SUBSURFACE MOISTURE STORAGE PATTERNS DERIVED FROM HYDROLOGIC MODEL AND SATELLITE MEASUREMENTS DURING EXTREME PERIOD OF DRYNESS

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by

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Author's Declarations

I hereby declare that I am the author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by the examiners.

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Abstract

Spatially distributed subsurface soil moisture dataset with suitable temporal scale are needed for a better understanding of the mechanisms responsible for the recurrent drought outbreaks over the Canadian Prairie. However, there are no soil moisture data at depths exceeding a few centimeters over the Canadian Prairie sub-catchments thereby placing enormous constraints on the feasibility of studies that require such information. Hence, this thesis explores the use of a physically based, spatially distributed hydrologic model in reproducing the patterns of the spatial and temporal distribution of soil moisture over the drought-prone 13,000 km^2 Upper Assiniboine River Basin (UARB) in the Canadian Prairie. Prior to making any inferences on the spatial and temporal dynamics of the simulated subsurface soil moisture over this large domain, a necessary requirement was to validate the model's simulated output of other hydrologic variables. These validations were accomplished using observed measurements of streamflow, snow depth, moisture storage change from geological weighing lysimeters and estimates of the total water storage from the Gravity Recovery And Climate Experiment (GRACE) remote sensing satellite system. After an assessment of the simulated outputs from the Variable Infiltration Capacity (VIC) model, which were found to be of acceptable quality, this thesis thereafter focused on assessing the spatial distribution of the subsurface soil moisture over the large catchment. Therefore, in the first case study undertaken in this thesis, it was demonstrated that with a structurally sound model (one equipped with adequate land surface parameterization) such as the VIC model, it is possible to generate soil moisture datasets at different spatial and temporal scales for use in areas such as the Canadian Prairie and other geologically complex terrains where observed soil moisture measurements are lacking.

Furthermore, retrieval of the terrestrial moisture storage dataset from the Gravity Recovery And Climate Experiment (GRACE) satellite remote sensing system is possible when the catchment of interest is of large spatial scale. These dataset are of paramount importance for the estimation of the total storage deficit index (TSDI), which enables the characterization of a particular drought event from the perspective of the terrestrial moisture storage over that catchment. Incidentally, the GRACE gravity signal over the

13000 km^2 Upper Assiniboine River Basin on the drought-prone Canadian Prairie is so poor therefore making the computation of the total storage deficit index for this basin infeasible. Consequently, the estimation of the terrestrial moisture storage from other reliable sources becomes imperative in order to enable the computation of the TSDI over this basin.

In the second case study undertaken in this thesis, simulation of the total moisture storage over the Upper Assiniboine River Basin was accomplished utilizing the spatially-distributed land surface model, VIC, which was then employed in the estimation of the TSDI over this basin for subsequent characterization of the recent Prairie-wide drought. Interestingly, the resulting temporal patterns in the computed TSDI from the land surface model reveal a strong resemblance with the same drought characterization undertaken over the larger adjacent Saskatchewan River Basin, which was accomplished utilizing terrestrial moisture storage from the GRACE-based approach. In this second case study, it has been shown that in the computation of the total storage deficit index over small-scale catchments during anomalous climatic conditions that propagate extreme dryness through the terrestrial hydrologic systems, simulations of the total water storage from a structurally sound model such as the VIC model could be resourceful for the computation of the monthly total storage deficit index if no constraint is placed on the availability of accurate meteorological forcing.

Finally, understanding the memory in land surface processes, such as that in the subsurface moisture storage has great implication for seasonal weather prediction over a catchment. However, given that there are no physical observations of soil moisture at depths of hydrological importance or measurements of the total water storage, it is infeasible to undertake studies on land-atmosphere interactions. In the last case study undertaken in this thesis, effort is focused on estimating the memory in the simulated deep soil moisture and total water storages over the 406,000 km^2 Saskatchewan River Basin (SRB) in the Canadian Prairies. Finally, given the similarity in the simulated deep moisture storage anomaly and the model-based TSDI, it was inferred that the former could serve as a descriptor of drought over this large Prairie sub-catchment.

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Chapter 1

Introduction

1.1 Background

Water availability in terms of its quantity and quality has myriad implications for the existence of all fauna and flora irrespective of their natural habitats and humans, the most advanced of all animal species, need water for multifarious purposes ranging from domestic through industrial to agricultural uses. Water availability in most regions of the globe is highly limited owing to frequent drought outbreaks, which spell harsh consequences on people that live in these areas. Droughts are complex natural hazards with multifarious definitions depending on the location and the usage to which water is put to in a specific region, hence, it is not uncommon to see people speak of all kinds of droughts from one location to the other. For instance, Manitoba Hydro, an electric energy and natural gas company located in one of the Canadian Prairie Provinces (Manitoba) could speak of drought from the point of view of insufficient water level needed to drive its turbines to generate electricity for its customers; whereas within the same time frame, majority of the residents of Saskatchewan, an adjacent Province to Manitoba, would rather approach the definition of drought from the perspective of insufficient available water required to support diverse forms of agricultural practices. Whatever definition is chosen to characterize the onset of a drought condition in a region, the fact remains that shortage of water poses a great deal of threat to nature, quality of life and the economy.

In comparison with other natural hazards such as flash floods, earthquakes and tsunami, drought occurrences are considered as far lesser threats and thus attracts far less attention in terms of government expenditures with respect to forecasting and prediction, committed approach to its science as well as prevention and control. This is so because drought develops very imperceptibly and remains unnoticeable for a very long time until its impacts become very grave and widespread. This insidiousness of drought occurrence makes it appear less threatening, less destructive and hence, many governments and non-governmental organizations globally have paid very little or no attention to its study. Droughts are recurring aspects of weather and climate extremes as are floods and tornadoes, but they differ substantially since they have long durations and lack easily identified onsets and terminations (Canada DRI, 2005).

Effective assessment of the patterns of the moisture storage in the subsurface profile up to a depth of a few centimeters over Canadian Prairie sub-catchments during drought episodes and non-drought periods depends on the accurate simulation of the streamflow and other components of the water budget in this region. However, the Canadian Prairie is characterized by recurrent droughts with widespread negative impacts spanning health through economic to social implications. In accordance with the Canadian Science and Environment bulletin (2003), drought occurrence remains the most expensive natural disaster in Canada and the most recent drought (1999-2004) in this region cost over $5 billion dollars with respect to mitigating its impacts on the agricultural sector alone. In a review of natural hazards in Canada, it was observed that over 70% of the natural hazards that occurred in Canada as a whole was concentrated on the Canadian Prairie sub-basins and over 80% of these natural hazards are drought occurrences of varying severities and intensities.

Given that the mitigation of the myriad negative impacts of drought on humans as well as on flora and fauna can be extremely expensive, unfortunately till date, there is inexistence of comprehensive water and energy budget studies on the Canadian Prairie to enhance future predictability of drought. Szeto (2007). Drought studies over a region cannot be adequately conducted without a closure on the water and energy budgets over such a region. In light of this, the Canadian Drought Research Initiative network (Canada DRI) was set up comprising scientists from various research backgrounds with the key objective of understanding the physical characteristics and processes responsible for the initiation, continuation and cessation of the recent Prairie-wide drought (Yirdaw et al., 2008). An agreement was thus reached by this group of scientists that a system of sustained research was desirable in order to better contribute to future drought prediction via a comprehensive and effective modeling of the watershed.

Moreover, reproduction of observed streamflow at a number of catchment outlets corresponding to the Water Survey of Canada (WSC) streamflow gauge stations over the Canadian Prairie sub-catchments via deploying different watershed models can be a daunting task. This is so because a greater proportion of these Prairie catchments are dominated and influenced by the presence of millions of small isolated wetlands often referred to as sloughs and potholes which play significant role in dictating the patterns of observed streamflow at the different basins' outlets. These sloughs have been found to constitute over 14% of the Canadian Prairie landscape, (Price et al., 2005), thereby constituting a source of enormous challenge when attempting to deploy catchment-scale models to capture the dynamics of runoff generation processes in this terrain.

Additionally, the above-stated problems associated with the dominance of wetlands and sloughs over Canadian Prairie sub-basins is compounded by the inexactness in determining the spatial extent of the contributing and non-contributing areas to runoff generation owing to the ever-changing nature of the wetlands' landscapes. The Canadian Prairie wetland hydrologic condition have been observed to be strongly affected and correlated with the effects of climate change as well as the changes in the land use in the surrounding uplands. Melt water from snow are received by these isolated wetlands at the end of the winter season in accordance with Winter (1989), and during the summer season, the accumulated water in these wetlands gets depleted via evapotranspiration from the open water surface as well as from the wetland vegetation (Hayashi et al., 1998a and Millar, 1971). Hence, water input to these catchments in the form of precipitation is mainly lost through evapotranspiration from the wetlands and does not eventually runoff to the rivers and streams as would be expected in most traditional watershed models. The storage of runoff by sloughs and wetlands could be of hydrological advantage during flood occurrence as they are crucial in slowing down discharge into stream and rivers, thereby helping to reduce flood peaks (Pomeroy et al., 2005).

1.2 Thesis Objectives

In order to understand the dynamics of moisture storage processes over a large domain that is characterized by incessant drought occurrence coupled with the challenges of watershed modeling due to the topographic complexity arising from the effects of wetlands storages, a number of different issues would need to be addressed. However, this thesis aims to address the following important objectives as they relate to the Canadian Prairie sub-catchments during anomalously dry periods as well as for normal years.

- Undertake a comprehensive water and energy budget studies of the Upper Assiniboine and Saskatchewan River Basins pre-, intra- and post recent Canadian Prairie-wide drought outbreak (1999 – 2004) employing the land surface scheme, the Variable Infiltration Capacity (VIC)
- Quantitatively assess the simulated total moisture storage change from a physically-based, spatially distributed hydrologic model utilizing total water storage change estimates from the Gravity Recovery And Climate Experiment (GRACE) remote sensing system as well as total water storage change estimates from the areally integrated geological weighing lysimeters
- Estimate the Total Storage Deficit Index (TSDI; Yirdaw et al., 2008) from a physically based, spatially distributed hydrologic model over the Upper Assiniboine River Basin on the Canadian Prairie where the GRACE-derived total moisture storage signal is poor. Additionally, to undertake an assessment

of the correlation if any between the model-derived TSDI with that computed from the GRACE technique would be undertaken

- Employ relevant statistical techniques in the estimation of the inherent memory in the simulated soil moisture store from a physically based, spatially-distributed hydrologic model driven with observation-based forcing over the 406,000km^2 Saskatchewan River Basin
- Computation of the persistency in the simulated total water storage and subsurface soil moisture simulated from a land surface model as well as those in the atmospheric fields of precipitation, net radiation and evapotranspiration to ascertain the level of relationship that exists between these variables over the study domain; and
- To quantitatively evaluate and inter-compare the memory in the computed monthly terrestrial storage deficit index (TSDI; Yirdaw et al., 2008) from a hydrological model and that estimated from the terrestrial moisture storage retrieved from the Gravity Recovery And Climate Experiment (GRACE; Tapley et al., 2004) satellite remote sensing system

1.3 Motivation

The underlying motivation for this thesis stems from the complexity associated with adequately deploying a watershed model to simulate the patterns of streamflow over the Canadian Prairie, which is directly linked with the problem of quantifying the contributing and non-contributing areas to runoff generation over Canadian Prairie sub-catchment. Given that the cost of mitigating the negative impacts of a drought outbreak can be extremely high and especially, it can be much higher during periods of economic recession as the world faces currently, it is of paramount importance to understand the key processes responsible for the initiation, continuation and cessation of incessant drought occurrence over the Canadian Prairie. A number of stakeholders ranging from the government through to the insurance and power-generating companies as well as farmers are all keen to know how dry or wet the subsequent year would look like to be better prepared to adapt to the changing climate conditions.

However, in order to fully understand the processes in the lower atmospheric boundary, which might lead to anomalous dry conditions (precipitation deficit), there is a need to understand the intricate processes taking place in the land surface system since there are strong interactions existing between the land surface processes and the lower atmosphere. The subsurface soil moisture is one such hydrologic variable in the terrestrial system that strongly influences the atmosphere. In recent times, the subsurface soil moisture in the Canadian Prairie sub-catchments has been adduced as one of the principal slow drivers of the Canadian Prairie incessant drought. Incidentally, given that there are no soil moisture measurements at depths of interests in the Canadian Prairie sub-basins, it becomes almost infeasible to undertake detailed land surface-atmosphere interaction studies in these basins. In light of these issues and challenges, it becomes necessary to undertake a research that could help address some of these problems as well as provide important dataset that could prove resourceful to other researchers working in the Canadian Prairie to address drought-related issues.

1.4 Thesis Hypothesis

It is hypothesized in this thesis that given the myriad constraints posed due to unavailability of measured soil moisture data over the drought-prone Canadian Prairie sub-catchments such as, in the Saskatchewan and Upper Assiniboine River Basin, it is possible to overcome this challenge by relying on the simulated output of the soil water content from a structurally-sound and physically-based hydrological model such as, the Variable Infiltration Capacity (VIC) model. It is also hypothesized that the patterns in the deep moisture store simulated from this land surface model can serve as an indicator of extreme dryness over the Canadian Prairie sub-basins.

1.5 Contribution to Scientific Research

There are four main contributions to the hydrology of droughts arising from the research completed in this thesis and these are;

- Successful deployment of a land surface model over Canadian Prairie sub-catchments, which are heavily dominated by wetlands, sloughs and potholes.

  Inexistence of comprehensive water and energy budget studies to enhance future predictability of drought occurrence on the Canadian Prairie has been a major concern to the community of researchers working in this region. Hence, one main contribution of this research lies in the successful deployment of a land surface model over the Canadian Prairie sub-catchments, which are heavily dominated by sloughs and potholes. By carefully calibrating and validating the land surface model over the Canadian Prairie sub-catchments, new and reliable moisture storage dataset as well as other state variables with high spatial and temporal resolutions are now made available to scientists working as part of the Canadian Drought Research Initiative (Canada DRI) who are charged with the key responsibility of ascertaining the dominant processes leading to the evolution, continuation and cessation of the recurrent Prairie-wide droughts.

- Development of the Total Storage Deficit Index (TSDI) for Canadian Prairie drought characterization and monitoring.

This thesis has also pioneered the development of a new index referred to as the total storage deficit index (TSDI) for the characterization and monitoring of drought episode using simulation outputs from a hydrologic model for smaller- and medium-size catchments in drought-prone regions. This is an important accomplishment given that the dataset for the computation of the TSDI are generally retrieved from the GRACE gravity measurements over very large basins. However, GRACE signals are generally weak for smaller size catchments owing to the large spatial scale associated with its coverage; therefore, in the event of drought outbreaks over these catchments, it is impossible to compute the TSDI relying on the derived terrestrial moisture storage from GRACE. Under this circumstance, it has been demonstrated in this thesis that such a problem can be overcome by utilizing total moisture storage dataset derived from a structurally sound land surface model.

- The use of GRACE-derived as well as geological lysimeter estimate of the total moisture storage as additional validation data sources for the computed change in total moisture storage simulated from the Variable Infiltration Capacity (VIC) model over Canadian Prairie sub-catchments.

Land surface models have had their internal parameters traditionally calibrated and validated by adjusting them until the simulated hydrologic response, which is usually the simulated streamflow, matches existing historical observed discharge data. However, it has to be emphasized that accurately simulating a streamflow record at a catchment's outlet does not necessarily indicate that the internal parameters of the model have been carefully optimized or that the model structures are robust enough to capture the relevant hydrologic processes over such a catchment. It could simply mean that the evapotranspiration scheme within the model for instance, may have performed poorly in accounting for the moisture loss over such a catchment thereby giving rise to accurate or near-accurate simulated streamflow record. A more holistic approach to assessing a model's performance would need to evaluate the model's computation of the total moisture storage. This research would be one of the first attempts in using GRACE-derived as well as geological lysimeter estimate of the total moisture storage as additional validation data sources for the computed change in total moisture storage simulated from the Variable Infiltration Capacity (VIC) model over the Canadian Prairie sub-catchments.

- Successful assessment of the deep moisture storage memory and its role as a slow driver of Canadian Prairie drought.

By estimating inherent memories in the anomalies of the simulated subsurface moisture storage as well as in other hydroclimatological variables over the Canadian Prairie sub-catchments, this thesis has further demonstrated that the anomalies in the deep moisture store simulated from the VIC hydrologic model can serve as a better predictor of the recurrent Canadian Prairie droughts than does any of the atmospheric fields over this domain. This finding is significant in that it is novel and it corroborates one of the underlying hypotheses of this thesis.

1.6 Atmospheric and Oceanic Indices for Drought Monitoring

Although, this thesis focuses mainly on using a physically-based hydrological model for the reproduction of the temporal and spatial patterns of the 1999-2004 Canadian Prairies hydrological drought from the perspective of subsurface moisture storage, it is imperative at this point to briefly discuss different Atmospheric and Oceanic patterns that may serve as mechanisms for the frequent prairie drought. Most of the discussion in this section is based essentially on the climatological assessment report developed by the Alberta Department of Environment for the Canadian Prairie drought. An earlier study by Dey and Chakravarty (1976) identified the presence of a mid-tropospheric ridge centered over the Prairie Provinces, which culminates in extended dry spells and precipitation deficits during the summer season. Similarly, Bonsal et al. (1999) extended this idea by attempting to develop a causal relationship between the patterns of the sea surface temperatures (SST) over the North Pacific and the extended dry spells over the Canadian Prairies. In this later study, it was found that a certain configuration of the SST pattern-anomalously cold water over an area between 140 and 160°W longitude and centered around 30°N latitude in conjunction with anomalously warm water off the coast of northern British Columbia are favorable for the development of a mid-tropospheric ridge over the prairies. This ridge development was noted to result in extended dry spells and drought during the summer season.

Moreover, the influence of large-scale atmospheric and oceanic flow patterns on the Canadian Prairies' weather and climate and specifically on the prairie grain yields which have been documented in several studies (Handler, 1990; Garnett and Khandekar, 1992; Garnett, 2002) have shown that, in general, El Nino (La Nina) events in the equatorial eastern Pacific are associated with drier (wetter) winter months immediately following these events and wetter (drier) spring to summer months on the Canadian prairies. This analysis has also led to a hypothesis, now generally accepted, that El Nino and La Nina play important roles in Canadian Prairies' agriculture. Also, it has equally been shown in these earlier studies that rains and grain yields (corn in the U.S. and wheat in Canada) are higher during the summer following an El Niño event whilst grain yields are correspondingly lower in the summer following a La Nina event.

The North Atlantic Oscillation (NAO) has been extensively studied in a number of earlier works (Hurrell, 1995; Hurrell and van Loon, 1997) and has been recognized as having a significant impact on temperature and precipitation patterns over eastern Canada. This impact is believed to extend occasionally into central Canada and eastern prairies. From several studies to assess the causes of droughts over the Canadian Prairie, it has now become generally accepted that large-scale drought on the prairies of a long duration (a few weeks to several months, or longer) is primarily caused by a certain SST distribution in the equatorial Pacific and the central and eastern North Pacific. The Canadian Prairie drought has been linked to a cold phase of ENSO or a La Nina event in the central or eastern equatorial Pacific. An assessment of a number of studies undertaken over North America have identified weather patterns and anomalies over this region to associated with the El Nino and La Nina events. However, it has been stressed that every El Nino and La Nina events is different from the previous ones and that these events can and do produce different and often unpredictable impacts, depending on the interaction of these events with existing atmospheric flow patterns. The weather patterns and anomalies produced by a particular El Nino event also depends on its strength and the way the event develops over the central and eastern North Pacific. The interaction of a given El Nino event with atmospheric flow patterns can often be analyzed by simply using representative indices of well-known large-scale atmospheric oscillations and flow patterns. It is now recognized that these large-scale flow patterns play an important role leading to dry and wet seasons over the Canadian Prairies.

The El Nino-Southern Oscillation is one of the best-known and analyzed large-scale flow patterns. In accordance with Gan and Gobena (2006), the relationships between hydroclimatic variability and large-scale climate anomalies such as ENSO could provide predictive skills up to several months of lead time. The ENSO phenomenon is an inter-annual source of climate variability with its origin in the tropical Pacific but its impact extends into the mid-latitudes, particularly during its mature phase in winter (Horel and Wallace, 1981). The ENSO index is a combination of the SST and SO (Southern Oscillation) indices. As briefly stated above, it is now generally agreed that El Nino (La Nina) events are followed by warmer (colder) and drier (wetter) winter seasons and possibly wetter (drier) summer season. From the areally averaged composite standardized precipitation anomalies for southern Canada, it has been shown that precipitation decreases (increases) significantly during winter months following an onset of El Nino (La Nina) and has a small secondary increase (decrease) later during the summer months.

