée puis appliquée aux bassins hydrographiques où des hydrogrammes ne sont pas disponibles pour le processus d’étalonnage standard. Des mesures d’humidité du sol in situ tirées de six sites de l’Alberta ont également été employées pour la validation du modèle. Le modèle VIC a donné de bons résultats tant pour l’étalonnage que pour la validation des bassins hydrographiques. Les résultats démontrent clairement que l’intégration de bassins hydrographiques à contribution nulle dans les calculs du ruissellement pouvait améliorer considérablement la capacité du modèle VIC à simuler l’écoulement de surface et l’écoulement hypodermique dans les régions où un piètre aménagement du réseau hydrographique constitue une caractéristique dominante des bassins versants. La moyenne sur 60 ans de l’humidité du sol pour la couche supérieure de 1 m, reconstituée grâce au modèle VIC, révèle certaines caractéristiques climatologiques prévues des Prairies. Par exemple, les données climatologiques reconstituées de l’humidité du sol dépeignent bien la région sèche du triangle de Palliser et la zone aride des Prairies dans le sud des Prairies. L’humidité du sol simulée grâce au modèle VIC a servi au calcul de l’indice SMAPI1 quotidien pour les trois couches du sol; l’indice SMAPI peut être utilisé en tant qu’indice de la gravité de la sécheresse agricole, en tenant compte de la climatologie. La valeur de l’indice SMAPI calculé dans la quantification et la documentation des événements de sécheresse dans les Prairies est démontrée au moyen d’un examen approfondi de la sécheresse qui a sévi en avril 2002.

Introduction

Severe droughts are extreme events, which can have devastating impacts on almost all sectors in our society. Most regions of Canada have frequently experienced droughts in the past and will continue to do so. Droughts are responsible for four of the six most costly natural disasters in modern Canadian history. Notably, all four droughts took place within the last 25 years (Environment Canada, 2003). The upward trend of frequent droughts in the last 25 years is likely the result of global change. Recent observations and climate modelling studies have shown that the impact of climate change could be greatest at middle to high latitudes according to the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2007). Drought is therefore a major concern in Canada especially in the changing climate.

The Canadian Prairie Provinces are roughly described by latitude (90°W-120°W) and longitude (49°N-60°N). The Prairies mainly comprise the provinces of Alberta, Saskatchewan and Manitoba, and the three provinces occupy approximately 20% of Canada’s territory (1,964,000 km²) and contain more than 85% of Canada’s arable land, forming one of the world largest agricultural areas. Alberta possesses the world’s largest oil sand deposits and could become the single biggest contributor to new global oil supplies in the coming decade. The Canadian Prairies are thus of great agricultural, environmental and socio-economic importance.
The natural ecosystems, socio-economic development and agricultural activities in the Prairies are closely tied to and sustained by the availability of water resources. However, the scarcity of water resources has been one of the major obstacles to the Prairies’ sustainability of natural ecosystem and socio-economic development (Pomeroy et al., 2007). The situation is further complicated by the fact that the Prairies are particularly susceptible to drought (Roberts et al., 2006), and there was at least one catastrophic drought per century dating back to the 17th century. During the past century, the most severe droughts were the multi-year droughts of the early 1930s and the 1980s. The most recent prairie drought began in 1999 and ended in 2005. The latter drought peaked during 2001 and 2002, and has been recognized as one of Canada’s worst natural disasters (Wheaton et al., 2007). It was estimated that the national Gross Domestic Product lost about CDN$5.8 billion during the 2001-2002 episode of the drought alone. It also caused a decrease in employment exceeding 41,000 jobs and resulted in devastating consequences for prairie farmers who experienced negative or zero income for the first time in 25 years (Wheaton et al., 2005). As the result, the Canadian Drought Research Initiative (DRI) was established in 2005 (Stewart et al., 2008). One of the major objectives of the DRI is to assess and reduce uncertainties in the prediction of drought over the Prairies. Reconstructing recent drought events would enhance our knowledge of drought characteristics, and thus improve drought predictability. The DRI has generated common interests since its inception among many sectors in both Canada and the United States.

A drought is an extended period of abnormally dry weather, which is sufficiently prolonged for the lack of water to cause a serious hydrological imbalance in the affected area. However, a precise quantification of drought is still an open question, as there are many different definitions of drought (e.g., meteorological, hydrological, agricultural and socio-economic droughts). In general, agriculture is often the first sector to be affected by the onset of drought (Narasimhan and Srinivasan, 2005). Sufficient water supply is essential for the growth of crops at different stages. Crop production is thus strongly influenced by soil moisture conditions. Soil moisture is of more direct interest to agricultural operations and is related to atmospheric circulation patterns through precipitation and evapotranspiration (Wittrock and Ripley, 1999), and to soil textures (Wen et al., 1998). According to the World Meteorological Organization (WMO; Hounam et al., 1975), agriculture drought relates to a shortage of available water for plant growth, and is assessed as insufficient soil moisture to replace evapotranspirative losses. Having accurate soil moisture information is thus essential and important to assessing and predicting agricultural drought that is one of the focusing issues in the DRI.

It is difficult to obtain soil moisture measurements from field surveys on large scales in Canada. Soil moisture often exhibits strong small scale spatial and temporal heterogeneity, which further complicates interpretation of observations. Soil moisture can vary significantly among different in situ measurements even within a small area. This is mainly due to irregular inputs of water to the soil column from variations in precipitation, snow accumulation or runoff, and redistribution of soil water along hillslope gradients, all of which can vary with soil, vegetation, and topographic characteristics (Gray et al., 2001; Pomeroy et al., 2007). There are no consistent soil moisture monitoring networks that can provide long datasets of soil moisture conditions in both Canada and the United States. Such a dataset would be required to conduct a systematic study of the agricultural drought history and trends for large areas, such as the Canadian Prairies, and over long periods.

