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MODELLING STREAMFLOW AND SEDIMENT EXPORT IN POTHOLE-DOMINATED, COLD-CLIMATE PRAIRIE WATERSHEDS USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

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Abstract: The Canadian prairies are dominated by millions of depressions, or potholes, that have a significant impact on streamflow generation in the region. It has been difficult to incorporate the dynamic storage, or "fill and spill", processes of these depressions in hydrologic models of prairie watersheds. Additionally, the region has a cold-climate, where snowmelt and soil thaw processes impact the generation of streamflow, sediment export, and non-point source pollutants. This paper discusses improvements to the hydrological model SWAT (Soil and Water Assessment Tool) for modelling streamflow and sediment export in two pothole-dominated watersheds in Saskatchewan: the Assiniboine and Qu'Appelle watersheds. The Pond module of SWAT was modified to incorporate dynamic storage in the potholes using a probability distribution to assess how many of the depressions would be spilling and therefore contributing to streamflow. Soil erodibility coefficients were adjusted seasonally to improve estimates of sediment export. Improved performance for simulating streamflow was seen over the existing SWAT Pond module for simulating landscape storage. Sediment export estimates improved when using seasonally adjusted erodibility coefficients over annual sediment erodibility coefficients.

1 INTRODUCTION

1.1 Background

There is much interest in predicting streamflow and water quality for streams in the prairie region of Canada, both for development of capabilities to better assess potential flooding and for developing strategies for overcoming water quality challenges locally or nationally. Modelling the hydrology of the region has been a challenge; it is dominated by millions of depressions, called potholes and sloughs, which significantly influence runoff generation in the region (Eulis *et al.* 1999; Hayashi *et al.* 2004). For example, Godwin and Martin (1975) estimated that about 67 % of the Assiniboine Watershed at Kamsack is intercepted by potholes. When not full, such as would occur in dry periods, the ponds intercept runoff and an area can become non-contributing to streamflow. When full, the ponds can interconnect and do contribute to streamflow. Due to the "fill-and-spill" characteristics of the ponds, the contributing areas for streams in the prairie region are dynamic (Shaw *et al.* 2011).

To begin to incorporate the dynamic storage effects into hydrological models for the prairie region, researchers have attempted to describe in detail the physical processes occurring for individual depressions in their models (e.g. Su et al. 2000; Pomeroy et al. 2007; Fang and Pomeroy 2008; Shook et al. 2013; Chu et al. 2013). Due to this physical detail, their work has tended to be for smaller scale watersheds (or at plot scale). For example, Su et al. (2000), Pomeroy et al. (2007) and Fang and Pomeroy (2008) tried to simulate the water budget for an individual wetland. Shook et al. (2013) used a fully-distributed hydrological model for three small-scale watersheds to model the fluxes from the depressions. Chu et al. (2013) used a physically-based distributed model to simulate the pothole water balance on plot scale.

Conversely, Abedini (1998) used the probability distributed models that were used to describe soil moisture storage (e.g. Moore, 1985) for describing landscape depression storage and its heterogeneity. Using this approach for laboratory and plot scale measurements, Abedini (1998) simulated streamflow from surfaces dominated by depressions. M.A. Mekonnen et al. (2014) also implemented a probability distributed model for depression storage in the prairie region within the Modélisation Environmentale Communautaire - Surface and Hydrology (MESH) model. They simulated runoff from depressions for a portion of Saskatchewan's Assiniboine Watershed (an area of 1939 km^2). However, they did not attempt to find the parameters of the probability distribution used to describe storage capacity from the topography of the watershed and could not validate their model due to data limitations.

This paper reports on a study to incorporate a probability distribution to describe landscape depression storage heterogeneity into SWAT (the Soil and Water Assessment Tool) in attempt to improve streamflow simulation results for two Canadian prairie watersheds in Saskatchewan: the Assiniboine and the Qu'Apelle watersheds. Both are large watersheds where the land use is predominantly for agriculture. Additionally, the modified SWAT model that includes this probability distributed approach was used to model sediment export in the watersheds and these results are also reported. Among the reasons the SWAT model was chosen for this study were its development for agriculture-dominated watersheds, its wide application, the free access to its source code (Neitsch et al. 2011), and computational efficiency that affords its use to very large watersheds.

1.2 SWAT Model Description

The Soil and Water Assessment Tool (SWAT) is a continuous, semi-distributed hydrological model. The version used for the work described herein was SWAT2009. SWAT simulates the different hydrological processes of a watershed and can estimate water, sediment, and pollutant yields (Arnold *et al.* 1998). In SWAT, a watershed is partitioned into sub-basins that are further grouped into what are called "Hydrological Response Units" (Arnold *et al.* 1998). These HRU's are non-spatially specific lumped areas within a sub-basin that are comprised of unique combinations of land cover, soil type, and slope (Neitsch *et al*. 2011).