The Pacific North American (PNA) atmospheric flow pattern is a characteristic and persistent pattern that controls the weather and climate of North America, especially during the winter season. The PNA index is defined in terms of 70-kpa height anomalies and is a representative measure of the mid-tropospheric atmospheric flow over the central and eastern North Pacific and North America. A positive value of the index suggests a more meridional flow over the eastern North Pacific and northwestern North America, while a negative value suggests a more zonal flow. These different flow patterns can result in weather and climate anomalies over the Canadian Prairies. The Pacific Decadal Oscillation (PDO) and its associated index are derived using several oceanic indices over different regions of the North Pacific. The PDO maybe viewed as an ENSO-like oscillation exhibiting inter-decadal climate variability. The PDO index is derived as the leading principal component of monthly SST anomalies of the North Pacific Ocean poleward of 20°N. A positive monthly value of PDO means a warmer SST pattern in the North Pacific while a negative value represents a colder SST pattern.

1.7 Earlier Modeling Efforts in the Canadian Prairie

A technical committee (Drainage and Flood Control Committee (DFCC report, 2000)) was setup to undertake the simulation of streamflow generation for the various sub-basins in the Canadian Prairie using a hydrologic model. This effort was geared towards addressing issues bordering on the hydrologic impacts of agricultural drainage and land clearing in the various sub-basins in the Prairie. The committee had envisaged such a model to serve as a veritable tool, which would be maintained and applied to assist in the water management decision-making subsequent to the study.

The committee setup evaluated and examined 15 hydrologic models based on a number of criteria as to which of the models would be most suitable in actualizing the afore-stated objectives. Assessed candidate models include; Coupled Hydro-geomorphic Model (CLAWS), Guelph All Weather Sequential Event Runoff Model (GAWSER), TOPMODEL, Flood Forecasting System (WATFLOOD/SPL7), TR-20 - U.S. Soil Conservation Service Model, Hydrological Simulation Program - FORTRAN (HSPF), Fourth generation model, Système Hydrologique Européen (MIKE SHE), Simple Lumped Reservoir Parametric (SLURP), Minnesota Model for Depressional Watersheds (MMDW), Hydrologic Modeling System (HMS) - Revised version of the U.S. Army Corps of Engineers HEC-1 and a few others.

At the onset, a number of criteria were spelt out as to which of the models was to be selected on the basis of the goals of the study as earlier defined; such criteria included whether the model was semi-distributed or fully distributed, the continuity of the model which assesses if the model operates over several days or many months or even years as required. Further criteria employed were based on how the model handles snowmelt runoff computation and channel routing was equally considered. Choices were made on the basis of which of the model would best be deployed in the light of the existing data within the watersheds. The final selection was narrowed down to the National Water Research Institute's (NWRI) SLURP model. The NWRI model is the result of many decades of hydrologic research and development based primarily out of the National Hydrology Research Centre located in Saskatoon.

Notwithstanding that the Center's location is in the Canadian Prairie for over 15 years, to date there has been no successful application of the SLURP model to a large watershed on the Prairie. However, it should be noted that none of the other hydrologic models has been successfully applied on the Prairie examined by the Drainage and Flood Control Committee (DFCC). Several upgrades were incorporated into the SLURP model (version II) to better simulate hydrologic processes on the prairie. The three important upgrades made were: modification to the winter evaporation and soil drainage routines, wind redistribution of snow during the winter and infiltration of snowmelt into frozen soils. This upgraded version of SLURP was subsequently referred to as PBS-SLURP (Pomeroy et al., 1998).

The PBS-SLURP model was then run in two selected periods; 1954 to 1957, and from 1993 to 1996, which are characterized by high flow years. The SLURP model requires the division of a watershed into aggregated simulation areas (ASAs). Each ASA is then subdivided into areas of different land covers. For each land cover area, the model carries out a vertical water balance at a daily time-step. The earlier postulation was that any difference in hydrologic response between these two periods would be attributable to variation in land cover in combination with drainage development in the intervening four decades and not to the prevailing hydrologic /meteorologic cycle. Hydrometric data in the basin were scarce especially in the period prior to the mid-1950s in addition to the difficulty associated with the acquisition of aerial photography on which to determine the land cover.

In assessing the PBS-SLURP model performance in the different sub-basins, the yardsticks employed were the annual volume, spring peak flow magnitude, timing of spring peak flow and r-squared values. The r-squared values were computed for each station and each year using the difference between the daily recorded and daily simulated flows over the entire calendar years. Moreover, the simulated hydrographs were also examined visually for goodness of fit to the recorded daily flows placing high emphasis on a good fit during the spring runoff period rather than at other times during the years.

Based on a thorough review of the results of each test for the individual stations, the

DFCC's opinion was that the model was not sufficiently reliable to form conclusions as to the effect or impacts of land cover change on the basin's hydrology. The results obtained from the models could not address the impacts of agricultural drainage on peak flows and flow volumes in the Assiniboine River. SLURP performed well though post-calibration and verification stages in a few of the sub-basins but yielded unreliable results in the sensitivity-testing phase.

1.8 Organization of Thesis

The subsequent chapters are organized based on the objectives spelt out for this thesis and the content of each chapter is summarily outlined here.

- Chapter 2 details the various methodologies and associated dataset utilized for the research conducted in this thesis. The main physics of the internal routines of the land surface model employed are explored in conjunction with the techniques involved in the retrieval of the total moisture storage from satellite and geological lysimeter measurements
- Chapter 3 is reproduced from an accepted article in the Journal of Hydrology, which explores the validation of the employed hydrologic model using multiple data sources. The simulated soil moisture dataset from the model are subsequently assessed for periods pre-, intra- and post recent Canadian Prairie drought outbreak. Full reference to this chapter can be found in: Agboma C.O. and Yirdaw, S.Z. 2010: Moisture Storage Patterns Derived from a Hydrologic Model Validated with Outputs from GRACE and Deep Well Observations. ASCE Journal of Hydrologic Engineering. Under Review.

- Chapter 4 is reproduced from a published article in the Journal of Hydrology and is geared towards the development of a drought characterization and monitoring index over two Canadian Prairie sub-catchments. Full reference to this chapter can be found in: Agboma C.O., Snelgrove, K.R. and Yirdaw, S.Z. 2009: Intercomparison of the Total Storage Deficit Index in two Canadian Prairie Catchments. Journal of Hydrology, 10.1016/j.jhydrol.2009.06.034.
- The content of chapter 5 is reproduced from a submitted manuscript to the Journal of Hydrology and focuses on the estimation of the memory in the time series of the simulated subsurface moisture storage as well as those from different hydroclimatological variables over a large Prairie catchment. Complete reference can be found in: Agboma, C.O., Yirdaw, S.Z., Lye, L.M., 2010. Memory Estimation in the Simulated Moisture Storages and other Hydroclimatological Variables over a Drought-Prone Canadian Prairie Catchment. Submitted to Journal of Hydrology.
- Chapter 6 summarizes the outcomes from the different case studies undertaken for the thesis and provides brief recommendations to support future research pertinent to these case studies.

Note:

The methodologies described in chapters 4 and 5 are slight variants from that described in chapter 3.

Chapter 2

Methodology

2.1 Land Surface Modeling Using the Variable Infiltration Capacity Model

2.1.1 Introduction

The Variable Infiltration Capacity (VIC) model (Wood et al., 1992; Liang et al., 1994; Lohmann et al., 1998a) is a common example of the explicit soil moisture accounting (ESMA) models, which are typically constructed from connected storage elements, with parametric functions controlling the exchanges between elements, losses to evapotranspiration and discharges to the stream. Usually, all the parameters associated with these kinds of models are effective catchment-scale parameters, which can be determined on the basis of calibration by comparing observed or predicted discharges and gradually adjusting the values of the parameters until a best fit is obtained. The VIC model is an energy and water balance model that has found application as a land surface scheme in some climate models. This parameterization of the land surface processes within a climate model enables the simulation of several elements of the surface hydrologic cycle such as evapotranspiration, runoff, snow water equivalent, snow depth, soil moisture storage at different depths, and changes in the total water storage.

This model parameterizes the dominant hydro-meteorological processes by considering subgrid spatial variability in precipitation and infiltration as well as in its representation of the different vegetation covers and bare soil. In the 3-layer model implementation, the subsurface is characterized as comprising of three soil layers with N+1 land cover types in the representation of the land surface. The leaf area index (LAI), canopy resistance and the relative fraction of roots in the three soil layers are used in defining the various land cover types when driving the model. Moreover, evapotranspiration from each vegetation type is characterized by the potential evapotranspiration in conjunction with the canopy resistance as well as the aerodynamic resistance to the transfer of water and architectural resistance. The uppermost soil layer is designed to represent the dynamic response of soil moisture to rainfall events whilst the deepest soil layer is structured so as to reflect the seasonal soil moisture behavior. Additionally, two different time scales of runoff (fast runoff and slow runoff) are included in the model to capture the dynamics of runoff generation from a grid cell or from the catchment.

2.1.2 Evapotranspiration Module

Evapotranspiration plays a major role not only in terms of its instantaneous impact, but also in terms of its cumulative temporal effect on the soil moisture volume depletion (Todini, 1996). In the land surface model, VIC, evapotranspiration is computed utilizing the popular Penman-Monteith formulation (Liang et al., 1994). Essentially, three types of evaporation are considered and computed within this hydrologic model; the first of which is evaporation from the canopy of each vegetation class whilst transpiration from the individual vegetation class serves as the second form of moisture loss to the atmosphere that is computed with the last form of computed evaporation being evaporation from bare soil. With these, the total evapotranspiration is estimated as the integral sum of the moisture losses from the canopy, transpiration and bare soil components of the land surface system with the assigned weights proportional to the respective surface cover area fraction of each component.

The combination of the simplified energy balance equation for a particular surface with the equations for the transport of sensible heat and latent heat fluxes away from the surface form the basis of the Penman-Monteith equation, which is often referred to as the big leaf model. The energy balance equation is expressed as:

$$H = R_n - A - G - S \qquad \text{Equation 2.1}$$

Where H denotes the total energy available for evapotranspiration, R_n represents the net radiation whilst A is the heat loss due to advection with G being the heat loss into the ground usually positive during the day and negative at night and S represents the energy flux into physical and biochemical storage in the vegetation. The Penman-Monteith equation is therefore expressed as:

$$\lambda E = \frac{\Delta_e H + \rho_a c_p \left(e_s(T_z) - e_z\right) / r_a}{\Delta_e + \gamma\left(1 + {r_c}/{r_a}\right)} \qquad \text{Equation 2.2}$$

In Equation 2.2 above,

λE = The latent heat flux which is the product of the latent heat of vaporization, $\lambda\left(= 2.47 \times 10^6\ jkg^{-1}\right)$, and E is the evapotranspiration rate $\left(kg\ \mathrm{m}^{-2}\ \mathrm{s}^{-1} \approx \mathrm{mm\ s}^{-1}\right)$

H = Available energy

Δ_e = The slope of the saturation vapor pressure versus the temperature curve

γ = Psychrometric constant $\left(66\, Pa\, K^{-1}\right)$

c_p = The specific heat capacity of air

r_a, r_c = Estimates of the resistance coefficients

e_z = Vapor pressure at the reference height z

e_s = Vapor pressure at the effective canopy surface

ρ_a = Density of air

For practical implementation in the internal routine of land surface model, a simplified approach is sometimes adopted to the Penman-Monteith algorithm since generally in certain basins the required historical data for its estimation are unavailable. In this approach which is directly related to that implemented in the ARNO model (named after River Arno), the effects of vapour pressure and wind speed are explicitly neglected and evapotranspiration is therefore computed using the radiation method of Doorembos et al., 1984.

$$ET_{0d} = C_v W_{ta} R_s = C_v W_{ta}\left(0.25 + 0.50\,\frac{n}{N}\right)R_a \qquad \text{Equation 2.3}$$

ET_{0d} = The reference evapotranspiration, i.e. evapotranspiration in soil saturation conditions caused by a reference crop (mm/day);

C_V = An adjustment factor obtainable from tables as a function of the mean wind speed;

W_{ta} = A compensation factor that depends on the temperature and altitude;

R_s = The short wave radiation measured or expressed as a function of R_a in equivalent evaporation (mm/day);

R_a = The extraterrestrial radiation expressed in equivalent evaporation (mm/day);

$\frac{n}{N}$ = The ratio of actual hours of sunshine to maximum hours of sunshine (values measured or estimated from mean monthly values).

The calculation of R_s requires both the knowledge of R_a which can be obtained from tables as a function of latitude and the knowledge of actual n/N values, which may not be available. When measured shortwave radiation values, R_s are unavailable and in the absence of the actual number of sunshine hours, which are needed to calculate R_s as a function of R_a, an alternate empirical equation can be used which relates reference evapotranspiration computed on a monthly basis using one of the available simplified expressions such as the one due to Thornthwaite and Mather (1995) to the compensation factor W_{ta}, the mean recorded temperature of the month T and the maximum numbers of hours of sunshine, N. This relationship is linear with respect to temperature (and hence additive), and allows the disaggregation of the monthly results into daily or sometimes hourly basis. Most other empirical equations are unsuitable for computation at time intervals shorter than monthly time steps.

2.1.3 Runoff Generation Module

In the VIC model's implementation, it is assumed that the infiltration capacities, which are directly linked, to the runoff generation and evapotranspiration vary within an area due to variations in topography, soil and vegetation. In this context, the infiltration capacity is generally employed to refer to the maximum depth of water that can be stored in the soil column for an incremental area fraction (Wood et al., 1992).

The schematic diagram in Figure 2.1 is a representation of the fast runoff generation function as well as the moisture storage within a catchment in the VIC model. The curved function depicts the distribution of local total storage capacities in the basin. As rainfall is added to the catchment, more and more of the storage capacities get fill and once these are filled, any excess rainfall in that part of the catchment is assumed to become fast runoff (Beven, 2000). In between consecutive precipitation events, it is assumed that all the storage gradually drain, thereby setting up the antecedent conditions prior to the next rainfall event.

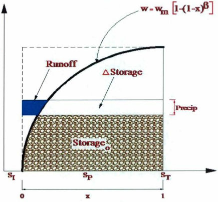

Figure 2.1: Runoff generation mechanism within a grid cell as implemented in the VIC

model (modified from Todini, 1996).

As shown in Figure 2.1, the expression for the cumulative distribution of the elementary area soil moisture at saturation is given as;

$$w = w_m \left[1 - (1 - x)^{\frac{1}{b}} \right] \qquad \text{Equation 2.4}$$

Where;

w is the elementary area soil moisture at saturation and w_m denotes the maximum soil moisture possible in any elementary area of the catchment.

Moreover,

$$x = \frac{S - S_I}{S_T - S_I} \qquad \text{Equation 2.5}$$

In Equation 2.5 above, x represents the proportion of the pervious area at saturation where $S - S_I$ is the generic surface area at saturation with $S_T - S_I$ representing the pervious area over the catchment.

Alternatively, if Figure 2.1 is redrawn and labeled as shown in Figure 2.2, A_s represents the proportion or fraction of the grid whose infiltration capacities are filled, which in turns means that A_s denotes the proportion of the catchment that is saturated when the soil moisture storage is the depth W_o. During a precipitation event, the fraction A_s will generate direct runoff whilst the infiltration capacity i_o represents the maximum infiltration capacity for the saturated fraction. The initial soil moisture storage W_o is the areally integrated infiltration capacity from zero to i_o which is the area to the right of the infiltration curve from the horizontal intercept at i_o as depicted in Figure 2.2.

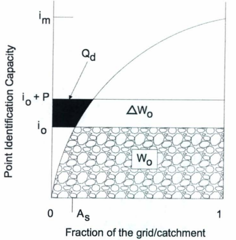

Figure 2.2: Schematic diagram showing the runoff and infiltration relationships as a function of grid wetness and infiltration capacity (After: Wood et al., 1992)

Therefore, for a precipitation amount over the basin, which occurs during the time period and with initial soil moisture storage, the amount of the precipitation that infiltrates is the areally integrated infiltration capacity;

$$P_{\inf iltrates} = \int_{i_o}^{i_o+P} A(i)\mathrm{di} \qquad \text{Equation 2.6}$$

The remainder of this is the amount that is contributing to the direct runoff, which is;

$$P_{runoff} = P - \int_{i_o}^{i_o+P} A(i)\, di \qquad \text{Equation 2.7}$$

The proportion of the precipitation that are retained as storage in the soil as well as those that runoff to the next grid cell or to the catchment outlet as the case may be are depicted respectively as ΔW_o and Q_d in Figure 2.2. Hence, the direct runoff, Q_d is the amount of P that falls on the saturated fraction A where the infiltration capacities are less than i_o and have been filled (Wood et al., 1992). The maximum soil moisture storage over the area expressed as depth is:

$$W_c = \frac{i_m}{(1+B)} \qquad \text{Equation 2.8}$$

In Equation 2.8, i_m represents the maximum infiltration storage capacity for the area whilst B is a shape parameter controlling the form of storage distribution. During rainstorm, average catchment rainfall in excess of any canopy interception losses is added to the upper soil layer storage at each time step. The saturated area is calculated as that part of the catchment for which the upper layer storage exceeds the infiltration storage capacity for that time step (Beven, 2000). Evapotranspiration is assumed to take place at the potential rate for the area that is saturated and at a reduced rate depending on storage deficit for the remaining part of the area. At the end of the time step, the upper layer storage is depleted by drainage to lower soil water storage, assuming that drainage is due primarily to gravity and the capillary potential and the unsaturated hydraulic conductivity in the upper layer can be described as a function of the storage in that layer using the

Brooks-Corey relation.

2.1.4 Snow Module

Snow plays a crucial role in the Canadian Prairie region hydrologic processes, since it is a dominant component of winter precipitation as well as source of runoff to some of the rivers within the sub-catchments. In the presence of snow, the model is coupled with a single layer, energy- and mass-balance snow accumulation model (Wigmosta et al., 1994). At the snow-air interface, the energy exchange is described by the net radiation, sensible heat, evaporation from the water in the snowpack and sublimation or condensation, and the heat advected to the snowpack by rainfall. At the snow-ground interface, zero energy flux boundary is assumed. Snow albedo is determined based on snow age.

Melt water from snow can be estimated using both the energy balance and temperature index approach in the VIC model. The snow model within the VIC model computes the snow density based on the day of the year. Once the snow is on the ground, it becomes part of the snowpack, which is an amalgamation of the old and the new snow. Old snow suffers changes, which are induced by added weight (leading to denser packing), freeze and thaw cycles, and rainfall. Aging of the snowpack entails a change from crystal to granular structure with a corresponding increase in density, a change in albedo, a move toward homogeneous temperature distribution as well as an increase in the liquid-water content. The density of a snowpack is highly variable since the density of new-fallen snow ranges from about 0.05 to 0.2 g cm^{-3} with a modal value near or somewhat below the commonly used value of 0.1 gcm^{-3} (Bras, 1990). Consequently, this leads to the issues of changing snow density, water content, albedo and other characteristics with time. Given that this research considered the simulation of snow depth over the Canadian Prairie sub-catchments and since the depth of snow is strongly affected by its density, which is known to be variable, the subsequent paragraphs would assess how the VIC model estimates varying snow density.

Snowpack density increases with depth and as the accumulation season progresses. Figure 2.3 is an illustration of increased snow density with time for different North American region.

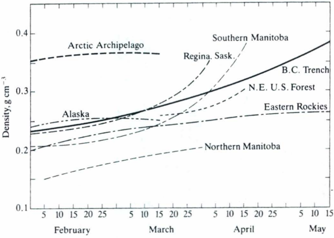

Figure 2.3: Seasonal variation in typical snow densities from various geographic areas.