Recent advances in the development of macroscale land surface hydrological models offer the potential to reconstruct and continually update spatial and temporal distribution of soil moisteres over a large area. The VIC (Variable Infiltration Capacity; Liang et al. 1994; 1996) model is such a land surface macroscale hydrology model. It uses a spatial probability distribution function to represent sub-grid variability in soil moisture storage capacity. Such a function is used in the Xinanjiang hydrological model (Zhao et al., 1980), the Hamburg Climate Model (Dümenil and Todini, 1992), the Interface Soil Biosphere Atmosphere model (ISBA; Habets et al., 1999), and Canadian Land Surface Scheme (CLASS; Verseghy, 1991; Verseghy et al., 1993; Wen et al., 2007) for calculating saturation excess runoff, and the General Runoff Yield model (Wen et al., 1982) for generating infiltration and excess runoff. The function is designed to take into account heterogeneity of land surface properties, and can provide more realistic treatment of hydrological processes within a model grid cell. Nijssen et al. (2001)
used VIC to generate 14 years (1980–1993) of global daily soil moisture at a resolution of 2° × 2°. Su and Xie (2003) studied the effect of climate change on China’s runoff using VIC simulations. Andreadis et al. (2005) reconstructed the drought history of the continental U.S. from 1920 to 2003 based upon VIC soil moisture and runoff at a resolution of 0.5° × 0.5°. Wu et al. (2007) recently applied VIC to generate 35 years (1971–2005) of daily soil moisture over China at a resolution of 30 km × 30 km.

In this study, version 4.06 of VIC was used to reconstruct 60 years (1950–2009) of daily soil moisture values for three soil layers (0–20 cm, 20–100 cm, and 0–100 cm) over the three Canadian Prairie Provinces. This version of VIC includes modifications to improve its performance in cold regions and was tested using point data in the upper Mississippi River basin (Cherkauer and Lettenmaier, 1999). The freezing soil process is simulated by solving thermal fluxes through the soil column. Energy balance, based snow accumulation, and ablation algorithms are included in this version, as well as the algorithm that represents the effects of lakes and wetlands on surface moisture and energy fluxes (Cherkauer et al., 2003). In this study, VIC was applied over a grid of 4,393 points with a resolution of 0.25° × 0.25°, and was driven by daily maximum and minimum air temperature and precipitation from meteorological stations. The grid is shown in panel (a) of Figure 1. The current study is the first attempt in Canada to systematically reconstruct 60-year daily historical soil moisture conditions for the three Prairie Provinces using a macroscale hydrology model. First, VIC was calibrated and validated with observed daily hydrographs from 12 catchments, and also validated with observed soil moisture anomalies from six Alberta sites. Special attention was given to modelling rainfall-runoff processes over the non-contributing drainage area of the Prairies. The calibrated VIC model was then run over each of the 4,393 grid points to compute daily soil moisture values for the three soil layers from January 1, 1950 to December 31, 2009. The VIC simulated soil moisture was used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI; Bergman et al., 1988), which can be used as a measure of the severity of agricultural drought on a global basis. The details of SMAPI are discussed in a later section. The calculated SMAPI from each of the 4,393 grid points can be ultimately used to quantify the most documented prairie drought events of the past 60 years.

### VIC Application

#### Characteristics of Prairie Provinces

The location of the Prairie Provinces (panel (a) of Figure 1) on the lee-side of the Rocky Mountains can result in low, but highly variable, precipitation across the Prairies (Bonsal and Regier, 2007). Climatologically, the Prairies belong to semi-arid to sub-humid classes with cold and relatively long winters during which soils freeze to depths exceeding 1 m. In contrast, the Prairie summer is short but warm and dry (Phillips, 1990). Average annual precipitation is unevenly distributed, and varies from 300 mm in the relatively drier southeast corner in Alberta to over 600 mm in the southeast corner in Manitoba. Most precipitation occurs as rainfall in the growing season from April to August. The month with the lowest average precipitation is February with only 18 mm, while July usually receives the highest precipitation amount of 75 mm. Snow can contribute more than 80% of the annual local surface runoff (Gray and Landine, 1988; Pomeroy and Goodison, 1997). The mean annual temperature ranges from 0°C in the northeast of Manitoba to 5°C in the southwest corner in Alberta. As reported in many studies (e.g., Conly and van der Kamp 2001; Covich et al., 1997; Cutforth et al., 1999; Gray, 1970; Gray et al., 1985; Hayashi et al., 2003; Herrington et al., 1997; Pomeroy and Granger 1997; Pomeroy et al., 2007; Woo and Rowsell 1993), the Canadian Prairies exhibit great interannual and interseasonal variations in temperature, precipitation, streamflow, and soil moisture.

Grass is identified as the dominant type of natural vegetation in the southern regions of the Prairies, and is often associated with brown and black soil types that contain high organic matter content and are fertile. The northern Prairies are generally dominated by the boreal forest, which is one of the world’s largest remaining forest regions. The lowland forests of the boreal ecosystem in Saskatchewan and Manitoba grow on flat terrain with a mineral soil base overlain by a thin layer of live and dead non-vascular plant material. Hydrologically, the boreal lowland soils behave like a gently rolling-impermeable floor with a thin layer of cotton on top.

Topographically, there is no significant relief in the Prairies, even though three ascending levels of plains can be identified (Hare and Thomas, 1979).
Level topography and post-glacial drainage networks result in millions of small depressions or wetlands in the prairie landscape. These wetlands are also known locally as “prairie potholes” or “sloughs”. It is estimated that the wetland density in the agricultural region of southern Saskatchewan is on average of 20 sloughs per square kilometre (Huel, 2000). However, many of those wetlands may dry up completely during drought years, causing water shortages for farming and other activities. These wetlands vary in size from a few centimetres to tens of kilometres, and collect runoff primarily from the melting of snow drifts deposited during blowing snow storms (Fang and Pomeroy, 2008). They receive runoff when soils are saturated, normally during snowmelt and heavy rainfall (Hayashi et al., 2003). Since there is a lack of connection amongst these wetlands as well as to the main prairie streams, these wetlands are often internally drained and can form closed drainage catchments. Where there is internal drainage under normal conditions, these catchments are termed non-contributing areas (Godwin and Martin, 1975). The latter is likely to bring challenges to hydrological modelling in the Prairies in the current study. The non-contributing drainage areas of the three Prairie Provinces are shown in panel (b) of Figure 1, as determined by the Prairie Farm Rehabilitation Administration (PFRA Hydrology Division, 1983)

Figure 1. (a) The VIC model grid over the Canadian Prairies with 4,393 grid points, at a resolution of 0.25° × 0.25°; the dots represent the 1,167 meteorological stations used in this study. (b) The identified non-contributing drainage areas of the Prairies are shaded grey.