(After: Mckay and Thompson (1967))

As given in Anderson and Crawford (1964), the following relationship represents the reduction in depth of the snowpack due to the compaction of the snow:

$$\Delta D = \frac{P \times D}{WE}\left(\frac{D}{10}\right)^{0.35} \qquad \text{Equation 2.9}$$

Where ΔD is the change in depth; P is the water equivalent of new snow, which is a function of its density as depicted in Figure 2.3. D is the present snowpack depth whilst WE is the water equivalent of the snowpack. Equation 2.9 assumes inches as unit of depth. The same authors parameterized the density of new snow as:

$$\rho_N = 0.05 + \left(T_a/100\right)^2; \quad \text{for} \quad T_a > 0^0 F \qquad \text{Equation 2.10}$$
$$\rho_N = 0.05; \quad \text{for} \quad T_a \leq 0.05,$$

Where T_a is the air temperature and the density, ρ_N is in grams per cubic meter. Therefore, from the Equation 2.10 and taking the density of water as $1gcm^{-3}$, the depth of the new snow becomes;

$$D_N = \frac{P}{\rho_N} \qquad \text{Equation 2.11}$$

and the new depth of the snowpack becomes

$$_2D = {_1D} - \Delta D + D_N \qquad \text{Equation 2.12}$$

Where $_1D$ and $_2D$ are the old and new snow depths, respectively. The water equivalent of the snowpack can also be updated as:

$${}_{2}WE = {}_{1}WE + P$$ Equation 2.13

and the new snowpack density relative to that of water therefore becomes;

$${}_{2}\rho_{p} = \frac{{}_{1}WE}{{}_{2}D}$$ Equation 2.14

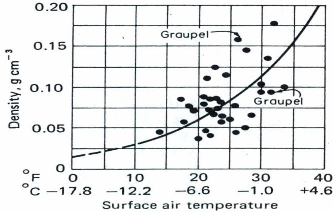

Figure 2.4: Density of new-fallen snow. (After: Gray (1973)).

2.1.5 Hydrologic Model Input Dataset

Meteorological forcing required for driving the VIC model can be obtained from the North American Regional Reanalysis (NARR) dataset at a resolution of 32 x 32 km. The NCEP North American Regional Reanalysis (NARR) is a long-term, dynamically consistent, high-resolution, high frequency, atmospheric and land surface hydrology dataset for the North American domain. Meteorological variables retrieved from the

NARR database consists of the total surface precipitation in kg/m^2, surface downward long wave flux in W/m^2, surface downward short wave flux in W/m^2, specific humidity in kg/kg, 2 m above ground temperature in Kelvin and the magnitude of the vertical and horizontal components of the wind speed which are 10 m above the ground surface in unit of m/s.

Given that the precipitation dataset obtained from the NARR database is especially problematic and unreliable as input into the VIC model for the simulation of streamflow at a number of outlets over the Canadian Prairie sub-catchments, it becomes imperative to rely on other sources of data in retrieving usable precipitation fields for the hydrologic model. The Meteorological Services of Canada (MSC) provides daily data of precipitation, maximum and minimum temperature at a number of stations in the Canadian Prairie, which can be used as forcing variables for hydrological modeling purposes over this domain.

The VIC model needs a number of soil and vegetation parameters to describe the unique properties of the grid cells in the basin. These dataset can be obtained from different databases; for instance, soil parameters can be retrieved from the 5 minutes Food and Agriculture Organization (FAO) soil map of the world. The individual soil parameters for driving the model over the Canadian Prairie sub-watersheds include; percentage of sand and clay in the soil types, porosity ϕ_S (m^3m^{-3}), saturated soil potential φ_S (m), saturated hydraulic conductivity $K_s(ms^{-1})$, bulk density kg/m^3 and a host of others which are derived based on the work of Cosby et al. (1984). The field capacity and wilting point supplied to the hydrologic model are described as a fraction of the maximum moisture where the maximum moisture for each soil layer is the depth times the porosity. The saturated hydraulic conductivity employed in VIC is expressed in mm/day derived from the Brooks-Corey relationship for estimating the hydraulic conductivity in unsaturated flow. Additionally, vegetation parameters such as the rooting depth (total depth root penetration), fraction of root in the current root zone, the monthly leaf area index (LAI) and the fraction of grid cell covered by vegetation can be obtained directly from the North American Land Data Assimilation Scheme (NLDAS) domain.

3 arc-seconds Shuttle Radar Topography Mission (SRTM) digital elevation dataset was used in the delineation of the boundaries of the Canadian Prairie sub-catchments investigated in this thesis. The digital elevation data was produced using radar images gathered from NASA's shuttle mission. Two antennae receive the reflected radar pulses at the same time; one antenna is located in the shuttle's cargo bay whilst the other is positioned at the tip of a 60 m long mast. This configuration allows single-pass radar interferometry, and consequently the generation of a highly accurate global elevation model with a vertical accuracy of 6 m and a horizontal pixel spacing of 30 m. The data covers the entire globe (latitudes 60N – 60S), with downgraded resolution of 3 arc-seconds. The 1 arc-second original data have been made available to the public only for basins in the United States. Whilst the data coverage is global, some regions have missing data because of a lack of contrast in the radar image, presence of water, or excessive atmospheric interference. These data holes are especially concentrated along rivers, in lakes, and in steep regions (often on hillsides with a similar aspect due to

shadowing, particularly in the Himalayas and the Andes, for example).

2.2 Satellite Gravity Measurements for Hydrologic Modeling

More recently, the utilization of gravity measurements have provided a new frontier in the measurement of integrated subsurface water storage change. Changes in subsurface water storage volumes imply changes in subsurface mass, hence, accurate gravity measurements, in principle are capable of providing integrated measures of all the storage change components (Bardsley and Campbell, 2000). This approach to water storage measurement has a great appeal in that it is quite easier to undertake gravity measurements than setting up multiple measurements for soil moisture, subsurface moisture storage and water table. Since the early part of this decade (March 2002), it has become possible to directly quantify water storage changes at the regional scale by using satellite instrumentation to detect the associated small changes in the regional gravity field. This satellite mission mounted with high-precision instrumentation capable of measuring variations in the earth gravity field owing to temporal and spatial variations in its mass is known as the Gravity Recovery And Climate Experiment (GRACE) remote sensing system.

In order to provide estimates of the mass anomalies over the entire globe, the Gravity Recovery and Climate Experiment remote sensing satellite mission was launched in 2002 (Tapley et al., 2004b). These dataset produced from the GRACE mission have coarse spatial resolution of about few hundred kilometers with a corresponding temporal resolution of about 1 month. However, given the coarseness in these generated dataset, the potential of the GRACE-derived terrestrial water storage for hydrological studies in large basin is high. Moreover, the GRACE mission has proven invaluable in the provision of data for continental-scale river basin water balance studies. A good level of agreement was obtained in the direct comparison of the terrestrial water storage (TWS) from the GRACE gravity measurements (Swenson et al., 2006). Furthermore, by employing GRACE data, it has become possible to successfully estimate evapotranspiration and snow mass (Rodell et al. (2004); Ramillien et al.(2006); Boronina and Ramillien (2008); Niu et al. (2007)).

The preliminary dataset retrieved from GRACE satellite remote sensing mission are transformed to time series of geopotential spherical harmonic coefficients (level 2 dataset) by different research groups at the Center for Space Research (CSR) at the University of Texas, the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum fur Luft und Raumfahrt (DLR) in Germany. These are then distributed freely up to 120 degrees and orders to different GRACE data user globally for hydrological and sundry applications. Essentially, the non-hydrological gravitational contributions, such as atmospheric and oceanic contributions plus solid earth tides, are removed in the level 2 products (Chen et al., 2005a). Thus, the initial step for studying the monthly variation of temporary change in total water storage entails extracting monthly variations of these storages from hydrological reservoirs.

Sequences of 46 monthly variations of gravity field estimates were extracted from GRACE level 2 data (CSR RL01) collected between April 2002 and May 2006 (except for May, June, July 2002 and June 2003). Due to large non-physical variability in GRACE data, C_{20} geopotential spherical harmonic coefficient was excluded in these computations (Sitotaw et al., 2008). Moreover, only the first fifteen spherical harmonic coefficients were used since spherical harmonic degrees greater than 15 are presently dominated by errors (Wahr et al., 2004). The change in average terrestrial water storage resulting from GRACE was determined according to the approach of Heiskanen and Moritz (1967), Wahr et al. (1998) and Ramillien et al. (2004). Thereafter, an 800 km Gaussian smoothing radius was employed to derive GRACE-based terrestrial water storage as this produces minimum RMS (Root Mean Square) residuals over the land surface (Chen et al., 2005b).

2.2.1 GRACE Gravity Model

The global gravity field of the earth can be represented in terms of the shape of the geoid, the equipotential surface that mostly coincide with the mean sea level over the ocean. The geoid shape (N) outside of the attracting masses can be expanded into a sum of spherical harmonics as given by Equation 2.15 (Heiskanen and Moritz, 1967).

$$N(\theta,\phi)=a\sum_{l=0}^{\infty}\sum_{m=0}^{l}P_{lm}(\cos\theta)\{C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi)\} \qquad \text{Equation 2.15}$$

In the Equation 2.15 above, θ is the co-latitude, ϕ is the longitude, a represents the mean radius of the earth, C_{lm} and S_{lm} denote the dimensionless Stokes coefficients for degree l and order m of the harmonic function. The degree l is a measure of the spatial scale of a spherical harmonic. The half wavelength of spherical harmonic having degree l and order m serves as an approximate representation of the spatial scale and is roughly 20,000/l km. The higher the degree l, the finer is the spatial resolution. The order m describes the amplitude of the harmonic component. The P_{lm} are the normalized associated Lengendre functions (Heiskanen and Moritz, 1967).

The time variable geoid anomaly is useful as it aids the study of fluid contributions to gravity field. This associated anomaly can be determined from the monthly geoid N(t) measured by GRACE and the static mean component N_0 (Ramillien et al., 2004)

$$\Delta N(t) = N(t) - N_0 \qquad \text{Equation 2.16}$$

Several months or years of average GRACE measurements or any accurately determined gravity model could be used as the static mean component (N_0). Generally, it represents the main contribution to the gravity field from the solid part of the Earth.

Usually, the gravity measurements from GRACE satellite remote sensing system are expressed in geoid coefficients. The bulk of the monthly variations in the earth's gravity is as a result of changes in the total water storage of hydrologic reservoirs such as groundwater, unsaturated soil moisture, surface water including lakes and rivers as well as snow accumulation and atmospheric moisture storages. Therefore, in order to express measured mass changes from GRACE in terms of equivalent water thickness, the approach of Wahr et al. (1998) is adopted. In this approach, a relationship is established between the surface density coefficients and the equivalent water thickness as expressed in Equation 2.17.

$$C^{w}_{lm}(t) = W_l * C_{lm}(t)$$
$$S^{w}_{lm}(t) = W_l * S_{lm}(t) \qquad \text{Equation 2.17}$$

Where;

$$W_l = \frac{\rho_{avg}}{3\rho_w}\frac{2l+1}{1+k_l}$$

The combination of Equations 2.16 and 2.17 results in Equation 2.18 which expresses the change in surface mass as a function of the equivalent water thickness, $N^{w}(t)$.

$$N^{w}(t) = \frac{a\rho_{avg}}{3\rho_w}\sum_{l=0}^{l_{max}}\sum_{m=0}^{l}P_{lm}(\cos(\theta))\frac{2l+1}{1+k_l}\left[C_{lm}(t)\cos(m\phi) + S_{lm}(t)\sin(m\phi)\right] \qquad \text{Equation2.18}$$

In the above expressions, ρ_{avg} denotes the average density of the earth (5517 kg/m^3) whilst ρ_w is the density of water (1000 kg/m^3) and k_l is the Elastic Love Number (ELN) which is taken into consideration to account for the underlying solid earth which causes additional geoid contribution besides the gravitational attraction of the surface mass and can be obtained from the work of Wahr et al. (1998).

2.3 Geological Weighing Lysimeters Estimate of Water Storage Change

Quantification of the area-integrated subsurface water volumes is a difficult task. This is so because the estimation of the area-integrated subsurface water volume at a basin-scale is possible, however, the outcome from such measurements may be fraught with errors arising from a number of sources (Bardsley and Campbell, 2000). Usually, water-storage changes for a drainage basin can be estimated as the difference between water inputs from rainfall and water outputs from basin evaporation and river discharge. Incidentally, drainage basin estimate of rainfall and evaporation are fraught with significant measurement errors, which in turn compound the error of the storage change estimate for the specific catchment.

Weighing lysimeters are essentially large mechanical devices that possess the capability to record water-storage changes in real time owing to changes in the weight of a soil monolith as it responds to water inputs and outputs. This water-storage change measurement has its limitation; the first being that the monoliths are small in dimension to be representative of the natural or actual storage changes in the basin (typically, monoliths are a few meters in diameters). Furthermore, this kind of measurements suffer from a great deal of bias arising from the disruptive effects of creating the monolith and isolating it on the weighing mechanism, thereby separating it from the natural effects of the lateral groundwater flow.

However, by relying on suitable subsurface geological formation, which serves as a natural weighing device, it is possible to overcome the limitation associated with mechanical weighing lysimeters. A necessary condition is that this formation needs to be highly isolated from groundwater throughput so as to create a situation where its pore water pressure suffers minimal impact from any deep recharge. Time-variation in formation pore water pressures will then reflect only the weight changes above the formation (Bardsley and Campbell, 2000).

These weight changes in a natural environment will essentially be dominated by the near-surface stored-water changes as well as changes in the atmospheric pressure. For a well level time series derived from a well that is completed in a confined aquifer, there are two main factors that could determine the rise or fall in the water level in such a well. The first of these factors is the barometric effect, which arises as a result of the well being exposed to the atmosphere. The barometric effect causes the well water level to fall as atmospheric pressure increase and vice versa. On the contrary, a second factor known as the loading effect causes a mass load added to the land surface to result in a rise in the well water level, whereas, a removal or mass added to the land surface would lead to a fall in its water level. A rise in the well water level can be caused by a precipitation event whilst evaporation causes a decrease in the surface loading, thus, resulting in a fall in the well water level.

The amount of well water level change caused by loading change can be quantified for an elastic aquifer using the loading coefficient, c where $c = 1 - b$ where b is the barometric efficiency. The barometric efficiency is a constant of proportionality that quantifies the degree to which the geologic formation pore water pressure near the well feels changes in the atmospheric pressure. Usually, b can be estimated by a simple comparison of well water levels and the atmospheric pressure changes expressed as meters of water.

In accordance with Bardsley and Campbell (2000), given a time sequence of water levels, which are denoted as $L_1, L_2 ... L_n$, recorded from a piezometer emplaced into a fully confined formation with an elastic loading response. Also, given a corresponding sequence of barometric pressures designated as $P_1, P_2 ... P_n$ which are recorded as length unit of equivalent water depths. Moreover, given a condition of static deep groundwater (i.e. no leakage in and out of the formation). Therefore, the time sequence of water-mass change on and below the land surface that is weighed by the formation is determined by the relationship earlier developed by Bardsley and Campbell (1994). This relationship is:

$$S_t = \left[L_t - \left(a - bP_t\right)\right]/c \qquad \text{Equation 2.19}$$

where:

$$a = L_1 + bP_1 \qquad \text{Equation 2.20}$$

and S_t is the change is stored water mass which is expressed as equivalent water length measured from zero at the time of the first observation. The actual land surface area weighed may extend up to hectares and the equation above has the physical interpretation of an estimated time series of area-integrated mass change as expressed in length units of water.

Chapter 3

Moisture Storage Patterns Derived from a Hydrologic Model Validated with Outputs from GRACE and Geological Weighing Lysimeters

Spatially distributed subsurface soil moisture dataset with suitable temporal scale are needed for a better understanding of the mechanisms responsible for the recurrent drought outbreaks over the Canadian Prairie. However, there are no soil moisture data at depths exceeding a few centimeters over the Canadian Prairie sub-catchments thereby placing enormous constraints on the feasibility of studies that require such information. Hence, this chapter explores the use of a physically based, spatially distributed hydrologic model in reproducing the patterns of the spatial and temporal distribution of soil moisture over the drought-prone 13,000 km^2 Upper Assiniboine River Basin (UARB) in the Canadian Prairie. Prior to making any inferences on the spatial and temporal dynamics of the simulated subsurface soil moisture over this large domain, a necessary requirement was to validate the model's simulated output of other hydrologic variables. These validations were accomplished using observed measurements of streamflow, snow depth, moisture storage change from well observations and estimates of the total water storage from the Gravity Recovery And Climate Experiment (GRACE) remote sensing satellite system. After an assessment of the simulated outputs from the Variable Infiltration Capacity (VIC) model, which were found to be of acceptable quality, this study thereafter focused on assessing the spatial distribution of the subsurface soil moisture over the large catchment. Therefore, this study has demonstrated that with a structurally sound model (one equipped with adequate land surface parameterization) such as the VIC model, it is possible to generate soil moisture datasets at different spatial and temporal scales for use in areas such as the Canadian Prairie and other geologically complex terrains where observed soil moisture measurements are lacking.

3.1 Introduction

Deploying a number of different watershed models for the accurate reproduction of the observed streamflow and other state variables at a number of catchment outlets corresponding to the Water Survey of Canada Hydrometric Stations over the Canadian Prairie can be a challenging task. This in part is attributed to the large proportion of these sub-catchments being dominated and influenced by the presence of millions of small isolated sloughs and potholes, which play significant roles in dictating the unique patterns of the observed streamflow at the gauged outlets. Watershed modeling over this domain is further complicated by the inexactness associated with the procedures for the accurate determination of the spatial extent of the contributing and non-contributing areas to runoff generation over the Canadian Prairie arising from the ever-changing distribution of water in the potholes' landscape.

This region's wetland hydrologic conditions have been observed to be strongly influenced and correlated with the changes in the land use in the surrounding upland regions as well as by changes in the climate. As noted in Winter (1989), melt water resulting from snow are stored by the myriad of isolated wetlands in this region and during the summer season, this accumulated water is lost via evapotranspiration from the open water surface as well as via wetland vegetation (Hayashi et al., 1998a and Millar, 1971). Therefore, most of the moisture input to the catchment in the form of precipitation is lost through evapotranspiration from the wetlands and uplands, contrary to the physical conceptualization implemented in most traditional watershed models; little or no runoff reaches the river systems within these sub-basins.

In addition to the afore-stated challenges, the Canadian Prairie is characterized by recurrent drought events with far-reaching implications on available water resources and on all sectors of the regional economy as well as on the people living in these areas. As reported in the Canadian Science and Environment bulletin (2003), drought occurrence is the most expensive single natural disaster in Canada and the outbreak of the 1999-2004 drought cost over $5 billion dollars with respect to mitigating its impact on the agricultural sector alone. Similarly, in accordance with Wheaton et al. (2005), the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba were characterized by abnormally high temperatures and these in conjunction with below normal precipitation and moisture-deficient winds, made the summer of 2003 one of the driest on records.

However, a number of processes have been adduced as the principal causes of the extreme climatic conditions over the Canadian Prairie, which gives rise to recurrent extended periods of dryness over this domain. The regional subsurface soil moisture over this domain is one of these hydrologic variables being currently investigated to ascertain its role as a slow driver of the Canadian Prairie drought. The inherent memory in the pores of soil has been observed to be considerably longer than the integral timescales for those of most atmospheric processes (Wu et al., 2002). Again, in accordance with Katul (2007), climate anomalies can be sustained through land surface feedbacks primarily because they can "feed off" on this long-term memory. The moisture in the uppermost layer of the land surface has been observed to control the intricate exchanges in the water and energy cycle at the land-atmosphere boundary. Therefore, the translation of the persistence in the soil moisture into persistence in the near-surface atmospheric fields such as those of humidity, temperature and precipitation is not unexpected, (Delworth and Manumbe, 1988).

In light of these challenges over a region subjected to frequent drought occurrences, the objective of this study is to quantitatively assess the simulated total moisture storage change from a physically-based, spatially distributed hydrologic model utilizing total water storage change estimates from the Gravity Recovery And Climate Experiment (GRACE) remote sensing system as well as measurements from the areally integrated geological weighing lysimeters. As observed in Troch et al. (2007), accurate estimation of the total water storage (TWS) over a region is of great importance for improved water management, and this holds especially true for the three Canadian Prairie Provinces of

Saskatchewan, Alberta and Manitoba given the recurrent drought events in these regions. Additionally, this study investigates the temporal and spatial dynamics of the subsurface soil water contents over one of the Canadian Prairie large sub-basins pre-, intra- and post-Prairie-wide drought outbreak. Accurate simulation of the soil moisture patterns over this region would serve as an excellent source of information for the community of researchers working as part of the Canadian Drought Research Initiative charged with the key objective of providing a better understanding of the physical characteristics and processes responsible for the initiation, continuation and cessation of the recent Prairie-wide drought.

The Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Nijssen et al., 1997; Lohmann et al., 1998) driven in the uncoupled mode was employed in the simulation of streamflow and in modeling soil moisture stores over the 13,000 km^2 Upper Assiniboine River Basin in Central Saskatchewan. Incidentally, the total amount of water stored in a river basin significantly affects the observed streamflow under different timescales and thus defines the river basin's response to atmospheric forcing (Troch et al., 2007). In accordance with Mahanama et al. (2008), in order to generate realistic values of soil moisture and groundwater states over a specific catchment, there is a need to drive a land surface model with observation-based meteorological forcing. This was the approach adopted in deploying the hydrologic model, VIC to close the water and energy budgets over the Upper Assiniboine River Basin. Meteorological forcing available for these simulations were retrieved from the Meteorological Services of Canada (MSC) whilst the North American Land Data Assimilation System (NLDAS) served as the repository from which the soil and vegetation parameters were obtained.

3.2 Study Area Description

The Upper Assiniboine River Basin lies within 51.8° to 53.0° N latitude and from 104.0° to 101.3° W longitude and has an estimated catchment area of approximately 13,000 km^2 for the basin's delineation with the outlet at Kamsack in the Saskatchewan Province (latitude 51°33'53" N and longitude 101°54'58" W). The Porcupine hills located northwest of the Preeceville in eastern Saskatchewan serves as the origin of the Assiniboine River whilst the Whitesand River northwest of Yorkton is its major tributary (DFFC Report, 2000).

Topographically, the basin's terrain is characterized by a gentle to moderately undulating surface with the northeast flank exhibiting a steeper relief. The ground surface is composed of clay-rich glacial tills intersected by glacial spillways and meltwater channels. Approximately 300 m of cretaceous shale associated with the Riding Mountain Formation underlie the glacial deposit The glacial tills and the shale have very low permeability, and thus regional groundwater flow is minimal.

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3.3 Total Water Storage Change Estimation Techniques

3.3.1 GRACE-Derived Total Water Change

In recent times, it has become increasingly possible to detect changes in the subsurface total water storage at basin scale through data acquired from the Gravity Recovery and Climate Experiment (GRACE) remote sensing satellite system. It has equally been observed that variation in the subsurface water storage volumes over a catchment is a reflection of the changes in the subsurface mass. The Center for Space Research (CSR) at the University of Texas undertakes the initial processing of the raw gravity data retrievals from the GRACE remote sensing satellite system into time series of geopotential spherical harmonic coefficients generally referred to as level 2 dataset. Moreover, the level 2 dataset are equally being generated by the National Aeronautics and Space Administration (NASA) as well as the Deutsches Zentrum fur Luft und Raumfahrt (DLR) in Germany. The GRACE remote sensing satellite systems essentially consists of two satellites which are spaced 220 km from each other and serve to detect variations in the Earth's gravity field by monitoring the changes in the distance between the two satellites as they orbit the Earth. For the purposes of diverse hydrological and environmental applications, these data are thereafter distributed freely up to 120 degrees and orders to numerous users globally.

The terrestrial moisture storage data retrieved from the GRACE remote sensing system can be sub-divided into component surface and subsurface storages which includes; surface water stored in rivers and reservoirs, soil moisture in the pores of the formation in the unsaturated layer, groundwater, snow and ice as well as biomass. Essentially, the non-hydrological gravitational contributions, such as those from the atmospheric and oceanic contributions plus solid earth tides, are removed in the level 2 products (Chen et al., 2005). Thus, the preliminary step involved in the assessment of the monthly variations of temporary change in the total water storage entails extracting monthly variations of these storages from hydrological reservoirs.

Hydrologic analyses utilizing gravity data from GRACE were not possible prior to March 2002 since the GRACE remote sensing mission was not launched prior to this time, therefore, terrestrial moisture storage change dataset used for the validation of the hydrologic model employed in this study commenced from 2002. Given that the Upper Assiniboine River Basin spans a catchment area of approximately 13,000 km^2, the terrestrial moisture storage anomaly signal over this terrain was poor which is not unexpected given the large spatial scale associated with the GRACE remote sensing system. In Yirdaw et al. (2008), the authors had generated time varying as well as spatial distribution map of the total water storage change over Western Canada, therefore, this current study utilizes a subset of this generated dataset over the Saskatchewan River Basin for the validation of the hydrologic model as would be discussed subsequently.

3.3.2 Hydrologic Model Estimate of the Total Water Storage Change

Estimation of the total water storage change is possible with a land surface model with sound internal model structure coupled with appropriate parameter estimation. The Variable Infiltration Capacity (VIC) model is a semi-distributed land surface model, which computes the balances in the mass and energy fluxes over a grid cell or a catchment of varying spatial resolutions. This model estimates the total water storage as the integral sum of the soil moisture storage, snow storage, canopy storage as well as the groundwater and surface water storages.

Closing the water and energy budgets over a catchment can be achieved on a user specified spatial scale, which can be as fine as a fraction of a degree to coarser scales (Maurer et al., 2001). Given the characteristic gentle gradients over the Upper Assiniboine River Basin in Central Saskatchewan coupled with the large surface storage due to the dominance of wetlands and sloughs over this domain, it is anticipated that the partitioning of the moisture inputs in the form of precipitation into surface runoff and soil moisture storage can be parameterized with the non-linear VIC's infiltration shape parameter.

For this study, this model was driven at a spatial resolution of 0.3° grid cells (~ 32 km x 32 km) to close the energy and water budgets over the grid cells comprising the current study domain. The unique features of the VIC model lie in its representation of subgrid variability in soil infiltration capacity, incorporation of mosaic vegetation classes in any grid cell and precipitation varying spatially within each grid cell (Maurer et al., 2001). Additionally, the soil layer depths were parameterized as being 10 cm, 50 cm and 1.5 m respectively from the surface to the deepest soil profile with gravity force serving as the driver of the drainage between the different soil layers. Moreover, the representation of the unsaturated hydraulic conductivity is expressed as a function of the degree of saturation (Campbell, 1974). The deepest soil layer serves the function of generating the baseflow, which is tailored after the non-linear ARNO scheme (Todini, 1996). Similarly, there is transpiration of moisture from all soil layers depending on the fraction of roots depths prescribed in each layer (Wood et al., 1997). Similarly, the VIC model makes provision for the upward transport of soil moisture on the condition that there is sufficient gradient resulting from surface drying. The overall approach here is that precipitation in excess of the available infiltration capacity within a grid cell or the catchment essentially results in the formation of the surface runoff.

Meteorological datasets needed to drive the model were retrieved from two sources at different spatial and temporal scales. The North American Regional Reanalysis (NARR) dataset with a spatial resolution of 32 km × 32 km grids and a temporal resolution of three hours served as the first data source for the numerical simulations over the basin. This data source served as the repository for the retrieval of the vapor pressure, air pressure, downward short- and longwave radiations as well as the magnitude of the wind speed components in the vertical and horizontal directions. The Meteorological Services of Canada database served as the additional data source for the retrieval of the observed meteorological variables for driving the land surface model. These dataset comprised daily precipitation, maximum and minimum temperatures obtained from twenty-two meteorological stations that are located non-uniformly within the Upper Assiniboine River Basin. Since the computation of the moisture and energy budgets are accomplished on a grid-based approach, it was necessary to re-grid the retrieved observed meteorological variables into a network of 32 km × 32 km grid cells using the Cressman analysis technique (Cressman, 1959).

An important consideration when mapping the precipitation field into grids relates to the terrain effects in defining the spatial distribution of precipitation especially over mountainous regions. Expectedly, terrain effects dominate the spatial patterns or increase the variability in the observed precipitation, however, over the current study domain, the effect of terrain on precipitation variability is not so pronounced since this catchment is characterized by flat or gently sloping topography. Hence, the application of elevation correction may not result in any significant difference for this specific study and was therefore not taken into consideration. Moreover, 90 m resolution Shuttle Radar Topography Mission (SRTM) elevation data was utilized in the delineation of the boundaries of the basin, which drains an approximate area of 13,000 km^2. Catchment topographic relief is a fundamental factor in current watershed modeling as it plays a predominant role in the distribution of fluxes of moisture and energy within a basin. Thus, the gridded elevation dataset enabled the generation of input variables to drive the VIC's routing model for the subsequent transport of moisture fluxes to the basin's outlet at the Kamsack hydrometric station (Figure 3.1).

Similarly, the model requires a number of soil and vegetation parameters in its description of the unique properties of the grid cells constituting the basin. The soil parameters utilized were based on the information retrieved from the 5-min FAO soil map of the world. The field capacity and wilting point supplied to the model are described as a fraction of the maximum moisture where the maximum moisture for each soil layer is the depth times the porosity. Also, the saturated hydraulic conductivity was derived from the Brooks-Corey relationship for estimating the hydraulic conductivity in the unsaturated flows. The depth of snow is also simulated based on the snow water equivalent and, allowing for increasing density of the snowpack with time.

In the Variable Infiltration Capacity model's implementation, the difference between the water and energy budget closures lies in the fact that the surface air temperature is assumed equal to the effective surface temperature in the former. Conversely, the later employs the continuous iteration of the effective surface temperature to close the energy balance (Lettenmaier, 2004). In order to assess the quality of the simulated soil moisture storage patterns from the land surface model, VIC, there is a need to validate its simulation of some components of the water balance with available physical observations over the basin as earlier stated. The model was driven to close the water and energy budgets over the Upper Assiniboine River Basin using two different time steps. Closing the water budget was undertaken at a daily time step whilst a three hourly time step was employed in solving for the energy balance. The rationale behind choosing two different time steps (for the water and energy balance computations) was to assess the implications of different modelling time steps on the simulated streamflow given the complex terrain over the Canadian Prairie. The 0.3^{o} spatial resolution used for this study was employed so as to correspond to the spatial scale of the North American Regional Reanalysis data whilst the model runs were made from January 1994 to December 2005 using a one-year spin-up period.

In order to determine the water content (w) stored within a soil layer of a prescribed depth at daily and monthly time steps, the expression in Equation 3.1 is adopted.

$$\frac{\partial w}{\partial t} = -ET(S,t) + P(t) - Q(S,t) \qquad \text{Equation 3.1}$$

Where the evapotranspiration rate ET(S,t), a function of storage and time, is simulated from the model according to the specified internal evaporation scheme utilizing observed precipitation and other surface atmospheric variables such as air temperature, radiation and wind speed which is defined at 2-m above the ground surface. Additionally, the measured precipitation rate, P(t) as well as the simulated streamflow, Q(S,t) are utilized in conjunction with the evaporation rate in estimating the total moisture storage change over the basin. The computation of the daily Upper Assiniboine River Basin total water storage anomalies can be achieved via using the expression given in Equation 3.2:

$$S_n = S_{n-1} + \left(\frac{\partial w}{\partial t}\right)_n \qquad \text{Equation 3.2}$$

Where S_n is the total water storage anomaly for the current day, S_{n-1} represents the total water storage anomaly for the preceding day whilst $\frac{\partial w}{\partial t}$ is the average daily change in moisture storage for the current day as stated earlier in Equation 3.1.

3.3.3 Geological Lysimeter Estimate of the Total Water Storage Change

Estimates of the area-integrated total water storage change derived from the land surface model, VIC and that from the GRACE remote sensing satellite sensor require validation before any deductions can be made with respect to the simulated temporal and spatial subsurface soil moisture variability over the Upper Assiniboine River Basin. In accordance with Bardsley and Campbell (2000), certain formations have the potential of serving as large-scale weighing devices for use in the measurement of area-integrated water mass changes. These formations which are often referred to as natural geological weighing lysimeters have found application in hydrology as they can be used in assessing the accuracy of any estimated regional water-mass time series as well as for the calibration of remote sensing satellite estimate of the terrestrial moisture storage change.

The utilization of sufficiently dense network of point measurements of water table and soil moisture is one approach that can be employed in the determination of the water storage change over a catchment. However, no such measurements are available over the Canadian Prairie neither are there measurements of soil moisture at depths of interest. In light of this existing condition, it becomes imperative to rely on deep well observations in the Saskatchewan River Basin which function as geological weighing lysimeters in the validation of the estimated total water storage change from the hydrological model, VIC and the GRACE estimate of the terrestrial water storage over the larger Saskatchewan River Basin.

In Southern Saskatchewan where the annual average precipitation varies approximately from 350 – 400 mm, a few deep confined aquifers have been observed to act as geological weighing lysimeters (van der Kamp and Maathuis, 1991). In their study, it was observed that the water level fluctuation in these formations was not attributable to the recharge into the aquifer from transient flow. Rather, these water level changes were as a result of the total mechanical load on the aquifer-aquitard system arising from the variations in total soil moisture, snow accumulation and groundwater storage changes. Interestingly, strong correlation was observed between plots of basin moisture accumulation, which is expressed as the difference between precipitation and the estimated area evaporation with the generated observed hydrographs for these deep aquifers. Additionally, it was emphasized that the well level fluctuations observed in the observation well located in the deep confined aquifers were very distinct and distinguishable from the seasonal fluctuation associated with the surficial and shallow semi-confined aquifers.

3.4 Results and discussion

Subsurface soil moisture over the Canadian Prairie sub-catchments is being currently investigated as one of the principal mechanisms serving as the slow driver of the recurrent drought events over this domain. As emphasized earlier on, over the Canadian Prairie, there are no such deep soil moisture measurements to enable an assessment of this inherent memory in the soil moisture pores, which could prove useful in studying the regional land-atmosphere interactions. In light of this, it becomes imperative to rely on numerical modelling to enable the reproduction of the unique patterns of the subsurface moisture storage during extended period of dryness as well as during normal years over this domain.

Dependence on the spatial and temporal soil moisture dataset from a land surface model for use in other hydrological studies requires calibration and validation of some of its simulated outputs with available observed measurements. Streamflow is one of the most measured components of the water budgets and therefore can provide a partial data source for evaluating the performance of a model's simulated runoff hydrograph. The focus of this section therefore, is to evaluate the performance of the land surface model, VIC in reproducing the relevant hydrologic processes dominating the Canadian Prairie sub-catchments. The simulated monthly times series of streamflow data obtained from the VIC model after careful parameter estimation are compared with the observed streamflow records over the Upper Assiniboine River Basin at the Kamsack hydrometric station. Although, a number of soil and vegetation parameters need to be defined for a successful model run, only six of these need to be calibrated during the parameter estimation phase. These are; the infiltration shape parameter b_inf_i; soil depths of the intermediate and the deepest layers (D_2 and D_3); and the three parameters related to the baseflow computation; D_m, D_s, and W_s, representing respectively, the maximum subsurface flow, the fraction of D_m, and the fraction of maximum soil moisture in the deepest soil layer. Numerical simulations with this land surface model to reproduce streamflow and other state variables essentially rely on the assumption that the other parameters are known (retrievable from available database); therefore these do not require calibration to determine their actual values. The comparison of the monthly simulated and observed streamflow records for the simulation period (January 1995 to December 2004) is as shown in Figure 3.2.

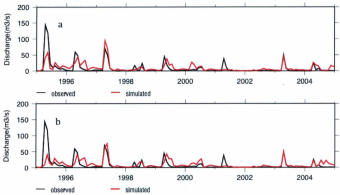


Figure 3.2: Net monthly streamflow a: From closing the water budget over the domain (using daily time step) b: From solving for the energy balance equation (using sub-daily time step)

As seen in Figure 3.2, there is no significant disparity between driving the model at a sub-daily (three hourly) time step as against driving it at a daily time step to close the water budget over the large catchment, therefore, it can be concluded that the temporal scale at which the VIC model is driven for this particular study is of little or no significance on the overall quality of the simulated streamflow when compared with the observation. Over the temporal frame assessed, there seems to be a qualitative agreement between the integrated runoff response at the Kamsack outlet generated by the VIC model and the streamflow observation by the Water Survey of Canada. On a closer visual assessment, it could be inferred that the simulation when driving the model to generate streamflow from the energy balance approach coincides slightly better with the observed discharge measurement as compared with the generated streamflow hydrograph resulting from closing the water budget over the catchment, however, a further quantitative assessment revealed no difference in performance.

The estimated Nash-Sutcliffe Efficiency (NSE) for the complete time series of measured and simulated runoff was 0.70 whilst the NSE value of 0.90 was computed for the observed and simulated flows whose values are below the median discharge value (low-flow fit). Moreover, the computed R-squared values for the complete time series of flows (observed and simulated) as well as those for the flows below the median flow are 0.80 and 0.97 respectively. Given the topographic complexity of the Prairie region coupled with the dynamic effects of the wetland landscape which often culminate in the loss of moisture input via evapotranspiration rather than runoff at the basin's outlet, it is fair to say that the land surface model, VIC did well in capturing the relevant hydrologic processes over this domain which can be challenging. It has to be emphasized here that the version of the land surface model, VIC used for this current study over the UARB does not clearly incorporate an internal process that represents land surface storages such as wetlands and sloughs but given the flexibility within the model, it is possible to mimic the dynamic behavior of the land surface storages by carefully calibrating the different parameters of the model thereby making moisture available for evaporation. A summary of the estimated parameters obtained from the calibration of the VIC model over the domain is revealed in Table 3.1.

Parameter Symbol	Physical Interpretation	Estimated Value	Parameter Limits
b_inf	Variable infiltration curve parameter	0.10	0.40 — 1.e-5
D_m	Maximum velocity of baseflow (mm/day)	10.00	20.00 — 5.00
D_s	Fraction of D_m where non-linear baseflow begins	0.01	0.50 — 1.e-5
W_s	Fraction of maximum soil moisture where non-linear baseflow occurs	0.75	1.00 — 0.25
D_2	Thickness of the second soil layer (m)	0.50	1.00 — 0.10
D_3	Thickness of the third soil layer (m)	1.50	2.50 — 0.50

Table 3.1: Estimated parameter values for the hydrologic model, VIC over the Upper Assiniboine River Basin

Furthermore, it is necessary to assess the hydrologic model's performance with respect to its simulation of the snow depth over the studied area. Validation of the VIC model's output of snow depth and snow water equivalent (SWE) utilizing existing available observation over the domain is of high importance. A partial assessment of the model's performance relying solely on the observed streamflow data might result in an overall misleading conclusion since observed streamflow at a catchment's outlet is a reflection of the basin's integrated hydrologic response. Snow accumulation and melting plays a crucial role in the seasonal water balance since they exhibit both strong seasonality as well as high spatial variability (Kling et al., 2006).

The plot of the long-term mean-monthly simulated snow depth from the model in conjunction with the available station observation of the snow depth over the Upper Assiniboine River Basin is as shown in Figure 3.3. The area-averaged basin snow depth records from the hydrometric stations with complete or partially missing snow depth dataset was computed for the domain and inter-compared with the simulation from the land surface model, VIC. Over the Canadian Prairie sub-catchments, there are very limited observed data of the snow water equivalent, however, a number of the hydrometric stations have long records of snow depth measurements, which can be utilized in the validation of the VIC model's output. The plot of the long-term mean-monthly simulated snow depth from the model in conjunction with the available station observation of the snow depth over the Upper Assiniboine River Basin is as shown in Figure 3.3. In this study, snow depth measurements were retrieved from January 1994 to December 2005 and this temporal length was chosen to enable an assessment of how well the VIC model performed in capturing the temporal dynamics of snow accumulation and melt during the period of the last Canadian Prairie drought.

Computation of the station-averaged basin snow depth records from ten hydrometric stations possessing complete time series of data was made and subsequently inter-compared with the VIC model simulation of the 1994-2005 mean monthly snow depth measurements over the catchment. These station measurements of snow depth were retrieved from the Canadian Daily Climate Data (CDCD) archive (available at http://www.climate.weatheroffice.ec.gc.ca/) which contains records of daily temperature, precipitation and snow-on-the-ground data for individual stations up to 2007.

As revealed in the plot of Figure 3.3, the VIC model simulation of the snow depth over the 13,000km^2 catchment shares a good level of resemblance with the individually observed measurements of the snow depth at the ten respective stations as well as that of the computed station average estimate. It is not unexpected to observe some apparent departures between the VIC model simulation of the snow depth and the measurements made at some hydrometric stations. These deviations maybe attributed to the quality of the input data (precipitation field) and the scanty number of available meteorologic stations utilized in the interpolation of the precipitation field.

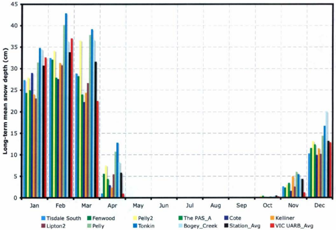


Figure 3.3: Long-term mean-monthly snow depth simulated from the VIC model and the average-station observations

Similarly, a time series plot of the monthly simulated and the area-averaged observed snow depth is illustrated in Figure 3.4 for the period under investigation. Again, the VIC model performed acceptably in capturing the dynamics of the relevant snow accumulation processes over the Canadian Prairie. Although, there appears to be some clear over-prediction of the snow depth in the months of January 2000 and January 2005 by the VIC model, however, over the temporal domain under assessment, there is a good agreement between the model's simulation and the average station observation over the catchment.