Figure 2. (a) The stars show the six Alberta sites where in situ soil moisture measurements are available; also shown are the seven calibration catchments (green) and five additional validation catchments (red) (see Table 2 for site details). (b) The average annual precipitation from 1950 to 2009 over the Prairies; seven sub-divisions show the VIC simulation regions (numerically ordered).
watershed project as discussed in Martin (2001). It will be shown in the results section that incorporating non-contributing drainage areas into runoff calculations can substantially improve the ability of hydrological models to simulate surface and sub-surface runoff in regions where the wetland is a dominant land cover feature, such as in regions of the southern Canadian Prairies (panel (b) of Figure 1).

VIC Calibration and Validation

The VIC model (version 4.04) was applied over the three Prairies Provinces with a total area of 1,964,000 km² to reconstruct daily soil moisture values for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) from January 1, 1950 to December 31, 2009. This version of VIC includes some of the new features described in Liang et al. (1999) and Cherkauer and Lettenmaier (1999). The VIC cold region hydrological process updates are specifically detailed in Cherkauer et al. (2003), which includes the explicit representation of the canopy energy balance separate from the land surface when snow is intercepted in the canopy, and the parameterization of the effects of spatial variability in soil freeze-thaw state and snow distribution on moisture and energy fluxes, as well as the effect of advection on snowmelt under conditions of partial snow cover. There are two modes available for running the VIC model; a water balance mode and an energy balance mode. In this study, a water balance mode is used, which employs an approximation to the relevant energy terms, e.g., the effective surface temperature is assumed equal to the air temperature. The energy balance mode was not considered as observations of shortwave radiation are not available for most of the Prairies. The modelling domain, with a resolution of 0.25" × 0.25", is shown in panel (a) of Figure 1. For each grid point, the global 10-km soil profile dataset (Reynolds et al., 2000) and the global 1-km land cover classification dataset (Hansen et al., 2000) are used to define the VIC soil and vegetation parameters. Both soil and land cover data were first aggregated into 0.25" × 0.25" cell sizes. The catchment parameters of VIC were determined using the Global 30 Arc-Second Elevation Data Set from the U.S. Geological Survey, and observed time average near-surface air temperatures and precipitation. VIC has seven user-calibrated hydrological parameters. The thickness of the first soil moisture layer is often kept constant with a value of 0.1 m; the calibration procedure is then applied to the remaining six parameters that are listed in Table 1. Detailed discussions on the methodology for the determination of VIC parameters are found in Wu et al. (2007).

The National Climate Data and Information Archive contains official climate and weather observations for Canada, which is operated and maintained by Environment Canada (2010a). In this study, VIC was driven by observed daily maximum and minimum air temperature and precipitation from 1,167 meteorological stations on the Prairies as shown in panel (a) of Figure 1. The National Water Data Archive, operated and maintained by the Water Survey of Canada (Environment Canada, 2010b), provides observed daily hydrographs for both VIC calibration and validation. In situ soil moisture measurements from six Alberta sites were only used for model validation. As shown in panel (a) of Figure 1, the meteorological stations are unevenly distributed over the Prairies with a dense coverage in Alberta and southern Saskatchewan, while most regions in northern Saskatchewan and Manitoba have scarce coverage. The continually updated meteorological dataset has been available since January 1, 1950. Some station precipitation and temperature observations have been incorporated with a number of statistical adjustments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_infilt</td>
<td>variable infiltration curve</td>
</tr>
<tr>
<td>Dmax (mm/day)</td>
<td>maximum velocity of baseflow</td>
</tr>
<tr>
<td>Ds</td>
<td>fraction of Dmax where non-linear baseflow begins</td>
</tr>
<tr>
<td>Ws</td>
<td>fraction of maximum soil moisture where non-linear baseflow occurs</td>
</tr>
<tr>
<td>d1 (m)</td>
<td>thickness of first soil moisture layer</td>
</tr>
<tr>
<td>d2 (m)</td>
<td>thickness of second soil moisture layer</td>
</tr>
<tr>
<td>d3 (m)</td>
<td>thickness of third soil moisture layer</td>
</tr>
</tbody>
</table>

Table 1. The seven VIC user-calibrated hydrological parameters.
to their original station values (Environment Canada, 2010c), and are thus quality-controlled. The daily meteorological observations were interpolated onto each of the 4,393 VIC modelling grid cells using the inverse distance weighted method.

Hydrographs were not corrected for operations of impoundments, wetland drainage, reservoirs, municipal withdrawals, industrial withdrawals and irrigation as it was not possible to obtain such information. Therefore, some calibration and validation cases are affected by such operations, for example, the South Saskatchewan River regime has been heavily modified since the early 1960s from irrigation withdrawal and the operation of Gardiner Dam, and the Qu’Appelle River has had its flows supplemented from the South Saskatchewan River since the late 1960s.

The six VIC user-calibrated hydrological parameters mentioned earlier were first calibrated using observed daily hydrographs at the outlets of each of the seven calibration catchments as shown in panel (a) of Figure 2. The total drainage areas of these catchments vary from 3,750 to 7,870 km$^2$ (Table 2) and they have minimal impoundments or withdrawals. The catchments were chosen from seven VIC simulation regions of the Prairies, which are identified in panel (b) of Figure 2. The determination of the seven simulation regions was based solely upon the characteristic of the average annual precipitation from 1950 to 2009 (panel (b) of Figure 2). The calibration process began by selecting the best parameter estimates for each model grid point of the seven calibration catchments. VIC was then forced by gridded daily maximum and minimum air temperatures and precipitation for each catchment over periods of 6-11 years, depending on the availability of observed hydrographs, with a model time step of 24 hours. An auto-optimization procedure for calibration was used based on Rosenbrock (1960). The optimization procedure uses two objective functions:

$$E_r = \frac{1}{Q_o} \sqrt{\sum_{i} (Q_{i,c} - Q_{i,o})^2}$$

$$E_c = 1 - \frac{\sum_i (Q_{i,c} - Q_{i,o})^2}{\sum_i (Q_{i,o} - \bar{Q}_o)^2}$$

where, $\bar{Q}_c$ and $\bar{Q}_o$ are the time averaged simulated and observed discharges respectively, and $E_r$ is the relative error; $Q_{i,c}$ and $Q_{i,o}$ are the simulated and observed discharge at time step $(i)$, respectively, and $E_c$ is the Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970).

Validation of the calibrated VIC over the Prairies involved the following three parts. First, VIC was validated using observed daily hydrographs from the same seven calibration catchments taken over different periods than for calibration as described in Table 2. This is the conventional procedure for validating a hydrological model. Second, VIC was further validated using observed daily hydrographs from five additional catchments with total drainage area varying from 36,500 to 131,000 km$^2$ (panel (b) of Figure 2; Table 2). As shown in panels (a) and (b) of Figure 1 and in panel (b) of Figure 2, the five additional catchments are partially covered by six of the seven simulation regions of the Prairies, with relatively dense coverage of meteorological stations, except for Churchill. The drainage areas of the five catchments are much larger than those of the seven calibration catchments. VIC was eventually applied to all seven simulation regions covering the entire Prairie Provinces to reconstruct daily soil moisture values from January 1, 1950 to December 31, 2009. In addition, many prairie catchments are ungauged. The five additional catchments were treated as ungauged, meaning that no hydrographs were available to determine model parameters through the standard calibration process. Instead, a procedure was developed to estimate the six VIC user-calibrated hydrological parameters mentioned earlier. It is assumed that the six VIC parameters optimized over the seven calibration catchments can be transferred directly onto the seven simulation regions of the Prairies. This simply means that the same set of the calibrated VIC parameters can be assigned to each model point covered by the same simulation region. In this study, the six VIC parameters of the five additional catchments were determined using the calibrated parameters from either several simulation regions or a single one. For example, the Athabasca catchment is partially covered by three simulation regions as shown in panels (a) and (b) of Figure 2; thus three sets of the calibrated parameters were used for VIC simulations over that catchment. This procedure allowed testing the transferability of the calibrated VIC parameters within the same simulation region. Thus, a total of 12 catchments were used for VIC calibration and validation; they were selected to reflect the Prairies’ various precipitation conditions and for consistency in catchment characteristics.

The main purpose of this study, however, is soil moisture prediction rather than hydrological prediction. In the third part of VIC validation over the Prairies, the
Table 2. Description of the 12 calibration and validation catchment characteristics, and results of the calibration and validation (last four columns). The catchment elevations are given in the column 9. $E_r$ and $E_c$ are the relative error and the Nash-Sutcliffe model efficiency coefficient respectively. For the column labeled “period”, the period of the calibration record is first given, followed by the validation period in brackets. For example, 94-05 (79-93) indicates the calibration record is 1994-2005, and the validation record is 1979-1993.

<table>
<thead>
<tr>
<th>Catchment</th>
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<th>Lat. ('N)</th>
<th>Long. ('W)</th>
<th>Total</th>
<th>Effective</th>
<th>Elev. (m)</th>
<th>Ave. T (°C)</th>
<th>Annual Precip. (mm)</th>
<th>Period</th>
<th>$E_r$ (%)</th>
<th>$E_c$</th>
<th>$E_r$ (%)</th>
<th>$E_c$</th>
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<td>Thompson</td>
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<td>97.36</td>
<td>6110</td>
<td>6110</td>
<td>259</td>
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<td>509</td>
<td>94-05 (79-93)</td>
<td>7.3</td>
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<td>Wheeler</td>
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<td>7730</td>
<td>7730</td>
<td>501</td>
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<td>94-05 (81-93)</td>
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<td>5</td>
<td>Whitemouth</td>
<td>Whitemouth</td>
<td>05PH003</td>
<td>49.94</td>
<td>95.96</td>
<td>3750</td>
<td>3750</td>
<td>325</td>
<td>2.1</td>
<td>593</td>
<td>94-05 (79-93)</td>
<td>19.1</td>
<td>0.70</td>
<td>-5.0</td>
</tr>
<tr>
<td>6</td>
<td>Bow</td>
<td>Calgary</td>
<td>05BH004</td>
<td>51.05</td>
<td>114.05</td>
<td>7870</td>
<td>7740</td>
<td>1953</td>
<td>-1.5</td>
<td>691</td>
<td>90-99 (00-05)</td>
<td>-0.4</td>
<td>0.87</td>
<td>7.0</td>
</tr>
<tr>
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<td>Marwayne</td>
<td>05EE007</td>
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<td>110.4</td>
<td>7270</td>
<td>3110</td>
<td>649</td>
<td>1.9</td>
<td>418</td>
<td>81-90 (91-00)</td>
<td>31.6</td>
<td>0.58</td>
<td>15.4</td>
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<tr>
<td>8</td>
<td>Athabasca</td>
<td>McMurray</td>
<td>07DA001</td>
<td>56.78</td>
<td>111.4</td>
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<td>131000</td>
<td>807</td>
<td>0.2</td>
<td>533</td>
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<td>0.62</td>
<td>-5.4</td>
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<td>9</td>
<td>Churchill</td>
<td>Otter Rapids</td>
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<td>119000</td>
<td>112000</td>
<td>523</td>
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<td>10</td>
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<td>05GG001</td>
<td>53.20</td>
<td>105.77</td>
<td>131000</td>
<td>72300</td>
<td>814</td>
<td>1.5</td>
<td>465</td>
<td>91-00</td>
<td>-5.1</td>
<td>0.69</td>
<td>-8.8</td>
</tr>
<tr>
<td>11</td>
<td>South Sask.</td>
<td>Saskatoon</td>
<td>05HG001</td>
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<td>106.64</td>
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<td>88100</td>
<td>965</td>
<td>3.0</td>
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<td>0.72</td>
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</tr>
<tr>
<td>12</td>
<td>Assiniboine</td>
<td>Brandon</td>
<td>05MH013</td>
<td>49.87</td>
<td>100.1</td>
<td>93700</td>
<td>36500</td>
<td>576</td>
<td>1.9</td>
<td>434</td>
<td>77-87</td>
<td>-5.4</td>
<td>0.77</td>
<td>-8.8</td>
</tr>
</tbody>
</table>
simulated soil moisture anomalies were compared with in situ observations from six Alberta sites. The locations of these soil moisture sites are identified in panel (a) of Figure 2. The measurements were taken daily at four vertical levels starting from near surface down to 1 m depth (5 cm, 20 cm, 50 cm, 100 cm) from January 2002 to March 2007. The six VIC user-calibrated hydrological parameters were not specifically optimized over any of the six sites. Instead, the calibrated values for the seven simulation regions of the Prairies were used in the soil moisture simulations. For example, the Lethbridge site is located in the seventh simulation region as shown in panels (a) and (b) Figure 2; the calibrated VIC parameters of this region were thus used for the soil moisture simulation over Lethbridge. As soil properties are highly heterogeneous, point soil moisture observations are typically inconsistent with model results which represent grid cell averages. Therefore, comparison of simulated soil moisture with in situ observations is problematic and an issue of active debate. Nevertheless, in situ soil moisture anomalies were used for model validation; the high resolution model simulation would also help in this respect.