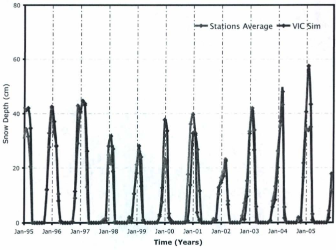


Figure 3.4: Time series of monthly snow depth simulation from VIC and area-average basin observation

A scatterplot of the VIC-simulated snow depth against average station snow depth observation yielded a correlation coefficient of 0.92, which is considerably high whilst the difference between the simulated output and the observed snow depth measurements being Gaussian distributed.

Having assessed the VIC model's simulations of streamflow and snow depth over the domain, there is a need to subsequently explore how well the computations of the total water storage from the VIC model compares with those estimated from the GRACE and lysimeters measurements over the larger Saskatchewan River Basin. GRACE retrieved terrestrial moisture storage signal over the Upper Assiniboine River Basin is poor owing to the large spatial scale associated with the remote sensing satellite coverage (Agboma et al., 2009). It therefore becomes imperative to assess VIC estimated total water storage with the GRACE-derived terrestrial moisture storage over the larger Saskatchewan River Basin for a meaningful comparison to be achieved.

Although, the Prairie-wide drought commenced in 1999, the GRACE-derived terrestrial moisture storage dataset were not available until March 2002, consequently, no inferences can be drawn with respect to the temporal and spatial patterns of the subsurface moisture storage from the standpoint of the GRACE estimates of the terrestrial moisture storage change in the early phase of the drought development in this region. The spatial variability in the estimated monthly total water storage anomalies from the GRACE remote sensing system over Western Canada is as shown in Figure 3.5.

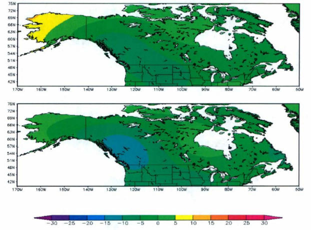


Figure 3.5: Terrestrial moisture storage anomalies relative to the mean storage for October 2003 (top) and November 2003 (bottom). After: Yirdaw et al. (2008).

These plots represent the monthly terrestrial moisture storage anomalies for October and November 2003, which are computed as the deviations from the long-term mean (from April 2002 to May 2006) of the time series of the GRACE estimated change in terrestrial moisture storage over western Canada. As would be expected during this anomalously dry period, most of the sub-basins in the Canadian Prairie were characterized by monthly terrestrial moisture storage anomalies, which are well below the mean storage values for the entire region. Similar patterns were observed for plots of the terrestrial moisture storage anomalies made for the later part of 2002 indicative of the amount of moisture loss from this region during the last drought outbreak over the Canadian Prairie.

Moreover, moisture storage changes deduced from records of deep observation wells in southern Saskatchewan which act as geological weighing lysimeters are depicted in Figure 3.6 in conjunction with the total water storage change computed from the hydrologic model, VIC as well as the GRACE estimate over the region. These measurements were made at deep observation wells and obtained from the Saskatchewan Watershed Authority [http://www.swa.ca/WaterManagement/Groundwater.asp]. Water level dataset from four deep observation wells located within the vicinity of the boundaries of the Upper Assiniboine River Basin were analyzed; however, none of these wells lie exactly within this basin as depicted in Figure 3.1. The observation wells have the following geographic coordinates; Duck Lake No.2 (52° 54' 56" N, 106° 13' 25"W), Hearts Hill (52° 5' 3"N, 109° 33' 49"W), Lilac (52° 45' 26"N, 107° 54' 59"W) and Tyner (51° 1' 27" N, 108° 25' 27"W).

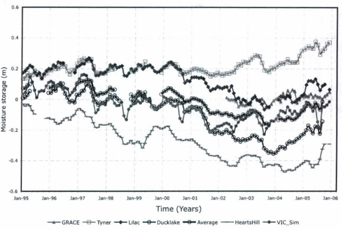


Figure 3.6: Moisture storage change from the VIC model, GRACE and Geological Lysimeters

The illustration of Figure 3.6 is quite interesting in terms of the level of agreement between the total water storage change computation of the hydrologic model, VIC compares with those of the area-average estimate of the geological weighing lysimeters as well as the GRACE-derived total water storage change over the domain. Over the eleven years period under investigation, there is an apparent similarity in the temporal dynamics of the estimated total moisture storage change from the VIC model with those from the average well observations and GRACE as reflected in the patterns of the moisture storage change from the three methods. During the later drought period (2002 to 2004), the moisture deficit resulting from the GRACE-derived terrestrial moisture change appears to be smaller than the moisture deficit computed for the hydrologic model as well as that of the area-average estimate resulting from the geological weighing lysimeters. This apparent disparity between GRACE-estimated total moisture storage change with those from the hydrologic model and the average well observation may be attributed to the type and dimension of the filter radius employed in the initial smoothing of the gravity data. On the contrary, the VIC model as well as the average estimate of geological lysimeters captured the onset of the last Canadian Prairie drought as evident in the progressive decline in the change in moisture storage commencing late 1999 with the eventual recovery from the drought episode indicated by the continuous moisture gains from August 2004.

Since no suitable observation well records are available within the Upper Assiniboine River Basin whilst the four weighing lysimeter observation wells are located outside this catchment, thus, a perfect agreement between the VIC and lysimeter results is not expected. Interestingly, the fluctuating patterns in the moisture storage change from the lysimeters share resemblance with that from the hydrologic model, VIC over the study period. Given that these three techniques have different spatial scales associated with their estimation of the subsurface total moisture storage change, it is unlikely that a one-to-one match in the computed total moisture storage change over this very large catchment is feasible. . In light of this level of agreement between the hydrologic model estimates of the total water storage change with the other techniques (GRACE and

Geological Weighing Lysimeters), it can be deduced that the simulation of the subsurface moisture storage change from the hydrologic model is of acceptable quality.

Having successfully validated the VIC model's simulated output of streamflow at the catchment's outlet in conjunction with the validation of the average snow depth over the basin as well as the total water storage utilizing available observation and remote sensing source, there is therefore a sufficient level of confidence to make inferences with respect to the model's simulation of the subsurface soil water storage patterns over this large basin. As expressed in the introductory section of this paper, soil moisture data measurements at depths of about 1 metre and deeper are unavailable over the Canadian Prairie thereby constraining certain drought studies that require knowledge of the temporal and spatial variability of subsurface soil moisture. Equally, the role of the soil moisture in governing the water and energy exchanges at the land-atmosphere boundary is of great importance and an essential component of the land surface hydrology over the Prairie region. This constraint posed due to inexistence of observed soil moisture data can be overcome by relying on simulated output of soil moisture content from carefully calibrated and validated hydrologic model with sufficient structure and physics such as the Variable Infiltration Capacity (VIC) model, which underlies the main motivation for this study.

An intercomparison is made of the VIC model simulation of the monthly soil moisture content in the deepest moisture store with the well water level observation from a shallow well located at the Stenen station (51° 49' 15"N, 102° 24' 36"W) which lies within the

Upper Assiniboine River Basin (UARB). As depicted in Figure 3.7, the onset of the recent Prairie-wide drought is marked by the continuous depletion in the deep soil moisture store simulated by the VIC model, which is also apparent in the decrease in the recorded water level elevation from the shallow observation well at Stenen.

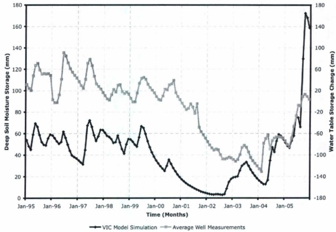


Figure 3.7: Simulated deep soil moisture content from the VIC model compared with water level fluctuations at the Stenen station

Moreover, the recovery from the drought episode as captured in the VIC model simulation from April 2004 is evident in the increase in the measured water level elevation at the well observation station. This agreement in the temporal pattern simulated from the hydrologic model, VIC and the water level fluctuations recorded at the shallow well at the Stenen station indicates how well the model performed in capturing the relevant soil hydrological processes within this domain during normal and anomalous years.

A time series plot of the simulated average monthly soil moisture storage in the deepest moisture store from the hydrologic model is depicted in Figure 3.8c. Correspondingly, the cumulative departures for the monthly mean of the precipitation over the Upper Assiniboine River Basin derived from the spatial interpolation of the station precipitation dataset is shown in Figure 3.8a whilst the observed streamflow measurement by the Water Survey of Canada at the Kamsack outlet is illustrated in Figure 3.8b.

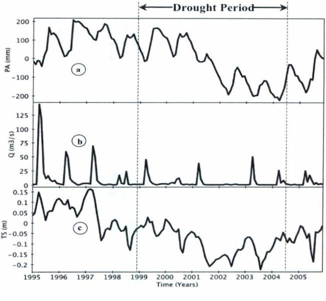


Figure 3.8: Monthly Time Series Plots of (a) Cumulative Departures from Monthly Mean Precipitation, (b) Measured Streamflow, (c) Simulated Deepest Layer Soil Moisture Content

This temporal pattern depicted in these plots as simulated by the model is consistent with the observed cycle of the last drought event over this region. A further inspection of the time series of Figures 3.8 a-c reveals that the decline and subsequent rise in the subsurface soil moisture store over the entire basin corresponds to a remarkable deviation in the temporal patterns of the computed cumulative departures of the monthly mean precipitation time series over this large catchment prior to the drought outbreak and during the drought episode. Evidently, it can therefore be inferred from the signatures of the time series of the precipitation anomalies that the moisture deficit in this atmospheric variable (meteorological drought) does propagate through the terrestrial component of the hydrologic cycle, which manifests in the soil moisture anomaly (soil moisture drought) over the Canadian Prairie.

The spatial distribution of the average subsurface soil water content over the 13,000 km^2 basin pre-, intra- and post- recent Canadian Prairie drought as simulated from the VIC model is illustrated in Figure 3.9. During the pre-drought period (January 1995 to December 1998) as depicted in Figure 3.9a, the moisture content in the subsurface moisture store up to a depth of about 1.5 m over this basin vary approximately from 32 mm to a peak of about 172 mm with the northeastern flank of the catchment revealing a higher degree of wetness relative to the other flanks of the catchment.

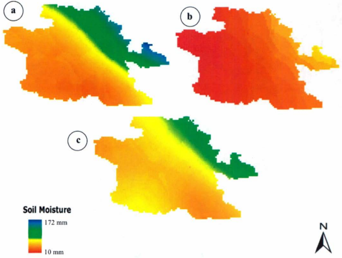


Figure 3.9: Subsurface soil moisture distribution in mm over the UARB domain (a) Pre-drought soil water content (b) During drought soil water content and (c) Post-drought soil water content

However, during the middle of the drought episode (from January 2000 to December 2003), the spatial dynamics of the subsurface soil moisture reveal much lower moisture content as captured by the hydrologic model. This trend is expected given that the last Prairie-wide drought was characterized by very high temperatures coupled with high evapotranspiration rates, which led to the drying up of a number of small streams and depletion in the subsurface soil moisture storage over the domain. The subsurface soil water content simulated during this extended period of dryness spans from 11 mm of moisture storage to a maximum of approximately 66 mm with the northeastern flank of the catchment showing a sign of higher moisture storage than does any other part of the basin. Overall, the catchment maximum soil water content during this devastating drought episode is far less than the average simulated moisture content during the non-drought years.

In the post-drought period as simulated by the land surface model and illustrated in Figure 3.9c, there is an apparent recovery of the soil moisture store attributed to the heavy rainstorm in late 2004 and early 2005 that brought an end to the drought episode. The minimum soil water content simulated by the hydrologic model during this temporal domain considered is approximately 42 mm with a peak in the neighborhood of about 117 mm over the Upper Assiniboine River Basin. In accordance with Agboma et al. (2009), it has been shown that the soil moisture anomaly in the deepest soil moisture store exhibits higher autocorrelation over lag times than the precipitation anomaly over this domain. The implications of this long memory in the deep soil moisture in better understanding the mechanism of drought evolution, persistence and cessation over the Canadian Prairie would be an interesting research issue for future investigation.

3.5 Conclusions

As recurrent drought outbreaks over the Canadian Prairie continues to take its toll on all sectors of the Canadian economy and especially on the people living in the affected regions, there is an urgent need to better understand the mechanisms responsible for the evolution, continuation and cessation of drought events over this region. More recently, one of the dominant mechanisms being investigated as one of the slow drivers of the Canadian Prairie drought is the subsurface soil moisture within this domain. Incidentally, the Canadian Prairie suffers from a lack of physical measurements of soil moisture at depths of up to 1m and deeper thereby placing enormous constraints on the feasibility of such studies that require such information.

Sequel to the above, this study explores the use of a physically-based, spatially distributed hydrologic model in reproducing the unique patterns of the spatial and temporal distribution of soil moisture data at desired depths over the drought-prone 13,000 km^2 Upper Assiniboine River Basin in the Canadian Prairie. Prior to making any reasonable inferences on the spatial and temporal dynamics of the simulated subsurface soil moisture over this large domain, a necessary requirement was to validate the model's simulated output of other hydrologic variables. These validations were accomplished using physically existing observed measurements of streamflow, snow depth, moisture storage change from well observations and estimates of the total water storage from the Gravity Recovery and Climate Experiment remote sensing satellite system. After careful assessment of the simulated output from the Variable Infiltration Capacity model which were found to be of acceptable quality, this study thereafter focused on assessing the spatial distribution of the subsurface soil moisture over the large catchment.

The temporal pattern depicted in the generated plots as simulated by the hydrologic model is consistent with the observed cycle of the last drought event over the Canadian Prairie. Expectedly, the subsurface soil water content spatial distribution over the Upper Assiniboine River Basin simulated from the VIC model during the drought years is far lesser than the corresponding simulated soil moisture pre- and post- last drought outbreak over the Prairie. Overall, the northeastern flank of this large catchment revealed a higher degree of soil wetness when compared to other parts of the basin for the temporal domain considered for this study.

Chapter 4

Intercomparison of the Total Storage Deficit Index (TSDI) over Two Canadian Prairie Catchments

Retrieval of the terrestrial moisture storage dataset from the Gravity Recovery And Climate Experiment (GRACE) satellite remote sensing system is possible when the catchment of interest is of large spatial scale. These dataset are of paramount importance for the estimation of the total storage deficit index (TSDI), which enables the characterization of a particular drought event from the perspective of the terrestrial moisture storage over that catchment. Incidentally, the GRACE gravity signal over the 13000 km^2 Upper Assiniboine River Basin on the drought-prone Canadian Prairie is so poor therefore making the computation of the total storage deficit index for this basin infeasible. Consequently, the estimation of the terrestrial moisture storage from other reliable sources becomes imperative in order to enable the computation of the TSDI over this basin.

This chapter explores the utilization of the Variable Infiltration Capacity (VIC) model, a physically based, spatially distributed hydrologic model to simulate the total moisture storage over the Upper Assiniboine River Basin which was then employed in the estimation of the TSDI over this basin for subsequent characterization of the recent Prairie-wide drought. Interestingly, the temporal patterns in the computed TSDI from the VIC model reveal a strong resemblance with the same drought characterization undertaken over the larger adjacent Saskatchewan River Basin, which was accomplished utilizing terrestrial moisture storage from the GRACE-based approach. Additionally, these independent techniques employed in the characterization of the last Prairie drought over the two adjacently situated basins resulted in similar drought severity classification from the standpoint of the total moisture storage deficits over these basins. This study has therefore shown that in the computation of the total storage deficit index over small-scale catchments during anomalous climatic conditions that propagate extreme dryness through the terrestrial hydrologic systems, simulations of the total water storage from a structurally sound model such as the VIC model could be resourceful for the computation of the monthly total storage deficit index if no constraint is placed on the availability of accurate meteorological forcing.

4.1 Introduction

Integrated watershed moisture storage derived from the Gravity Recovery And Climate Experiment (GRACE) satellite remote sensing system has recently been advocated as a better surrogate for the deficiencies associated with the estimation of the integrated catchment moisture storage simulated from traditional land surface models (Yirdaw et al., 2008). These deficiencies in computed watershed storage were essentially attributed to the way in which these land surface models transport moisture and energy between the internal models' stores by relying on physically based transfer laws and conservation equations. Moreover, utilization of GRACE-derived integrated water storage was further emphasized on the premise that there is non-uniqueness in the approach with which land surface model generate streamflow hydrographs. So many studies have demonstrated the capabilities of watershed models in the simulations of different hydrological processes over a catchment. The focus of this study is to ascertain how well the simulation of the total water storage from a hydrologic model over a basin compares with that retrieved from a remote sensing system over an adjacent basin through the computation of a moisture storage index. Characterizing the last Canadian Prairie drought employing terrestrial moisture storage estimated from hydrologic and remote sensing sources of varying spatial scales are of interest to scientists working as part of the Canadian Drought Research initiative (Canada DRI).

The Upper Assiniboine and Saskatchewan River Basins are medium- and large-scale catchments respectively located on the drought-prone Canadian Prairie. Extreme weather condition in the form of drought over the Prairie region are quite recurrent and are associated with devastating consequences on the region's agricultural practices, national economy and on the health of the people living in this region. As reported in the Canadian Science and Environment bulletin (2003), drought occurrence is the most expensive single natural disaster in Canada and the outbreak of the 1999-2004 drought cost over $5 billion dollars with respect to mitigating its impact on the agricultural sector alone. Similarly, in accordance with Wheaton et al. (2005), the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba were characterized by abnormally high temperatures and these in conjunction with below normal precipitation and moisture-deficient winds, made the summer of 2003 one of the driest on records. Also, this same year was recorded as the driest in the up lying province of British Columbia where the precipitation was so minimal and infrequently distributed temporally. The resultant effects of these led to the drying up of small rivers whilst flow in the average-sized rivers was so low that it could not support even the smallest fishes. Coupled with these, this acute drought event led to an abnormal drop in the groundwater level over this region.

Therefore, the essence of this study is to estimate the Total Storage Deficit Index (TSDI) from a physically based, spatially distributed hydrologic model over the Upper Assiniboine River Basin on the Canadian Prairie where the GRACE-derived total moisture storage signal is poor. This is not unexpected since Rodell and Famiglietti (1999) have demonstrated that the gravity data from GRACE becomes resourceful on a spatial scale when the catchment being studied is large (> 150 000 km^2). This in part is due to the coarseness of the spatial resolution of the GRACE remote sensing satellite. Subsequently, an assessment of the correlation if any between the model-derived TSDI with that computed from the GRACE technique would be undertaken. The total water storage from the GRACE-based technique was validated using the atmospheric-based P-E computation of the terrestrial moisture storage over the larger Saskatchewan River Basin also located on the Canadian Prairie. Spatially distributed total water storage is a vital hydrological variable that can be used for comprehensive drought studies since drought characterization is possible if available stored moisture in the soil can be measured or accurately estimated. The applicability and utilization of GRACE-derived terrestrial moisture anomalies for hydrological applications is apparent in the works of Rodell and Famiglietti (2002), Rodell et al. (2004), Tapley et al. (2004), Yeh et al. (2006), Syed et al. (2005 & 2007) and Boronina and Ramillien (2008). Moreover, Rodell and Famiglietti (1999) emphasized how the gravity data from the GRACE remote sensing satellite could be employed as a constraint for the simulated total water storage in the land surface models when combined with subsurface soil moisture storage and changes in the groundwater in conjunction with the intermediate zone storages.

The GRACE remote sensing satellite mission platform was originally launched in March 2002 to measure, among other things, the gravitational field of the earth. It is the first remote sensing satellite mission that is directly applicable for the assessment of the integrated subsurface moisture storage under all types of terrestrial conditions (Tapley et al., 2004). Over its life span, these orbiting satellites have generated time series of mass changes of the earth-atmosphere system. On a long-term basis, this will yield a highly refined picture of the earth's gravitational fields, which are indicative of the distribution of the global mass variations. Usually, for hydrological applications, the emphasis is on capturing the month-to-month variations in the earth's gravity fields, which are then transformed into integrated values of a watershed's total water storages. The GRACE generated geopotential spherical harmonic coefficients are variables of interest, which are subsequently converted to produce a basin's spatially varying time series of integrated subsurface moisture storage. These spatial estimates are then converted to water equivalent amounts and are therefore inter-compared with the monthly estimates of the basin's total water storage derived from traditional in-situ measurements and hydrological model outputs.