In addition to VIC calibration and validation discussed above, the effect of non-contributing drainage areas on runoff calculations was studied over the five additional catchments. As shown in panel (b) of Figure 1 and panel (a) of Figure 2, and Table 2, three out of the five catchments contain large portions of non-contributing drainage areas, the exceptions being the Athabasca and Churchill River basins.

**Soil Moisture Anomaly Percentage Index (SMAPI)**

As discussed earlier, agricultural drought is an important consideration in the DRI. The precise quantification of a drought event is a classical issue and a difficult challenge in the geosciences. Several specialized drought indices have been proposed to describe four major types of drought: meteorological, hydrological, agricultural and socio-economic (Andreadis et al., 2005). The latter form can be considered the consequence of the other three physical types of drought. A useful survey on drought indices is found in World Meteorological Organization (WMO; 1975) and Heim (2000). Keyantash and Dracup (2002) evaluated the most prominent indices that measure each of the three physical types of drought using a set of six weighted decision criteria: robustness, tractability, transparency, sophistication, expendability, and dimensionality. The performance of each of the 14 evaluated drought indices is measured with an assigned value from 1 to 5 (5 being the highest). The average value of the six criteria is 3 for the Soil Moisture Anomaly Percentage Index (SMAPI) proposed by Bergman et al. (1988), which is second highest among the five evaluated indices for agricultural drought.

SMAPI was developed to characterize agricultural drought over a large area. The approach of SMAPI to defining drought severity is through measurement of the relative departure of soil moisture from the normal climate at a specific grid point or region. In this study, SMAPI was used as a measure of agricultural drought, which is defined as:

\[
SMAPI = \frac{\theta - \bar{\theta}}{\bar{\theta}} \times 100\%
\]

where, \(\theta\) and \(\bar{\theta}\) represent the current value of soil moisture and its climatology, respectively. Bergman et al. (1988) reported that SMAPI values change at a rate centered between the rapid Crop Moisture Index (CMI; Palmer, 1968) and the relatively slow Palmer Drought Severity Index (PDSI; Palmer, 1965). The rationale of using the relative soil moisture deficit rather than the absolute magnitude is because anomalies in absolute terms reflect different severities in different parts of a study domain. The absolute soil moisture deficit is thus not appropriate for the purpose of comparing drought severities at different grid points in this study. This SMAPI sensitivity study revealed that the soil moisture climatology (\(\bar{\theta}\)) has a strong influence on the calculated SMAPI values, and the current value of soil moisture (\(\theta\)) should be consistent with its climatology when calculating SMAPI. Thus, two points should be taken into consideration when calculating SMAPI for a specific region. First, a minimum of 20 years of soil moisture data should be used for the calculation of soil moisture climatology; and second, the current value of soil moisture and its climatology must come from the same data source, i.e., either observed or modelled.

SMAPI can thus be used to compare droughts in different regions. Based on an analysis of drought data from the ten sites, SMAPI values can be classified into nine categories as shown in Table 3. The proposed categories are similar to those of Palmer (1965).
Results

**Evaluation of VIC Calibration and Validation**

The calibration and validation results are shown in the last four columns of Table 2, using the relative error ($E_r$) and Nash-Sutcliffe model efficiency coefficient ($E_c$) for the total 12 catchments from the seven VIC simulation regions covering the entire Prairie Provinces (panels (a) and (b) of Figure 2). The validation period is different from the calibration period for the first seven calibration catchments as described in the table. For the five additional catchments, only validation results are provided in the last two columns of Table 2 as, in this case, the transferability of the calibrated VIC parameters within the same simulation region of the Prairies was tested.

As shown in Table 2, the values of $E_r$ and $E_c$ over the calibration period vary respectively from -23.1% to 31.6% and 0.58 to 0.87, and the average values over the seven calibration catchments are 4.6% and 0.74, respectively, indicating a satisfactory calibration. A deterministic hydrological simulation is considered good if $E_c \geq 0.7$ based on the study of Boone et al. (2004). These calibration results have some significance. This is mainly because there are many hydro-meteorological modelling conditions in the Prairie catchments that are not favourable for macroscale hydrology model applications such as VIC, e.g., semi-arid climate, flat and poorly drained terrain, snow redistribution and sublimation, snowmelt controlled by energy balance, high surface runoff over frozen soils, non-contributing drainage areas, and scarce meteorological coverage over some catchments (e.g., Odei and Geikie catchments as shown in panel (a) of Figure 1 and panel (a) of Figure 2). Also, this study is the first attempt in Canada to systematically conduct large scale calibrations of a hydrological model over the three Prairie Provinces. The calibration result seems to suggest that VIC works better where the prairie hydrological conditions mentioned above are less prevalent and, in particular, where low average annual precipitation has a strong influence on the model performance. As shown in Table 2, the best calibration ($E_r = -0.4\%$; $E_c = 0.87$) is obtained from the Bow catchment that drains the Rocky Mountains, with an annual precipitation of 691 mm, while the least favourable result ($E_r = 31.6\%$; $E_c = 0.58$) is for the Vermilion catchment that is representative of the prairie and parkland regions, receiving only 418 mm annual precipitation. Nevertheless, the calibration results are in agreement with the general consensus that hydrological models usually do not work well under arid conditions worldwide (WMO, 1975; 1986; 1992).

The following describes the validation results of VIC, which includes three parts. First, the simulated hydrographs were validated with observations over the same seven calibration catchments, but for different periods than calibration. This is a conventional procedure for hydrological model validation. As shown in Table 2, the values of $E_r$ and $E_c$ over the validation period vary respectively from -18.3% to 15.4% and 0.52 to 0.78 for the seven calibration catchments, with average values of -3.3% and 0.63, respectively, indicating a satisfactory validation. The ranges of $E_r$ and $E_c$ over the validation period are even smaller than calibration (Table 2). For example, values of both $E_c (15.4\%)$ and $E_r (0.61)$ are actually improved slightly compared to that of validation over the Vermilion catchment, with a least favourable result during the model calibration. Thus, the result of conventional model validations is successful and compatible with calibration.

The validation results of the five additional catchments (shown in panel (a) of Figure 2) are numbered 8 to 12 in Table 2. These five catchments were treated as ungauged in the model simulations, meaning that no hydrographs were available to determine model parameters through the standard calibration process. Instead, the procedure described

<table>
<thead>
<tr>
<th>Category</th>
<th>SMAPI</th>
<th>Average Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>extreme drought</td>
<td>≤ -50%</td>
<td>0.005</td>
</tr>
<tr>
<td>severe drought</td>
<td>-50% to -30%</td>
<td>0.020</td>
</tr>
<tr>
<td>moderate drought</td>
<td>-30% to -15%</td>
<td>0.100</td>
</tr>
<tr>
<td>mild drought</td>
<td>-15% to -5%</td>
<td>0.200</td>
</tr>
<tr>
<td>near normal</td>
<td>-5% to 5%</td>
<td>0.350</td>
</tr>
<tr>
<td>slightly wet</td>
<td>5% to 15%</td>
<td>0.200</td>
</tr>
<tr>
<td>moderately wet</td>
<td>15% to 30%</td>
<td>0.100</td>
</tr>
<tr>
<td>very wet</td>
<td>30% to 50%</td>
<td>0.020</td>
</tr>
<tr>
<td>extremely wet</td>
<td>&gt; 50%</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 3. Soil moisture classifications based on the Soil Moisture Anomaly Percentage Index (SMAPI).
earlier was used to estimate the six VIC user-calibrated hydrological parameters for each grid point of the five catchments. As shown in Table 2, the values of $E_r$ and $E_c$ over the validation period vary respectively from -5.1% to 16.0% and 0.52 to 0.77 for the five catchments, with average values of 2.2% and 0.65, respectively, indicating a satisfactory validation. The least favourable result ($E_r = 16.0\%; E_c = 0.52\%$) is for the Churchill catchment, which is representative of the northern prairies and contains many lakes; the annual precipitation is 451 mm. As shown in both panels (a) of Figures 1 and 2, a scarce coverage of meteorological stations over the Churchill catchment will also affect the performance of VIC. It is noted that both $E_r$ and $E_c$ values tend to be evenly distributed during the model validation over the five additional catchments, and are compatible with the validation results of the seven calibration catchments as shown in Table 2. Thus, the transferability of calibrated VIC parameters within the same simulation regions of the Prairies can be considered successful in this study. Therefore, it was considered possible to apply VIC over the seven simulation regions covering the entire Prairie Provinces to reconstruct daily soil moisture values from January 1, 1950 to December 31, 2009.

In the third part of VIC validation, *in situ* soil moisture measurements from six Alberta sites were used to further validate the model. As shown in panels (a) and (b) of Figure 2, the six sites are located in three different simulation regions of the Prairies, and have low values of annual precipitation (Table 4) comparable to the average semi-arid to arid prairie climate. The latitude and longitude of the six sites and the corresponding VIC modelling grid coordinates are provided in Table 4. VIC was not specifically calibrated for any of these six grid points. Instead, the calibrated values for the seven simulation regions were used in the soil moisture simulations. The simulated soil moisture represents the average of a $0.25^\circ \times 0.25^\circ$ grid cell. The last three columns of Table 4 show the correlation coefficient ($r$) of simulated and observed soil moisture anomalies for the six sites, for depths of 0-20 cm, 20-100 cm, and 0-100 cm. In general, VIC reproduces reasonably well the observations over most sites as measured by the correlation coefficients, indicating satisfactory model performance. The Lethbridge site of southern Alberta has the best simulation results, with correlation coefficients of 0.67, 0.65, and 0.69 for the three depths. However, the model performed poorly at the Fort Vermillion site of northern Alberta, and shows a negative value of $r$ for the depth of 20-100 cm (Table 4). One obvious reason for the poor performance of VIC over this site is because the six VIC user-calibrated hydrological parameters are not optimized over any of the six sites. Another likely explanation might be the scarce coverage of meteorological stations over northern Alberta as shown in panel (a) of Figure 1. A similar discussion of the issue has been reported by Wu et al. (2007).

### Effect of Non-Contributing Drainage Areas

As discussed earlier, millions of small wetlands in the Prairies constitute countless numbers of internally closed drainage basins or non-contributing drainage areas. Such wetlands are often remote and difficult to measure, yet they are important for the hydrology of the region. VIC was not specifically calibrated for any of these six grid points. Instead, the calibrated values for the seven simulation regions were used in the soil moisture simulations. The simulated soil moisture represents the average of a $0.25^\circ \times 0.25^\circ$ grid cell. Table 4 shows the correlation coefficient ($r$) of simulated and observed soil moisture anomalies for the six sites, for depths of 0-20 cm, 20-100 cm, and 0-100 cm. In general, VIC reproduces reasonably well the observations over most sites as measured by the correlation coefficients, indicating satisfactory model performance. The Lethbridge site of southern Alberta has the best simulation results, with correlation coefficients of 0.67, 0.65, and 0.69 for the three depths. However, the model performed poorly at the Fort Vermillion site of northern Alberta, and shows a negative value of $r$ for the depth of 20-100 cm (Table 4). One obvious reason for the poor performance of VIC over this site is because the six VIC user-calibrated hydrological parameters are not optimized over any of the six sites. Another likely explanation might be the scarce coverage of meteorological stations over northern Alberta as shown in panel (a) of Figure 1. A similar discussion of the issue has been reported by Wu et al. (2007).
areas inside many prairie catchments, which poses particular challenges to the effort of hydrological modelling over these catchments. As shown in columns 4 and 5 of Table 5 and in panel (b) of Figure 1 and panel (a) of Figure 2, three of the five additional validation catchments contain large portions of non-contributing drainage areas. For example, the effective drainage area is only 39% of the total drainage area in the Assiniboine catchment, meaning that the runoff generated over 61% of the total area will not contribute to the hydrographs at the Brandon station situated at the outlet of the Assiniboine catchment.