The three-layer Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Nijssen et al., 1997; Lohmann et al., 1998) driven in the uncoupled (offline) mode was employed in the simulation of streamflow and in modeling soil moisture store up to a depth of about 1.5 metres over the 13,000 km^2 Upper Assiniboine River Basin. In accordance with Mahanama et al. (2008), in order to generate realistic values of soil moisture and groundwater states over a specific catchment, there is a need to drive a land surface model with observation-based meteorological forcing. This was the approach adopted in deploying the hydrologic model, VIC to close the water budget over the Upper Assiniboine River Basin. Meteorological forcing available for these simulations were retrieved respectively from the Meteorological Services of Canada (MSC) whilst the North American Land Data Assimilation System (NLDAS) served as the repository from which the soil and vegetation parameters were obtained.

Streamflow simulation with a hydrological model over the Canadian Prairie basins is compounded by the presence of thousands of small isolated wetlands and sloughs that dominate the basins' topography and usually serve as depression storage over this terrain. Consequently, the determination of the spatial extent of the contributing and non-contributing areas to runoff generation becomes an increasingly challenging task. The wetland hydrologic conditions have been found to be strongly linked and correlated by the effects of climate change as well as variations in the land use in the surrounding uplands. During the winter season, snowmelt water is transported and stored in these isolated wetlands and in the summer season, the accumulated water in these wetlands' storages gets depleted through evapotranspiration from the open water surface as well as from the wetland vegetation (Hayashi et al., 1998a and Millar, 1971). Consequently, water input in the form of rain and snowfall on these watersheds is mainly lost through evapotranspiration and hence, do not runoff into the rivers as would be conceptualized in most traditional watershed models. Runoff captured into the storage of sloughs and wetlands could be of hydrological advantage during flood occurrence as they are crucial in slowing down discharge into stream and rivers thereby helping to reduce flood peaks (Pomeroy et al., 2005).

4.2 Study Area Description

The total storage deficit indices were respectively computed for the Upper Assiniboine and Saskatchewan River Basins both located on the drought-prone Canadian Prairie. This section is dedicated briefly to describing the hydrologic characteristics of the two catchments. The Upper Assiniboine River Basin lies within 51.8° to 53.0° latitudinally and from -104.0° to -101.3° longitudinally and has an estimated catchment area of approximately 13,000 km^2 for the basin delineation with the outlet at Kamsack in the Saskatchewan Province (latitude 51°33'53" N and longitude 101°54'58" W). The Porcupine hills located northwest of the Preceeville in Eastern Saskatchewan serve as the origin of the Assiniboine River whilst the Whitesand River northwest of Yorkton is its major tributary (DFFC Report, 2000).

This basin is such that it is dominated by a number of lakes, notably the Good Spirit and Fishing lakes with the southern flank of Yorkton characterized by a number of interconnected as well as disconnected small lakes. As a whole, the Assiniboine River

Basin spans an area of approximately 21,000 km^2 and over three-quarter (79%) of this gross area is situated in the Canadian Province of Saskatchewan with the remainder extending into the adjacent province of Manitoba. As was stated earlier on in the introductory part of this article, the domain of this current study borders on the upper segment of the Assiniboine River Basin and not on the entire catchment that stretches into Manitoba.

The Saskatchewan River Basin (SRB) is located on the south of the Mackenzie River Basin and has been described as one of the most diverse basins in North America (Szeto, 2007). The gross drainage area bordering this river basin with its Grand Rapids outlet is approximately 406,000 km^2 and spans through three Canadian Provinces. This river is found to be the fourth largest in Canada and serves to drain most of the Canadian Provinces. Moreover, this basin has strong economic implications for Canada, as it is one of the most important agricultural regions of the country.

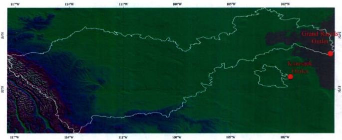


Figure 4.1: Saskatchewan and Upper Assiniboine River Basins showing outlets of interest

4.3 Methods and Datasets

4.3.1 Total Moisture Storage Estimation from GRACE

As briefly stated in the introductory section, the terrestrial moisture storage dataset utilized in the computation of the total storage deficit index (TSDI) for the recent drought characterization were retrieved from the Gravity Recovery And Climate Experiment (GRACE) remote sensing satellite system. This was the approach adopted by Yirdaw et al. (2008) in the computation of the total storage deficit index (TSDI) over the larger Saskatchewan River Basin on the Canadian Prairie. The raw gravity data from this remote sensing satellite are transformed into time series of geopotential spherical harmonic coefficients, which are generally referred to as level 2 dataset at the Center for Space Research (CSR) located at the University of Texas. Other organizations and research institutes involved in the generation of level 2 dataset from GRACE gravity fields are the National Aeronautics and Space Administration (NASA) as well as the Deutsches Zentrum fur Luft und Raumfahrt (DLR) in Germany. The GRACE satellite systems essentially consists of two satellites which are spaced 220 km from each other and serve to detect variations in the Earth's gravity field by monitoring the changes in the distance between the two satellites as they orbit the Earth. For diverse hydrological and environmental applications, these data are thereafter distributed freely up to 120 degrees and orders to users globally.

The terrestrial moisture storage retrieved from this remote sensing system can be sub-divided into component surface and subsurface storages which includes; surface water stored in rivers and reservoirs, soil moisture in the pores of the formation in the unsaturated layer, groundwater, snow and ice as well as biomass. Essentially, the non-hydrological gravitational contributions, such as those from the atmospheric and oceanic contributions plus solid earth tides, are removed in the level 2 products (Chen et al., 2005). Thus, the initial step for studying the monthly variations of temporary change in the total water storage entails extracting monthly variations of these storages from hydrological reservoirs.

4.3.2 Simulation of the Mass and Energy Fluxes in VIC Model

The macroscale Variable Infiltration Capacity model have been reviewed extensively in a number of studies such as in Wood et al. (1992) through Liang et al. (1994) to Nijssen et al. (1997) and Lohmann et al. (1996). This model computes the balances in the mass and energy fluxes over a grid cell or a catchment of varying spatial resolutions from as fine as a fraction of a degree to coarser scales (Maurer et al., 2001). Given the characteristic gentle gradients over the Upper Assiniboine River Basin coupled with the large surface storage due to the dominance of wetlands and sloughs over this domain, it is anticipated that the partitioning of the moisture inputs in the form of precipitation into surface runoff and soil moisture storage can be parameterized with the non-linear VIC's infiltration shape parameter.

This model was driven at a spatial resolution of 0.3 degree (~ 32 km) to close the energy and water budgets over the grid cells comprising the current study domain. The unique features of the VIC model lie in its representation of subgrid variability in soil infiltration capacity, incorporation of mosaic vegetation classes in any grid cell and precipitation varying spatially within a grid cell (Maurer et al., 2001). For this study, the soil layer depths were parameterized as being 0.10 m, 0.35 m and 1.00 m respectively from the surface to the deepest soil profile with gravity force serving as the driver of the drainage between the different soil layers.

Moreover, the representation of the unsaturated hydraulic conductivity is expressed as a function of the degree of saturation (Campbell, 1974). The deepest soil layer serves the function of generating the baseflow, which is tailored after the non-linear ARNO scheme (Todini, 1996). Additionally, there is transpiration of moisture from all soil layers depending on the fraction of roots depth prescribed in each layer (Wood et al., 1997). Similarly, the VIC model makes provision for the upward transport of soil moisture on the condition that there is sufficient gradient resulting from surface drying. The overall approach here is that precipitation in excess of the available infiltration capacity within a grid cell or the catchment essentially results in the formation of the surface runoff.

4.3.2.1 Dataset for Numerical Modeling

The meteorological forcing fields used to drive the VIC model over the Upper Assiniboine River Basin with its outlet at the Kamsack station (Figure 4.1) were retrieved from the Environment Canada twenty-two observation stations located within this catchment. This data source provided the daily precipitation, maximum and minimum daily temperature fields required to run the land surface model in the water balance mode. Additional data source used to retrieve some of the dataset required to drive the model to close the energy balance was from the North American Regional Reanalysis (NARR) dataset with a spatial resolution of 32 km × 32 km grids and a temporal resolution of three hours. The meteorological inputs from this source include downward longwave and shortwave radiations, vapor pressure, air pressures as well as the magnitude of the wind speed components.

Since the VIC model follows a grid-based modeling approach, it is desirable to spatially interpolate the station precipitation, maximum and minimum temperature fields into a 32 km × 32 km grids utilizing the Cressman Analysis Scheme (Cressman, 1959). An important consideration when mapping the precipitation field relates to the terrain effects in defining the spatial distribution of precipitation especially over mountainous regions. It is known that terrain effects dominate the spatial patterns or increases the variability in the observed precipitation. However, over the current study domain, the effect of terrain on precipitation variability is not so pronounced as this catchment is characterized by flat or gently sloping topography and the application of elevation correction may not result in any significant difference.

The digital elevation dataset obtained from the Shuttle Radar Topography Mission (SRTM) at a spatial resolution of 90 m was utilized in the delineation of the boundaries of the basin. Additionally, it equally enabled the determination of the channel networks and the principal flow direction with the resultant streams draining a total catchment area of 13000 km^2. Moreover, the land cover types characterizing the Upper Assiniboine River Basin is as shown in Figure 4.2 and as seen, agricultural cultivation is the mainstay of the local economies in this region as indicated by the highest proportion of the land surface occupied by the "cultivated land" class.

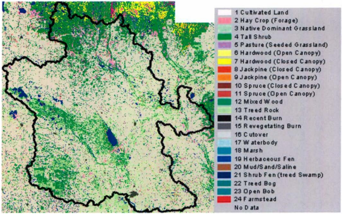


Figure 4.2: Land Cover types over the Upper Assiniboine River Basin

For modeling purposes over the catchment, the soil parameters utilized was based on the information obtained from the 5-minute Food and Agriculture Organization (FAO) global soil map. Several soil parameters are needed to build the soil database to drive the Variable Infiltration Capacity (VIC) model over a specific basin and some of these parameters are based on the work of Cosby et al. (1984). The maximum moisture storage for each soil layer corresponds to the depth of that layer multiplied by the porosity and this enables the estimation of the field capacity and the wilting point. The land data assimilation systems (LDAS) served as the repository from which the vegetation parameters such as the leaf-area index, albedo and the roughness length required to drive the model were retrieved.

4.4 Total Storage Deficit Index (TSDI) Formulations

The formulation of the Total Storage Deficit Index (TSDI; Yirdaw et al., 2008) bears resemblance to an earlier index developed by Narasimhan and Srinivasan (2005) generally referred to as the Soil Moisture Deficit Index (SMDI). This index relies essentially on the availability of meteorological and hydrological variables for drought characterization and monitoring and has potential application in the estimation of the total storage deficit (TSD) over a basin. Although, the most recent Canadian Prairie drought commenced in 1999 and terminated in 2004, the inter-comparison of the total storage deficit indices from the macroscale scale hydrologic model, VIC and that estimated from the remote sensing system, GRACE was particularly focused in the characterization of the devastating Prairie drought within the window time frame spanning from early 2002 to 2004. This is so because prior to March 2002, the GRACE remote sensing satellite mission was not launched, consequently, there is inexistence of the terrestrial moisture storage data from this source to enable the computation of the total storage deficit index (TSDI) over any basin globally.

This index is congruent in meaning to the more commonly used drought assessment tool developed by Palmer (1965) generally known as the Palmer Drought Severity Index (PDSI). In estimating this index over the Upper Assiniboine and Saskatchewan River Basins on the Canadian Prairie, the respective computed monthly total water storage anomalies from the two techniques were utilized in the estimation of the total storage deficit (TSD). This is expressed mathematically as:

$$TSD_{i,j} = \frac{TSA_{i,j} - MTSA_j}{Max\,TSA_j - Min\,TSA_j} * 100 \qquad \text{Equation 4.1}$$

From Equation 4.1, the $TSD_{i,j}$ represents the total storage deficit expressed in percent, $TSA_{i,j}$ is the monthly total storage anomaly retrieved from either the GRACE-based or from the VIC model computed terrestrial moisture storage and given in cm. The $MTSA_j$, $Max\,TSA_j$ and $Min\,TSA_j$ represent respectively, the long-term mean, maximum and minimum total moisture storage anomalies for the month which are also given in cm.

Using the Palmer (1965) approach, the computation of the TSDI can be achieved by taking into consideration the previous drought index in conjunction with the current month total storage deficit employing the expression given in Equation 4.2.

$$TSDI_i = p * TSDI_{i-1} + q * TSD_i \qquad \text{Equation 4.2}$$

From this latter expression, the parameters p and q can be determined from the cumulative TSD plot in conjunction with the relationships given in Equation 4.3. With these, the severity and duration of the recent Prairie drought from the standpoint of the terrestrial moisture storage deficit can be conveniently determined by making an incremental plot of the TSD.

$$p = 1 - \frac{m}{m + b}$$
$$q = \frac{C}{m + b} \qquad \text{Equation 4.3}$$

C in Equation 4.3 symbolizes the TSDI values retrieved from the best-fit line (drought monograph) for the period of dryness whereas m stands for the slope with b representing the intercept of the cumulative TSD plot.

4.5 Results and discussion

The plots of the cumulative total storage deficit (TSD) in percent computed from the terrestrial moisture storage retrieved from the GRACE-based technique over the Saskatchewan River Basin and that computed from the hydrologic model, VIC are illustrated in Figures 4.3 and 4.4 respectively. Given that the recent Canadian Prairies' drought commenced in 1999, the approach adopted here was to focus on the computation of the total moisture storage deficit from August 2000 for the simulation undertaken with the VIC model over the Upper Assiniboine River Basin to ensure that storage deficits over this basin due to the drought are well pronounced. Over the Saskatchewan River Basin, the estimation of the total storage deficit commenced two year later (August, 2002) as the gravity measurements from the GRACE satellite mission were not available prior to this time, hence, no retrieval of the terrestrial moisture storage from this source was possible.

These Figures (4.3 and 4.4) depict the temporal patterns in the historical dryness and wetness resulting from the study catchments. In the case of the Saskatchewan River Basin, the cumulative total storage deficit revealed that the last Canadian Prairie drought terminated around May 2004 as evident by the rising limb of the TSD curve in Figure 4.4. Correspondingly, the cessation of the last drought over the smaller basin was equally captured from the VIC model's computation of the total storage deficit around spring of 2004 (Figure 4.3). This in effect corresponds to the onset of the moisture storage recovery from the devastating last Canadian Prairies drought from the perspective of the simulated terrestrial moisture storage over the basins.

Moreover, the C parameter desired in the computation of the p and q duration parameters as given in Equation 4.3 above can be estimated from the line of best fit of the drought monograph. As given in Yirdaw et al. (2008) for the Saskatchewan River Basin, with the C value of -3, this yielded a corresponding p and q values of 0.304 and 0.070. From the total storage deficit computed from the VIC model, the line of best-fit corresponds to a value of -4 from the drought monograph and this in conjunction with Equation 4.3 resulted in p and q values of 0.147 and 0.089 respectively given that the estimated slope (m) and intercept (b) are -38.341 and -6.637 correspondingly.

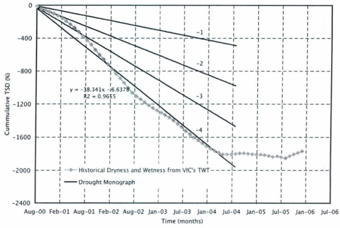


Figure 4.3: Cumulative Total Storage Deficit (TSD) over the UARB Domain Using the VIC-based Total Water Storage

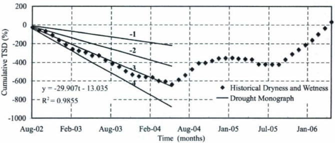


Figure 4.4: Cumulative Total Storage Deficit (TSD) over the SRB Domain Using the GRACE-based Total Water Storage

As would be anticipated, the severity of a drought event may not remain uniform through out the period of its occurrence as evapotranspiration and other hydrologic processes may vary considerably both temporally and spatially over the catchment coupled with other catchment dynamics. As depicted in Figure 4.3, there is a gradual increase in the severity of the recent Prairie drought as evident by the stepwise increase in the value of the drought monograph over the months under consideration. This increased severity of the drought from a terrestrial moisture storage perspective seemed to evolve and transit from a mild drought at the onset of the drought outbreak in February 2001 and worsened to a very severe drought by the month of February 2002. This level of severity was progressively sustained until the episode was terminated by the heavy spring precipitation in conjunction with snowmelt in May 2004 over the Upper Assiniboine River Basin. Moreover, this temporal pattern of the drought severity was equally well captured from the GRACE-computed total storage deficit over the larger Saskatchewan River Basin as shown in Figure 4.4.

The computation of the monthly total storage deficit is undertaken by substituting the values of p and q in Equation 4.2 and this yields Equation 4.4 for the Upper Assiniboine River Basin.

$$TSDI_t = 0.147 * TSDI_{t-1} + 0.089 * TSD_t \qquad \text{Equation 4.4}$$

Each of the terms in the above expression retains its definition as was stated in the preceding equations, therefore, using this equation, the monthly TSDI over the basin is generated and plotted as given in Figure 4.5. This plot shares strong similarity with the monthly computed TSDI using the GRACE-retrieved terrestrial water storage over the larger Saskatchewan River Basin as given in an earlier work by Yirdaw et al. (2008).

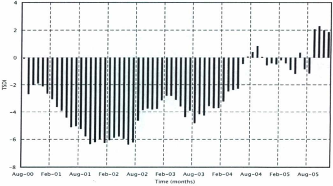


Figure 4.5: Monthly Total Storage Deficit Index over the UARB Domain

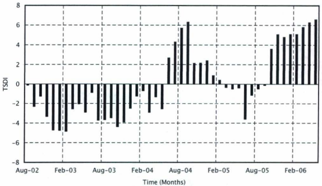


Figure 4.6: Monthly Total Storage Deficit Index (TSDI) over the SRB Domain (After Yirdaw et al., 2008)

As seen in Figure 4.5 for the individual monthly TSDI estimated from the VIC model simulations, there is a perpetuation of the negative total storage deficit over the basin from the first month of analysis (August, 2000) until about June 2004. A range of maximum amplitudes in the computed total storage deficit indices characterize the period commencing October 2001 up to July 2002 over the basin and this is indicative of the months of maximum severity of the last Canadian Prairies drought from the perspective of the catchment total subsurface storage. In the same vein, there was a perpetuation of the negative monthly total storage deficit over the larger Saskatchewan River Basin as estimated from the total water storage from the GRACE remote sensing satellite system as depicted in Figure 4.6. For the Saskatchewan River Basin, the cessation of the drought episode as seen in this latter figure occurred in June 2004 and high amplitudes of positive monthly total storage indices followed this.

As with the pattern observed in the time series of monthly total storage deficit index for the smaller Upper Assiniboine River Basin, spring 2004 precipitation over the Canadian Prairies although intense, was insufficient to cause the underlying subsurface moisture storage in this domain to completely recover from the devastating drought event. Hence, the momentary moisture gains over the two basins could not sustain the positive total water storage, thereby causing the basins to relapse into a state of negative total storage deficit thereafter. As a result, these yielded negative total storage deficit indices as computed from the total water storage dataset retrieved from the Variable Infiltration Capacity model as well as from the GRACE remote sensing system over these basins.

The cumulative total storage deficit index for the Upper Assiniboine River Basin is as shown in Figure 4.7 and the associated best-fit line has a slope, which is approximately -4. This indicates that the last Canadian Prairies drought as characterized utilizing the VIC model's simulations of the total moisture storage falls into the "very severe" category, which as observed is one level of severity higher than the same drought characterization undertaken over the larger Saskatchewan River Basin on the basis of the total water storage retrieval from the GRACE approach. A quick question that demands an answer is why did the two methods of characterizing the drought over two adjacent basins on the Canadian Prairies defined the severity of the last Prairie drought slightly different? A plausible response to this question is hinged on the spatial variability of precipitation over the two basins as evident in the differences in the average precipitation amounts over these basins with the Saskatchewan River Basin benefiting more from moisture inputs owing to the effects of the presence of the Rocky Mountains in its domain.

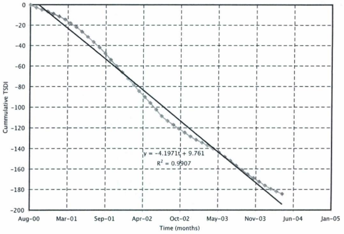


Figure 4.7: Cumulative total storage deficit index (TSDI) for the UARB Basin

In light of the foregoing analysis and comparison between the computed total storage deficit index and the strong similarities between the temporal patterns in the computed total storage deficit over the two Prairie basins estimated from the two independent approaches, the argument that there are strong deficiencies in the simulated watershed storage from hydrologic models as maybe opined initially may have to be re-assessed. This is so given that the performance of the VIC model simulations over the Upper

Assiniboine River Basin wherein the retrieval of the terrestrial moisture storage from GRACE resulted in poor signals.

Evidently, the GRACE gravity measurements could not capture the drought signals over this basin owing to the very coarse spatial resolution of this remote sensing system. On the contrary, it could be advocated here that for catchments globally with small spatial scales to enable the utilization of the terrestrial moisture storage retrieved from GRACE, terrestrial moisture storage estimated from the VIC or any other structurally sound models could serve as useful alternatives. Moreover, in the computation of the total storage deficit index over such catchments during anomalous climatic conditions that propagates extreme dryness through the terrestrial hydrologic systems, simulations of the total water storage from a physically based, spatially distributed model such as the VIC model could be resourceful for the computation of the monthly total storage deficit index if no constraint is placed on the availability of accurate meteorological forcing.

The computation of the total storage deficit index (TSDI) from the macroscale hydrological model, VIC depends to a very large extent on its ability to accurately simulate both the spatial and temporal patterns of the soil moisture store over the smaller Upper Assiniboine River Basin. The time series plot of the simulated average monthly soil moisture in the deepest moisture store from this land surface model is as illustrated in Figure 4.8c with the time series plot of the monthly total water storage depicted in Figure 4.8d. Additionally, the total monthly precipitation over the basin derived from the spatial interpolation of the station precipitation dataset is shown in Figure 4.8a with the observed streamflow measurement by the Water Survey of Canada at the Kamsack outlet illustrated in Figure 4.8b.

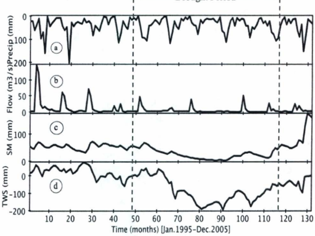


Figure 4.8: Monthly Time Series Plots of (a) Total Precipitation, (b) Measured Streamflow, (c) Deepest Layer Soil Moisture and (d) Total Water Storage over UARB Domain.

As seen from these plots, the Variable Infiltration Capacity model performed well in its ability to capture the onset and the cessation of the recent Canadian Prairies drought. It is worth mentioning here that snowmelt over the Prairie accounts for approximately 27% of the total precipitation input to these basins; with snow layer thickness reflecting high variability but a maximum of approximately 217 cm have been recorded so far on the Assiniboine River Basin. A closer look at the time series of Figures 4.8 a-d revealed that, although, there was a decline in the subsurface soil moisture store as well as in the estimated total water storage over the entire basin, there was no remarkable deviation in the total amount of precipitation input into the basin prior to the drought outbreak and during the drought episode. A plausible explanation for this pattern maybe attributed to the influences of the millions of wetlands that dominate this basin and serve as depression storages and the high rate of evapotranspiration enhanced by wind effects during the extended period of dryness that characterized the drought.

Over the Canadian Prairies, a number of processes have been adduced as the principal causes of extreme weather which gives rise to the recurrent extended period of dryness. Incidentally, the regional soil moisture over this domain is one of these mechanisms being currently investigated to ascertain its roles as a slow driver of the Canadian Prairies drought. It has been observed in Wu et al. (2001) that the inherent memory in the pores of the subsurface soil profile is considerably longer than the integral timescales for that of most atmospheric processes.

Figure 4.9 is the plots of the autocorrelation function versus lag in the time series of the anomalies in precipitation as well as in the corresponding subsurface soil moisture stores averaged over the Upper Assiniboine River Basin.

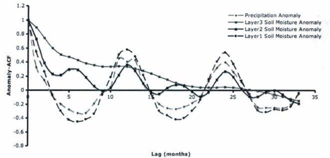


Figure 4.9: Autocorrelation Function Versus time Lag Plot for the UARB Domain

The value of this function at any specific time lag has been found to define the soil moisture memory in the subsurface moisture store. This plot shows that the soil moisture anomaly in the deepest layer has the longest persistence of all the hydroclimatic time series under consideration. Expectedly, the soil moisture anomaly in the deepest layer exhibits higher autocorrelation over longer lag times than the precipitation and this pattern agrees quite well with an earlier work by Lakshmi et al. (2004). The implications of this memory during anomalous climate that give rise to recurrent drought occurrences over the Canadian Prairies may be of pertinence for forecasting soil moisture states over this region.

4.6 Conclusions

The fact that the spatial scale of the gravity measurements from the Gravity Recovery And Climate Experiment (GRACE) satellite remote system is so coarse to enable the retrieval of the terrestrial moisture storage for the computation of the total storage deficit index (TSDI) over small catchments means that other ways of computing the terrestrial water storage over smaller catchments should be explored. Over the 13,000 km^2 Upper Assiniboine River Basin on the Canadian Prairies, there exists only a single grid cell of the GRACE gravity measurements, which did not capture the patterns of the last Canadian Prairies drought. Consequently, the computation of the total storage deficit index, which was formulated to characterize the Prairie-wide drought from the perspective of the subsurface terrestrial moisture storage using the total water storage from GRACE, becomes infeasible. The computation of the TSDI over the larger adjacent Saskatchewan River Basin and subsequent characterization of the last Prairie drought had been accomplished utilizing the terrestrial moisture storage from GRACE. This study had utilized a physically based, spatially distributed hydrologic model in the estimation of the total water storage over the smaller Upper Assiniboine River Basin which was then utilized in the characterization of the drought via computing the TSDI.

The monthly as well as the cumulative TSDI values estimated from VIC model computation of the total water storage were inter-compared with the computed TSDI values estimated from the terrestrial moisture storage obtained from the GRACE remote sensing satellite gravity measurements. Over the larger Saskatchewan River Basin, the GRACE-based computed TSDI led to the characterization of the last Prairie drought as severe whilst the TSDI value from the hydrologic model, VIC yielded a TSDI cumulative value that indicated that this drought fell under the classification of "very severe" drought. Since the estimated total water storage from the two different sources characterized the recent Prairie drought as severe from the computation over the two adjacent basins on the Prairie domain, this reflects the robustness of VIC model's parameterization in capturing the dynamics of the moisture storage patterns over the Canadian Prairies.

In order to ascertain the inherent memory in the hydroclimatic time series over the smaller Upper Assiniboine River Basin, the last segment of this article focused briefly on assessing the memories in the anomalies of the soil moisture at different soil depths in conjunction with the anomaly in the precipitation field over this basin. A follow up to this work maybe panned in the direction of understanding the implications of the inherent memory in the soil moisture of the deepest soil layer over this domain as a slow driver of the incessant Canadian Prairies drought.

Chapter 5

Memory Estimation in the Simulated Moisture Storages and other Hydroclimatological Variables over a Drought-Prone Canadian Prairies Catchment

Understanding the memory in land surface processes, such as that in the subsurface moisture storage has great implication for seasonal weather prediction over a catchment. The Canadian Prairies is a region of intense and recurrent drought outbreaks with myriad negative impacts on all sectors of the economy due to the associated high mitigation costs. However, given that there are no physical observations of soil moisture at depths of hydrological importance or measurements of the total water storage, it is infeasible to undertake studies on land-atmosphere interactions. This chapter is focused on estimating the memory in the simulated deep soil moisture and total water storages over the 406,000 km^2 Saskatchewan River Basin (SRB) in the Canadian Prairies using a physically-based land surface model. Using relevant statistical techniques, it is possible to quantify the persistency in the anomalies of the meteorological variables, modeled moisture storage components as well as the memory in the computed terrestrial storage deficit indices (TSDIs) estimated from the Gravity Recovery And Climate Experiment (GRACE) remote sensing satellite system and the Variable Infiltration Capacity (VIC) model. Finally, given the similarity in the simulated deep moisture storage anomaly and the model-based TSDI, it can be inferred that the former could serve as an indicator of drought over the large Prairie sub-catchment.

5.1 Introduction

The Canadian Prairies that stretches across three provinces (Manitoba, Saskatchewan and Alberta) is a region of frequent devastating drought occurrences. Given that the impacts of these recurrent drought outbreaks are far-reaching, drought mitigation cost in these provinces has remained the highest in comparison with any other natural disaster over this region. Understanding the processes, which lead to drought initiation, evolution, continuation and cessation over the Canadian Prairies require an understanding of the intricate relationship that exists between the atmospheric and land surface processes over this domain. In accordance with Agboma et al. (2009), the regional subsurface soil moisture over this domain is one of the hydrologic variables being currently investigated to ascertain its role as a slow driver of the Canadian Prairies drought. As noted in Mahanama et al. (2003), an anomalous atmospheric condition manifesting itself in the form of heavy rainfall or extremely dry spell (drought) could propagate an anomaly into the subsurface moisture store which may not dissipate until weeks or months later. Owing to this decreased rate of dissipation, the soil therefore develops the ability to recollect the wet or dry spell that generated the anomaly long after the atmosphere had exited from an anomalous condition. Moreover, a higher evaporation rate could be produced by a wet soil condition that was induced by heavy rainstorm event and this can subsequently induce additional precipitation events through local recycling and modifications in the large-scale circulation, which would ultimately help to sustain the original soil moisture anomaly (Koster and Suarez, 2001).

Soil moisture anomalies can persist for months, and although a paucity of observations prevents an unambiguous demonstration of soil moisture impacts on precipitation. These impacts are often seen in atmospheric general circulation model (AGCM) studies. As revealed in some AGCM studies, oceanic impacts on precipitation are small relative to soil moisture impacts during summer in continental mid-latitudes (Koster et al., 2004). The identification of regions on the Earth's surface where soil moisture anomalies have substantial impacts on precipitation could portend important implications for the design of seasonal prediction systems. Additionally, this can be resourceful for the development of ground-based and satellite-based strategies for monitoring soil moisture if such impacts were found to be local.

From the generated ensembles of boreal summers (June to August) simulations resulting from all the models participating in the Global Land-Atmosphere Coupling Experiment (GLACE), the estimated land-atmosphere coupling strength have revealed several distinct hotspots. These hotspots have been spotted in the Central Great Plains of North America, the Sahel, and Equatorial Africa. These hotspots of regions around the globe where precipitation variance is solely explained by variations in soil moisture.

Over a particular basin, the inherent memory in the soil could prove useful especially for long-term weather prediction. This is so because atmospheric variables do possess very short memory span and therefore, seasonal prediction of meteorological conditions cannot solely rely on the initialization and modeling of the atmosphere. In accordance with Koster and Suarez (2001), seasonal forecasting must rather rely on the response of the atmosphere to the components of the land surface such as the soil moisture whose anomalies dissipate over much longer timescales and that can be predicted months in advance. Hence, the pertinence of soil moisture memory in gaining a better insight into the land surface-atmosphere interactions over a domain such as the Canadian Prairies cannot be over-emphasized given that it can be used in the seasonal forecasting of the different atmospheric fields (precipitation, temperature, net radiation). However, the quantification of the inherent memory in the soil moisture store over the Canadian Prairies sub-catchments is highly constrained by the absence of observed soil moisture measurements. In light of this, the main objective of this study is to apply statistical techniques in the estimation of the inherent memory in the simulated soil moisture store from a physically based, spatially-distributed hydrologic model driven with observation-based forcing over a large catchment. It is anticipated that with the use of statistical techniques such as the estimation of anomaly persistence, autocorrelation function and wavelet analysis, it might be possible to extract some causal relations between the land surface processes over the basin (soil moisture and total water storage) and the meteorological variables such as, precipitation and net radiation. An additional goal of this study is to estimate the persistence in the simulated total water storage as well as those in the atmospheric fields of precipitation, radiation and evapotranspiration to ascertain what level of relationship exists between these variables over the study area. Furthermore, this study attempts to evaluate and compare the memory in the computed monthly terrestrial storage deficit index (TSDI; Yirdaw et al., 2008) from a hydrological model and that estimated from the terrestrial moisture storage retrieved from the Gravity Recovery And Climate Experiment (GRACE; Tapley et al., 2004) satellite remote sensing system. The interest here is to evaluate which of these differently computed indices is a better descriptor of the extreme weather condition over the Canadian Prairies.

In order to reproduce a realistic monthly time series of soil moisture dataset for use in the computation of the autocorrelation coefficients, this study employs the Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Nijssen et al., 1997; Lohmann et al., 1998) which was driven over the 406,000 km^2 Saskatchewan River Basin (SRB) which stretches across the three Canadian Prairies provinces utilizing observed meteorological data. This model was driven at a daily time step to close the water budget over this large catchment using meteorological forcing retrieved from the Meteorological Services of Canada (MSC) database whilst the North American Land Data Assimilation System (NLDAS) served as the repository from which the soil and vegetation parameters were obtained. The simulation period spans from January 1995 to December 2005 but emphasis is placed on analyzing the temporal patterns of the simulated soil moisture and the total water storage during the period of the recent devastating Canadian Prairies drought, which commenced in 1999 and continued until its cessation in 2004. It is hypothesized in this study that given the myriad constraints posed due to unavailability of measured soil moisture data over the drought-prone Canadian Prairies sub-catchments such as, in the Saskatchewan River Basin, it is possible to overcome this challenge by relying on the simulated output of the soil water content from a structurally-sound and physically-based hydrological model such as, the Variable Infiltration Capacity (VIC) model.

5.2 Study Area Description

The Saskatchewan River Basin (SRB) is located on the south of the Mackenzie River Basin and has been described as one of the most diverse basins in North America (Szeto, 2007). The gross drainage area bordering this river basin with its Grand Rapids outlet is approximately 406,000 km^2 and spans through three Canadian Provinces. This river is the fourth largest in Canada and its tributaries drain most of the Canadian Provinces. The elevation band ranges approximately from 214 to 3200 m with the portion of the basin in the province of Alberta exhibiting higher topographic relief and decreases progressively as the outlet of the basin in Grand Rapids Manitoba is approached. The basin has strong economic implications for Canada, as it is one of the most important agricultural regions of the country.

Topographically, the basin's terrain is characterized by a gentle to moderately undulating surface with the northeast flank exhibiting a steeper relief. The ground surface is intersected by glacial spillways and meltwater channels and is underlain by glacial deposit consisting mostly of clay-rich glacial tills. Approximately 300 m of cretaceous shale associated with the Riding Mountain Formation underlie the glacial deposit. The glacial tills and the shale have very low permeability, and thus regional groundwater flow is likely minimal. The principal source of surface water runoff for the Saskatchewan River Basin is the winter snowfall and accounts for approximately one-third of the total precipitation falling over this basin.

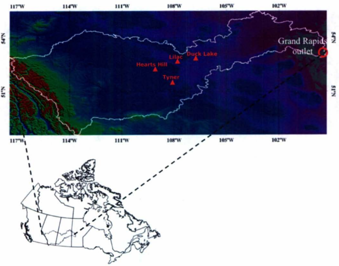


Figure 5.1: Saskatchewan River Basin showing the locations of the deep observation wells.

5.3 Methods and Datasets

5.3.1 Hydrologic- and GRACE-based Computation of the Total Moisture Storage

Similar to the modeling approach employed in the simulation of the total water storage change over the smaller and adjacent Upper Assiniboine River Basin (UARB) as discussed in Agboma et al. (2009), the Variable Infiltration Capacity (VIC) model was driven at a daily time step with a grid resolution of 0.125 x 0.125 degree in the computation of the mass balance components over the 406,000 km^2 Saskatchewan River Basin. This model estimates the total water storage as the integral sum of the soil moisture storage, snow storage, canopy storage as well as surface water storages.

The soil layer depths were parameterized as 10 cm, 30 cm and 100 cm respectively from the surface to the deepest soil profile with gravity force and suction serving as the driver of the drainage between the different soil layers. The soil water contents of the upper two layers generally determine the amounts of evaporation and infiltration over the basin. Furthermore, the representation of the unsaturated hydraulic conductivity is expressed as a function of the degree of saturation (Campbell, 1974). The deepest soil layer serves the function of generating the baseflow, which is tailored after the non-linear ARNO scheme (Todini, 1996). Also, there is transpiration of moisture from all soil layers depending on the fraction of roots depths prescribed in each layer (Wood et al., 1997). Similarly, the VIC model makes provision for the upward transport of soil moisture on the condition that there is sufficient gradient resulting from surface drying. The overall approach here is that precipitation in excess of the available infiltration capacity within a grid cell or the catchment essentially results in the formation of the surface runoff.

The Meteorological Services of Canada (MSC) database served as the repository for the retrieval of the daily precipitation as well as the minimum and maximum temperature daily fields whilst the vertical and the horizontal components of the wind speed was obtained from the North American Regional Reanalysis dataset with a spatial resolution of 32 x 32 km and regridded to the resolution of the VIC model run over the basin.

Employing the Cressman analysis technique (Cressman, 1959), 270 stations' dataset comprising 11 years of observed precipitation, minimum and maximum temperature records commencing from 1995 to 2005 were spatially interpolated into a network of grids over the basin to provide the meteorological forcing for the model run. In developing the input parameters for the VIC routing model, which handles the horizontal transport of fluxes over the catchment, the 90 m resolution Shuttle Radar Topography Mission (SRTM) elevation data was utilized. Similarly, the soil and vegetation parameters were retrieved from the North American Land Data Assimilation System (NLDAS) domain at the same spatial resolution as that of the VIC run over the catchment.

In order to determine the water content (w) stored on the surface and within the soil at daily and monthly time steps, the expression in Equation 5.1 is adopted.

$$\frac{\partial w}{\partial t} = -ET(s,t) + P(t) - Q(s,t) \qquad \text{Equation 5.1}$$

Where the evapotranspiration rate $ET(s,t)$, a function of storage and time, is simulated from the model according to the specified internal evaporation scheme utilizing observed precipitation and other surface atmospheric variables such as air temperature, radiation and wind speed which is defined at 2-m above the ground surface. Additionally, the measured precipitation rate, P(t) as well as the simulated streamflow, $Q(s,t)$ are utilized in conjunction with the evaporation rate in estimating the total moisture storage change over the basin. The computed monthly total water storage anomaly, which was averaged over the catchment, follows the expression given in Equations 5.2:

$$TWS_{monthly} = W_{monthly} - \overline{W_{monthly}} \qquad \text{Equation 5.2}$$

where $w_{monthly}$ represents the monthly values of the computed change in water content (w) and $\overline{w_{monthly}}$ is the mean of the time series of the monthly time series of the change in water content.

A detailed discussion on the computation of the total water storage from the Gravity Recovery And Climate Experiment (GRACE) remote sensing system has been undertaken in earlier works by the authors as in Yirdaw et al. (2008).

5.3.2 Terrestrial Storage Deficit Index, Autocorrelation and Wavelet Analysis

The terrestrial storage deficit index (TSDI) utilizes both hydrological and meteorological data in the characterization of a drought episode over a basin. It essentially relies on the computed monthly total water storage anomalies as computed from a hydrological model, such as those from the VIC model and the GRACE-based terrestrial moisture storage. The relevant mathematical relationships used in the estimation of the monthly terrestrial storage deficit index over the Saskatchewan River Basin have been explained in earlier works by Yirdaw et al. (2008) and Agboma et al. (2009). Subsequently, these computed monthly TSDI values were then evaluated using statistical tools as briefly discussed in the following section.

In this study, the estimation of the autocorrelation functions (Bras and Rodriguez, 1984; Awumah et al., 1990; Hipel and McLeod, 1994) was employed in the evaluation of the persistence and the temporal variabilities in the simulated and measured hydroclimatic time series over the basin. These techniques were also employed to assess potential causal relationship that may exists between the hydrologic variables simulated by the VIC model as well as the corresponding total storage deficit indices estimated from the remote sensing source, GRACE as well as that computed from the hydrologic model output over this large catchment.

In accordance with Delworth and Manabe (1988), if the time series of hydroclimatic variables resembles a red noise that can be represented by the first order Markov Process, therefore, the autocorrelation value can be calculated using the following expression:

$$r(t) = \exp\left(\frac{t}{\tau}\right) \qquad \text{Equation 5.3}$$

where τ represents the decay timescale and r is the autocorrelation that will reach the e-folding time when $t=\tau$. The autocorrelation function analysis is a well-established technique in time series analysis with positive autocorrelation being a specific form of persistence wherein a system exhibits a tendency to remain in the same state during successive observations. Over the Saskatchewan River Basin, the approach adopted was to employ the lag one-month autocorrelation to estimate τ. Moreover, the autocorrelation value provides a single parameter measure of the memory or persistence of the hydroclimatological variable and can also be used as a measure of the predictability (Wei et al., 2005).