In order to illustrate the effect of non-contributing drainage areas on runoff calculations, the six VIC user-calibrated hydrological parameters were calibrated using observed daily hydrographs at the outlets of each of the five additional catchments. VIC was calibrated over each catchment with and without consideration of the effect of non-contributing drainage areas in model runoff calculations. The areas are assumed to be stationary during VIC integrations. The results of the two-phase calibrations over the five additional catchments are shown in the last four columns of Table 5. Panels (a) and (b) of Figure 3 show the observed and the two-phase calibrated hydrographs at the outlets of South Saskatchewan and Assiniboine catchments. The effect of non-contributing drainage areas on runoff calculations can be clearly demonstrated by the statistics reported in the table as well as by the figure. As shown in Table 5, the values of $E_r$ and $E_c$ over the phase-one calibration vary respectively from 0.9% to 14.0% and 0.72 to 0.91 for the five additional catchments, with average values of 6.6% and 0.80, respectively, indicating a satisfactory calibration. The best calibration is obtained for the South Saskatchewan catchment (panel (a) of Figure 3), where the values of $E_r$ and $E_c$ are 3.1% and 0.91, respectively. This catchment has 38% non-contributing drainage areas as shown in Table 5. It is noted the the results of phase-one calibration over the five additional catchments are compatible with the calibration results of the seven calibration catchments as discussed earlier, which shows a consistent VIC performance over different prairies catchments.

In contrast to the phase-one calibration, almost no rainfall-runoff relations can be found from the results of phase-two calibration in two out of the five additional catchments as shown in Table 5. Negative values of $E_c$ are obtained for the North Saskatchewan and Assiniboine catchments; both of them contain large portions of non-contributing drainage areas. For example, the values of $E_r$ and $E_c$ are 163.2% and -2.23, respectively, over the Assiniboine catchment, indicating a complete failure of the calibration. As shown in panel (b) of Figure 3, the total runoff volume for the phase-two calibrated hydrograph is significantly overestimated compared to the observation over the Assiniboine catchment. However, the peak flow timing is well simulated for all flood events during the 11-year model calibration (1977-1987). This result shows clearly the direction of potential improvement in the VIC calibration, which is to improve the runoff calculation in this case. Coincidently, the non-contributing drainage areas occupy up to 61% of the total area of the Assiniboine catchment as shown in Table 5; the runoff generated over these areas do not

<table>
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<th>Catchment</th>
<th>Station</th>
<th>Total Drainage Area (km²)</th>
<th>Effective Drainage Area (km²)</th>
<th>Period</th>
<th>$E_r$ (%)</th>
<th>$E_c$ (%)</th>
<th>Without non-contributing area</th>
</tr>
</thead>
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<tr>
<td>8 Athabasca</td>
<td>McMurray</td>
<td>133000</td>
<td>131000</td>
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<td>14.0</td>
<td>0.81</td>
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<td>9 Churchill</td>
<td>Otter Rapids</td>
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<td>112000</td>
<td>63-05</td>
<td>9.9</td>
<td>0.72</td>
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<tr>
<td>10 North Sask.</td>
<td>Prince Albert</td>
<td>131000</td>
<td>72300</td>
<td>91-00</td>
<td>0.9</td>
<td>0.80</td>
<td>53.4</td>
</tr>
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<td>Saskatoon</td>
<td>141000</td>
<td>88100</td>
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<td>0.91</td>
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<tr>
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<td>Brandon</td>
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<td>36500</td>
<td>77-87</td>
<td>5.3</td>
<td>0.77</td>
<td>163.2</td>
</tr>
</tbody>
</table>

Table 5. Results of the two-phase model calibrations over the five additional validation catchments. The two-phase calibration means that VIC is calibrated with and without considering the effect of non-contributing drainage areas in model runoff calculations. $E_r$ and $E_c$ are the relative error and the Nash-Sutcliffe model efficiency coefficient, respectively.
contribute to the formation of hydrographs at the outlet of the catchment. Conversely, there is almost no difference between the results of the two-phase calibrations when VIC is calibrated over the Athabasca and Churchill catchments as shown in Table 5. These two catchments contain only 1.5% and 5.9% non-contributing drainage areas, respectively.

**Reconstructing Prairies’ Soil Moisture from 1950 to 2009**

Figure 4 shows the VIC reconstructed 60-year (1950-2009) average of the soil moisture in the top 1 m for the three Prairie Provinces along with the 200 mm soil moisture contour, showing modelled very dry areas. Alberta Agriculture studied the classification of soil moisture contents using field sampling and modelling approaches, and grouped the soil moisture content into four broad categories from high to very low depending upon the available moisture in soil columns (Howard et al. 1992). The 20% of soil moisture content (or 200 mm in this case) is the threshold for the category of very low. Thus, the 200 mm threshold was used to analyze the VIC soil moisture results and to identify very dry areas of the Prairies.

As shown in Figure 4, the distribution of VIC reconstructed 60-year average soil moisture shows some expected climatological features of the Prairies. Regional dry and wet areas can be seen clearly in the figure. There is a clear diagonal belt of wet to medium wet areas starting from the northwest corner in Alberta and passing though central regions of Saskatchewan and extending to the southeast corner in Manitoba. There are several very dry areas that have been identified using the 200 mm threshold. These areas lie on both sides of the diagonal belt. The simulated wet region corresponds to the boreal forest with the dry areas being the prairies to the south and tundra to the north. Soil moisture contents in most southern regions of the Prairies are either low or very low, as shown in Figure 4, and give clear evidence of arid and semi-arid characteristics. It is also noted that the distribution of VIC reconstructed soil moisture compares well qualitatively with the chart of available water capacity (AWC) of the southern Canadian Prairies in Nkemdirim and Weber (1999). The AWC was estimated based on field survey and previous studies of Jones (1984) and Smit (1989). VIC reconstructed wet and dry areas are closely related to the local soil textures as well as annual precipitation. As mentioned earlier, the global 10-km soil profile dataset of Reynolds et al. (2000) was used for setting up VIC in this study. Sandy loam is the dominate type of soils for both Rocky Mountains in Alberta and the regions of northeast Saskatchewan and northwest Manitoba; these are regions of exposed rock with thin soils. It is well known that moisture in soil columns cannot be easily retained in a sandy loam soil due to its large values of porosity and saturated hydraulic conductivity. The two sandy loam regions have been identified as very dry areas using the 200 mm threshold (Figure 4). The two areas are covered by the first, second and seventh simulation regions as shown in panel (b) of Figure 2; and the seventh region receives the highest annual
precipitation, on average, in the Prairies. On other hand, clay is the dominate soil type for the modelled wet areas in eastern Manitoba (Figure 4), while the areas receive a moderate annual precipitation in the Prairies (panel (b) of Figure 2). Thus, the nature of soils could be another important contributing factor for prairie susceptibility to drought, next to the lack of precipitation.