In order to decompose the generated time series over this large basin into time and frequency space to enable the detection and isolation of patterns across temporal scales in the hydroclimatic time series, a continuous wavelet transform (Torrence and Compo, 1998; Lakshmi et al. 2004) using the Morlet wavelet was employed. This transform allows the detection of the location-dependent, amplitude and phase for the different frequencies exhibited in the spatial series being analyzed. Generally, the continuous wavelet transform serves as an alternative approach to the short time Fourier transform in overcoming the problems of resolution associated with the later by transforming the simulated time series data from the model into varying frequencies with different resolutions. Essentially, this approach enables the analysis of the dominant features in the spatial series locally with a detailed match to the associated scale such that broad features are resolved at large scales whilst fine features are captured and resolved at smaller scales (Si, 2007). This characteristic of the wavelet transform is especially useful for assessing spatial variations that are non-stationary and possess transient components as well as features at various scales that have singularities.

5.4 Results and discussion

Water level records from deep observation wells located over the Saskatchewan River Basin were obtained directly from the Saskatchewan Watershed Authority [http://www.swa.ca/WaterManagement/Groundwater.asp] and were utilized to assess the simulated total moisture storage from the VIC hydrologic model as illustrated in Figure 5.2.

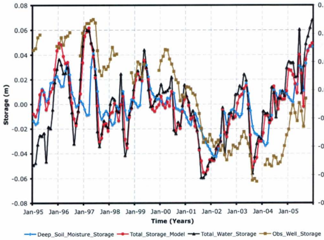


Figure 5.2: Simulated storages from the VIC hydrologic model and storage estimate from deep well measurements over the Saskatchewan River Basin.

As discussed in the methodology section, the VIC model runs span from January 1995 to December 2005 at daily time steps; however, the plotted storages were averaged over the large catchment and aggregated to monthly time steps. Aggregating the simulated storages to monthly timescale was necessary in order to better reveal the temporal feature of the recent Canadian Prairies drought. The data series plotted in Figure 5.2 labeled "Total_Storage_Model" represents the integral sum of the soil moisture storage in the upper, intermediate and deep moisture stores in conjunction with the modeled snow water equivalent (SWE) and the canopy storage. Moreover, the data series plotted in Figure 5.2

and labeled "Total_Water_Storage" is the resulting computed total water storage obtained using Equations 5.1 and 5.2 above. Plotting these two monthly time series is important to ensure that there are no wide disparity between the modeled storage and the estimates made directly from the water budget equation.

As illustrated in Figure 5.2, the recent Canadian Prairies drought was captured by the hydrologic model VIC as evident in the gradual decrease in the deep moisture storage as well as in the computed total moisture storage from 1999 to about the end of 2003. Although, there appeared to be a brief recovery in the subsurface moisture storage from mid-2003 but this was not sustained and the moisture depletion continued until the eventual slow recovery in 2004. The drought episode was truncated by the heavy precipitation events, which occurred in the later part of 2004 over the basin. A similar trend can be seen in the temporal pattern of the storage measurements for the deep wells in the basin. The pronounced moisture storage recovery noted in the time series of the deep and total modeled storage is not as pronounced in the deep observation well measurements possibly due to the slow response of these deep well to short precipitation events.

Over the 11 years of moisture storage simulation with the VIC hydrologic model, the maximum monthly total water storage is approximately 60 cm of equivalent water thickness whilst the maximum monthly storage averaged over the four deep wells is approximately 100 cm. In the same vein, the maximum moisture storage in the deep layer from the hydrologic model yielded about 40 cm of water thickness over the period of numerical simulations in the catchment.

The plot of the monthly total storage deficit index (TSDI) computed from the hydrologic model, VIC and the GRACE gravity measurements are illustrated in Figure 5.3. Although, the last Canadian Prairies drought commenced in 1999, the GRACE-based TSDI as revealed in the plot of Figure 5.3 commenced in August 2002 since prior to this time, the terrestrial moisture storage from the GRACE mission was not available. As evident in this plot, there is a good level of agreement between the total storage deficit indices computed from the VIC model with that computed from the remote sensing source, GRACE. Again, as depicted in this figure, there is a progressive gradual decrease in the monthly TSDI values from the hydrologic model from 1999 until it went completely negative in 2001 through to mid-2004. As captured by the land surface model, the range of maximum negative TSDI values lies between July 2001 and July 2002, which agrees with the most intense period of drought as witnessed in the Canadian Prairie provinces.

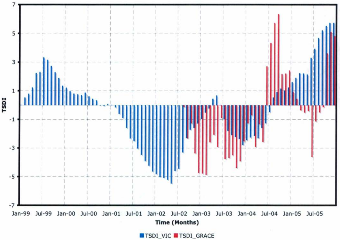
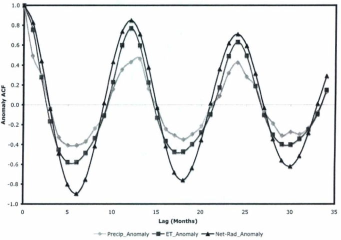
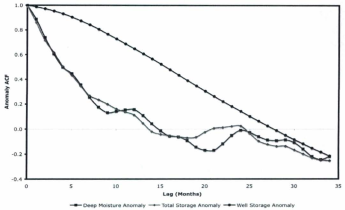


Figure 5.3: Monthly Total Storage Deficit Index (TSDI) computed from the VIC hydrologic model and the GRACE-based terrestrial moisture storage.

Furthermore, the GRACE-computed terrestrial moisture storage revealed strong positive TSDI values in the early part of the recovery from the devastating drought episode, which transited into negative values before shifting to positive values again in the subsequent months. However, the hydrologic model computation of the TSDI revealed a progressive increase in the TSDI values corresponding to the pattern of precipitation events, which led to the cessation of the recent Prairie-wide drought.

Furthermore, the autocorrelation functions for the anomalies in the meteorologic variables of precipitation, net radiation and that of evapotranspiration over the Saskatchewan River Basin are investigated and illustrated as shown in Figure 5.4a. Correspondingly, the computed autocorrelation functions for the anomalies in the basin storage components comprising those of the deep layer moisture storage, the total water storage and observation well storage are plotted in Figure 5.4b. Also, a plot of the computed autocorrelation function in the monthly terrestrial storage deficit estimated from the hydrologic model and the GRACE gravity measurements are shown in Figure 5.4c. From an assessment of the plots in Figure 5.4a, the autocorrelation functions in these meteorologic fields disappear just after a few weeks (approximately 3 months) supporting earlier conclusions that the memory or persistence in the anomaly of atmospheric variables, such as that in the precipitation field is short-lived.




1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Anomaly ACF
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5
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25
30
35
Lag (Months)
Deep Moisture Anomaly
Total Storage Anomaly
Well Storage Anomaly

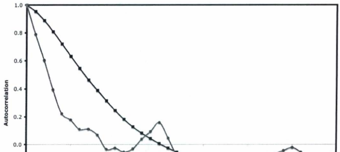
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Autocorrelation
0
5
10
15
20
25
30
35
Lag (Months)
TSDI_VIC
TSDI_GRACE

Figure 5.4: Computed autocorrelation functions versus monthly lagged times for anomalies in (a) precipitation, net radiation and evapotranspiration (b) simulated deep layer moisture storage, simulated moisture storage and well observation storage and (c) autocorrelation functions in the VIC-computed and GRACE-based TSDI.

However, during the recent drought period over this large catchment (1999-2004), the anomalies in the storage components as plotted in Figure 5.4b exhibit longer persistency, which signify longer memory as compared to the anomalies in the meteorologic fields. The anomalies in the observation well storage reveals the largest autocorrelation over monthly lagged time relative to those from the corresponding simulated deep layer moisture storage as well as the total water storage over the catchment. In Figure 5.4c, the VIC-computed autocorrelation resulted in longer persistence than that computed from the GRACE-based technique. As depicted in Figures 5.4b and 5.4c, it is apparent that there is a coincidence in the persistence in the model-estimated TSDI with that computed for the deep layer soil moisture. Since the TSDI has been used and can be used in drought characterization over a catchment, it can be inferred on the basis of the estimated memory that the anomalies in the simulated deep layer soil moisture from the VIC model can equally serve as a predictor of Canadian Prairies drought. This conclusion is congruent with an earlier study of droughts and floods over the Upper Mississippi River Basin conducted by Lakshmi et al. (2004).

Figure 5.5 comprises multiple plots of the continuous wavelet transform for the anomalies in the meteorologic variables (precipitation, net radiation, evapotranspiration) as well as those in the storage components (simulated deep soil moisture, total water storage and observation well storage) in conjunction with the wavelet power spectral generated for the terrestrial storage deficit index computed respectively from the hydrologic model, VIC as well as that based on the remote sensing source, GRACE. The continuous wavelet transform was computed for the hydroclimatic time series from January 1999 to December 2005 to cover the period of the last Canadian Prairies drought, however, the wavelet power spectrum computed for the GRACE-based TSDI commenced from August 2002 to December 2005 for the same reason stated earlier on with respect to the unavailability of GRACE gravity measurements earlier than August 2002.

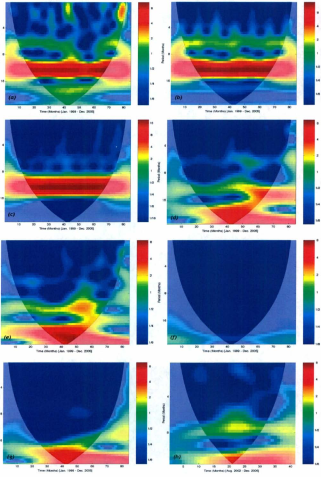
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Period (Months)
Time (Months) [Jan. 1999 - Dec. 2005]
Time (Months) [Aug. 2002 - Dec. 2005]

Figure 5.5: Continuous wavelet transforms in the anomalies of (a) precipitation (b) net radiation (c) evapotranspiration (d) simulated deep soil moisture storage (e) total water storage an (f) deep well storage and the continuous wavelet transforms for the (g) model-based TSDI and (h) GRACE-based TSDI

The vertical axes in these spectral plots are the Fourier periods, which are in monthly units whilst the horizontal axes represent the temporal length in monthly steps for the different hydroclimatic variables. Additionally, the cone of influence in the individual wavelet power spectrum represents the lower bound of the demarcation implying that any information below this demarcating line may be of spurious nature owing to edge effects as well as associated problem of short data record length. As seen in the wavelet power spectral plots for the meteorological variables, it is apparent that the 12-month period which represents the annual cycle in these variables are consistently dominant all through the temporal scale investigated over the large Saskatchewan River Basin.

However, the wavelet power spectral plots generated from the continuous wavelet transform for the simulated deep soil and total water storage (as shown in Figures 5.5d and 5.5e) over the catchment yielded a dominant feature which is much higher than that revealed in the meteorological variables. This dominant feature, which is its low-frequency nature, exceeds the 16-month period as evident in the wavelet power spectral plots of the simulated deep soil moisture and total water storages over the basin. This is also visible in the continuous wavelet transform spectrum in the model-computed terrestrial storage deficit index and to some extent in the wavelet spectrum in the

GRACE-based terrestrial storage deficit index. The implication of the similarity between the generated wavelet power spectrum of the VIC-simulated deep soil moisture anomaly and the wavelet power spectral for the terrestrial storage deficit indices from the hydrologic model and the remote sensing source over the this large catchment further strengthens the earlier argument that the VIC-simulated deep soil moisture anomaly can be used as an indicator of extreme dryness over this large catchment. On the contrary, no visible dominant feature exists in the wavelet power spectrum for the deep well storage over the basin. Given that the estimated autocorrelation function far exceeds that of the computed TSDI from the GRACE remote sensing satellite system and that from the hydrologic model, there is a likelihood of an over-prediction of the memory from the well storage and therefore may not be useful as an indicator of the recurrent drought over the Canadian Prairies sub-catchment.

5.5 Conclusions

Information on soil moisture and total moisture storages over a catchment is of importance in any land surface-atmosphere interaction studies. However, over the drought-prone Canadian Prairies sub-catchments, there are no soil moisture and total water storage measurements thereby placing constraints on studies that focus on the intricate inter-relationships between the land surface variables and atmospheric processes. Furthermore, given that the inherent memory in the subsurface moisture store is especially useful for long-term weather prediction as well as for seasonal forecasting of different meteorological fields, this study has therefore focused on the estimation of the memory in a number of different hydroclimatological fields over the 406,000 km^2

Saskatchewan River Basin in the Canadian Prairies. Since subsurface moisture storage information are lacking, the study employed the Variable Infiltration Capacity (VIC) model in reproducing the deep soil moisture as well as the total water storage over the basin which were then analyzed using statistical tools such as lagged one-month autocorrelation and continuous wavelet transform to assess the persistency in these variables.

Over the large SRB, the maximum monthly total water storage is approximately 60 cm of equivalent water thickness whilst the corresponding maximum monthly storage averaged over the four deep wells located on the basin yielded about 100 cm of water thickness. Similarly, approximately 40 cm of equivalent water thickness was estimated for the simulated moisture storage in the deep store from the hydrologic model. Moreover, the persistence observed in the meteorologic variables over the basin dissipated rapidly in less than a three-month time lag. However, the memory in the modeled storage components dissipated over much longer timescale, therefore, implying that they could be more useful for seasonal weather prediction purposes.

Given the level of agreement in the estimated memory for the hydrologic model-based terrestrial storage deficit index and the persistence estimated for the simulated deep moisture storage anomaly over this basin, it was inferred that the latter could be used as a descriptor of the Canadian Prairies drought. Additionally, this study has revealed on the basis of the generated continuous wavelet transform, that the dominant feature in the modeled storage components is essentially their low-frequency nature which is very similar to the dominant feature visible in the spectral plots for the computed TSDI from the hydrologic model as well as that from the GRACE remote sensing satellite system.

Chapter 6

Conclusions and Recommendations

6.0 Conclusions

The central goal of this thesis has been to understand and capture the relevant hydrologic processes over drought-prone, wetland-dominated Canadian Prairies sub-catchments. Of noteworthy is the effort of the scientists at the National Water Research Institute (NWRI) located at Saskatoon in modeling streamflow and snow redistribution processes in a number of Prairie sub-basins, which unfortunately did not yield much success. Given that the cost of drought mitigation over the Canadian Prairies is very expensive and since future drought occurrences are expected to affect this region in various negative ways, it becomes imperative to understand the pertinent processes in the land surface system that could influence the atmospheric processes over this large domain. This thesis has focused on deploying the Variable Infiltration Capacity (VIC) model over two Canadian Prairies sub-catchments in order to capture the temporal and spatial dynamics in the patterns of the seasonal and inter-annual soil moisture storage as well as changes in the total water storage anomaly averaged over the basins for a period of 11 years commencing 1994. Moreover, the conclusions reached based on the three different case studies undertaken in the course of this thesis are summarily discussed in the subsequent paragraphs.

As revealed in the first case study, the Variable Infiltration Capacity model was driven over 13,000 km^2 Upper Assiniboine River Basin in the Canadian Prairies to solve for the mass and energy budgets with the objective of reproducing the unique patterns in the spatial and temporal distribution of the soil moisture at depths exceeding 1 m over this basin. Since there are no measured soil moisture dataset at this depth to validate how well the model performed in capturing the relevant soil hydrologic processes over this basin, it was necessary to validate the model's other simulated outputs employing observed measurements (streamflow, snow depths) as well as estimates of the total moisture storage from satellite measurements and geological weighing lysimeters. After careful assessment of the simulated outputs from the Variable Infiltration Capacity model, which were found to be of acceptable quality, this first case study subsequently focused on assessing the spatial distribution of the subsurface soil moisture over the large catchment before, during and after the recent Prairie-wide devastating drought.

Furthermore, the temporal pattern depicted in the generated plots as simulated by the hydrologic model is consistent with the observed cycle of the last drought outbreak over the Canadian Prairies. Expectedly, the subsurface soil water content spatial distribution over the Upper Assiniboine River Basin simulated from the land surface model during the drought years is far lesser than the corresponding simulated soil moisture pre- and post- last drought outbreak over the Prairie. Overall, the northeastern flank of this large catchment revealed a higher degree of soil wetness when compared to other parts of the basin for the temporal domain considered in this case study.

The issue associated with the coarse resolution of the Gravity Recovery And Climate Experiment (GRACE) satellite remote system to enable the retrieval of the terrestrial moisture storage for the computation of the total storage deficit index (TSDI) over small-and medium-scale catchments was brought into focus in the second case study addressed in this thesis. The terrestrial water storage data retrieved from the GRACE measurements over the Upper Assiniboine River Basin did not reveal the expected drought signature during the temporal frame analyzed (Jan.1994 – Dec. 2005). Hence, the computation of the total storage deficit index, which was formulated to characterize the recent Prairie-wide drought from the perspective of the subsurface terrestrial moisture storage utilizing the total water storage from GRACE, becomes infeasible. Given that the computation of the TSDI over the larger adjacent Saskatchewan River Basin and subsequent characterization of the last Prairie drought had been accomplished utilizing the terrestrial moisture storage from GRACE. In the second case study, the land surface model, VIC was driven over this catchment using observation-based forcing in the estimation of the total water storage, which was then utilized in the characterization of the 1999-2004 Canadian Prairie drought by computing the TSDI.

The monthly as well as the cumulative TSDI values based on the VIC model computation of the total water storage were subsequently compared with the computed TSDI values estimated from the terrestrial moisture storage obtained from the GRACE remote sensing satellite gravity measurements. Over the larger Saskatchewan River Basin, the GRACE-based TSDI resulted in the characterization of the last Prairie-wide drought as severe whereas the TSDI value estimated from the hydrologic model, VIC resulted in the classification of the same drought as very severe. Since the estimated total water storage from the two different sources characterized the recent Prairie drought as severe sequel to the computation of the corresponding TSDI values over the two adjacent basins, this reflects the robustness of the VIC model's parameterization in capturing the dynamics of the subsurface moisture storage patterns over the Canadian Prairies.

In the last case study undertaken, the determination of the inherent memory in the subsurface moisture storage simulated from the hydrologic model in conjunction with those from other hydroclimatological variables over the 406,000 km^2 Saskatchewan River Basin in the Canadian Prairies was accomplished. This inherent memory in the subsurface moisture store is especially useful for long-term weather prediction as well as for seasonal forecasting of different meteorological fields. Since subsurface moisture storage information are lacking at depth of hydrological interest over this region, the study employed the hydrologic model, VIC in reproducing the deep soil moisture as well as the total water storage over this large basin which were then analyzed utilizing statistical techniques such as lagged one-month autocorrelation and continuous wavelet transform to assess the persistency in these variables.

Over the large SRB, the maximum monthly total water storage is approximately 60 cm of equivalent water thickness whilst the corresponding maximum monthly storage averaged over the four deep wells located on the basin yielded about 100 cm of water thickness. Similarly, approximately 40 cm of equivalent water thickness was estimated for the simulated moisture storage in the deep store from the hydrologic model. Also, the persistence observed in the meteorologic variables over the basin dissipated rapidly in less than a three-month time lag. However, the memory in the modeled storage components dissipated over much longer timescale, therefore, implying that they could be more useful for seasonal weather prediction purposes.

Given the level of agreement in the estimated memory for the hydrologic model-based terrestrial storage deficit index and the persistence estimated for the simulated deep moisture storage anomaly over this basin, it could be inferred that the latter could be used as a descriptor of the Canadian Prairies drought. Finally this case study has revealed on the basis of the generated continuous wavelet transform, that the dominant feature in the modeled storage components is essentially their low-frequency nature which is very similar to the dominant feature visible in the spectral plots for the computed TSDI from the hydrologic model as well as that from the GRACE remote sensing satellite system.

6.1 Recommendations

In order to clearly account for the total surface area occupied by wetlands, sloughs and potholes over Canadian Prairies sub-basin, airborne photography that produces high-resolution images may offer some solutions. The main challenge for future watershed modeling would then be how to incorporate these areas captured in airborne photography into physical parameters that can be calibrated within the land surface scheme. Additionally, it might be helpful to rely on higher resolution digital elevation dataset in the generation of the input data necessary for driving the routing model within the Variable Infiltration Capacity model so as to better produce a more representative river flow direction network within a basin.

Given that the Canadian Land Surface Scheme (CLASS) is quite popular amongst some Canadian researchers and hydrologists for modeling cold region hydrologic processes, it will be quite useful to assess the performance of CLASS in simulating the spatial and temporal distribution of soil moisture at different depths over the Canadian Prairies. The output from these simulations can then be compared with that resulting from the Variable Infiltration Capacity model to ascertain where there are potential similarities and discrepancies.

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