Perhaps the most important finding in Figure 4 is the identification of the Palliser Triangle region and the Prairie Dry Belt (Jones, 1987) in southern Prairies. Palliser Triangle is named after the Captain John Palliser, who was not optimistic about the settlement potential of the roughly triangular region mainly due to the drought that prevailed in that area during his visit in the 1850s (Nkemdirim, 1991). The VIC reconstructed 60-year soil moisture climatology accurately portrays both the dry Palliser Triangle region and Prairie Dry Belt in the southern Prairies. In particular, most of the Prairie Dry Belt is identified as very dry, where the VIC 60-year averages of the soil moisture in the top 1 m are less than the 200 mm threshold.

Calculation of Prairies’ Daily SMAPI

As discussed earlier, the VIC reconstructed daily soil moisture was used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI), which can be used as a measure of the severity of agricultural drought on a global basis. Daily SMAPI was calculated for the three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) at each of the 4,393 grid points covering the entire Prairie Provinces (panel (a) of Figure 1). The calculation period is from January 1, 1950 to December 31, 2009. The value of the calculated SMAPI in quantifying and documenting prairie drought events is demonstrated through an intensive examination of the April 2002 drought case below.

Figure 5 shows the SMAPI distributions of the three soil layers for April 20, 2002, together with the April 2002 average of the SMAPI in the top 1 m for the entire Prairie Provinces. As mentioned already, the most recent prairie drought of 1999-2005 peaked during the years of 2001 and 2002. Panel (a) of Figure 5 shows the distribution of SMAPI for the 0-20 cm depth; a few scattered moderate droughts (-30%<SMAPI<-15%; see Table 3) can be identified in the central and northeast regions of Saskatchewan and the northwest region
of Manitoba, indicating a moderate situation of soil moisture stress in the near surface layer over the Prairies on April 20, 2002. However, the situation is significantly different in the rooting zone of 20-100 cm as shown in panel (b) of Figure 5, as the memory of soil moisture in the deeper layer is much longer than that near the surface. Several severe droughts (-50% < SMAPI < -30%) and extreme droughts (SMAPI < -50%) can be clearly identified in the southeast areas of Alberta, the central to southern regions of Saskatchewan, and the southwest corner of Manitoba. For example, an extreme drought had been occurring in the area between Saskatoon and Prince Albert on April 20, 2002, which is shown in panel (b) of Figure 5. Not surprisingly, the distribution of SMAPI for the 0-100 cm depth (panel (c) of Figure 5) is very much similar to that for the rooting zone, as the calculation of SMAPI for the 0-100 cm depth considers 80% of the rooting zone’s contribution.

Daily SMAPI values can be aggregated into temporal averages for specific periods (e.g., week, month, seasonal, and annual) for diagnostic purposes, including drought onset, duration, cessation, areal extension, and severity. For example, panel (d) of Figure 5 shows the April 2002 average of the SMAPI in the top 1 m. Large scale droughts can be clearly seen in the southeast areas of Alberta, the central to southern regions of Saskatchewan, and the southwest corner of Manitoba. If the April 2002 average of SMAPI is combined with the corresponding daily SMAPI values, it is clear that these regions had been undergoing a severe situation of soil moisture stress for the month of April 2002. Most of the drought regions identified in

Figure 5. The VIC based SMAPI (Soil Moisture Anomaly Percentage Index) distributions of three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) for April 20, 2002 (2002-4-20), together with the April 2002 (2002-4) average of the SMAPI in the top 1 m for the Prairies.
panels (b, c, d) of Figure 5 should normally be covered by the non-contributing drainage areas as shown in panel (b) of Figure 1. However, many of the wetlands on the Prairies might dry up completely during drought years as reported in many previous studies based on field surveys. The SMAPI results have reconfirmed these studies using large scale model simulations. Ongoing research involves examining studies and reports of Prairies’ drought history from 1950-2009, together with SMAPI results. Preliminary results indicate that the reconstructed daily soil moisture and SMAPI correlate well in both time and space with the recent severe drought of 1998-2005 over the Prairies. These results will be reported in a future publication.

Conclusions

This study used the VIC land surface macroscale hydrology model to reconstruct 60 years (1950-2009) of daily soil moisture values for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) over the Canadian Prairies (1,964,000 km²). VIC was applied over a grid of 4,393 points with a spatial resolution of 0.25° × 0.25°, and was driven by observed daily maximum and minimum air temperature and precipitation from 1,167 meteorological stations. VIC was calibrated and validated using observed daily hydrographs from 12 catchments, and also validated using observed soil moisture anomalies from six Alberta sites. Special attention was given to modelling rainfall-runoff processes over the non-contributing drainage areas of the Prairies. An estimation procedure to determine VIC parameters was developed and applied to catchments where hydrographs were not available for the standard calibration process. The calibrated VIC model was run over each of the 4,393 grid points to compute daily soil moisture values for the three soil layers from January 1, 1950 to December 31, 2009. The VIC simulated soil moisture was used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI), which is as a measure of the severity of agricultural drought. This study is the first attempt in Canada to systematically reconstruct daily historical soil moisture conditions for the Prairies using a macroscale hydrology model.

A satisfactory VIC calibration and validation were obtained over the 12 catchments as revealed by favourable values of the relative error and the Nash-Sutcliffe model efficiency coefficient. The simulated soil moisture anomalies agree reasonably well with in situ observations from six Alberta sites. The results also clearly demonstrate that incorporating non-contributing drainage areas into runoff calculations substantially improved the ability of VIC to simulate surface and sub-surface runoff in regions where poor drainage network development is a dominant feature of drainage basins.

The VIC reconstructed 60-year (1950-2009) average of the soil moisture in the top 1 m shows some of the expected climatological features of the Prairies. For example, the reconstructed soil moisture climatology accurately portrays the dry Palliser Triangle region and the Prairie Dry Belt (Jones, 1987) in the southern Prairies. The value of the calculated SMAPI in quantifying and documenting prairie drought events was demonstrated through an intensive examination of the April 2002 drought case.

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