Water balance computations and hydrological process simulations are performed at the HRU level and either the modified Curve Number Method (SCS: USDA Soil Conservation Service 1972) or the Green-Ampt method (Green and Ampt 1911) is used to compute surface runoff. Potential evapotranspiration is estimated using one of three methods: Hargreaves (Hargreaves *et al.* 1985); Priestley-Taylor (Priestley and Taylor 1972), or Penman-Monteith (Monteith 1965). The actual evaporation from soils and plants is calculated by the method presented in Ritchie (1972). For the estimation of baseflow, groundwater is partitioned into a two-aquifer system, which represent its shallow and deep components (Arnold *et al.* 1998). To find the water yield to the main channel within a sub-basin, the contributions from each HRU within the sub-basin are summed. The water is then routed to the outlet of the sub-basin using either the variable storage coefficient method (Williams 1969) or the Muskingum routing method (Cunge 1969).

With respect to the cold-climate features of SWAT, for snowmelt prediction a temperature-index method is used (Neitsch et al. 2011). Other modifications include a seasonally variable snowmelt rate (Fontaine et al. 2002), division of each sub-basin into 10 elevation bands (Fontaine et al. 2002), and modification of the curve number value for frozen soil conditions for enhanced surface runoff and reduced infiltration (Tolston and Shoemaker 2007).

Soil erosion within SWAT is quantified for each HRU using the modified Universal Soil Loss Equation (MUSLE) (Williams 1975) and the estimated surface runoff. The sediment export on a given day, S, in metric tons is given as:

[1] $S=11.8(QqA_{hru})^{0.56}K \bullet LS \bullet C \bullet P \bullet CFRG$

where Q is the surface runoff volume (mm H_2O/ha); q is the peak rate of runoff (m^3/s); A_{hru} is the HRU's area (ha); K is the soil erodibility factor; LS is a topographic factor; C is a cover and management factor; P is a supporting practice factor; and CFRG is coarse fragment factor. The soil erodibility factor in SWAT2009 is an annualized value (it does not vary with season). Before reaching the main channel of a sub-basin, sediment that is mobilized can be lagged and routed through grassed waterways, vegetative filter strips, and wetlands. Sediment is then moved through the main channel considering deposition and erosion processes. The equations used to describe these processes are reviewed in Mekonnen et al. (2016b).

1.3 Previous Uses of SWAT in Depression-Dominated Prairie Watersheds

SWAT has been used to model streamflow in the prairie region in several previous studies (e.g. Sophocleous et al. 1999; Shrestha et al. 2011; Almendinger et al. 2012), for which either the landscape depressions were neglected or treated as a lumped storage component. In their work, Shrestha et al. (2011) assumed the entire watershed area was contributing to the watershed outlet for all events. Conversely, Sophocleous et al. (1999) treated the depressions as if they were always non-contributing. In Almendinger et al. (2012) depressions were aggregated as a single, lumped storage per sub-basin using SWAT's surface depression module. The latter approach appeared to improve streamflow simulations and could provide some simulation of the dynamic storage in the ponds, but did not bring in considerations of the heterogeneity in storage capacity of the ponds. Studies where incorporation of heterogeneity was attempted include Wang et al. (2008), who developed a routine to simulate the processes occurring for each individual depression. However, because of computational demands with this type of approach, it was considered unsuitable for the simulations of the very large watersheds that were the focus of the work herein.

2 STUDY WATERSHEDS

The first study watershed was the Assiniboine River Basin, which drains areas in Eastern Saskatchewan and Western Manitoba and terminates at the Red River in Winnipeg. Figure 1 shows a map of the watershed. The Saskatchewan portion of the watershed is 17,300 km^2 in area. For the simulations, data from a gauging station on the Assiniboine River was used (Kamsack Gauging Station – Water Survey of Canada Station No. 05MD004 at 51°33′53″N latitude and 101°54′48″ W longitude). Measurements of the daily flow and daily sediment load were available at this station, which were obtained from the Environment Canada HYDAT hydrometric database. At the Kamsack gauging station, the station has a gross drainage area of 13,000 km^2. However, only 4320 km^2 of the area is considered contributing by the definition of Godwin and Martin (1975), which considered what areas of the watershed would be contributing in a 1:2 year storm. In the northwest and southwest region of the watershed, the elevation is about 718 m and near the Kamsack gauging station the elevation is about 428 m. The mean annual precipitation is 450 mm per year, while the mean annual temperature is about 1˚C (Saskatchewan Watershed Authority (SWA) 2005). It is estimated that 63 % of the total streamflow in the watershed is generated from snowmelt runoff in April and May (SWA 2005). The land use in the watershed is predominantly agriculture, with 62 % of the watershed in annual crops, 25 % in pasture and range grass, and 11 % in forest (Oltholf *et al.* 2008). Soils in the watershed are predominantly characterized as Black Chernozemic soils (70 %) (SWA 2005).

The second watershed studied was the Moose Jaw River watershed, which is within the Qu'Appelle watershed (Fig. 1). The Moose Jaw River is a major tributary of the Qu'Appelle River. For the simulations, daily flow and daily sediment data from the gauging station near Burdick (50°24′1.2″ N latitude and 105°23′52.3″W longitude; Station No. 05JE006) were used. The watershed has a gross drainage area of 9230 km^2; however, for the 1:2 year return period storm, only 3470 km^2 is considered to be contributing to streamflow (Godwin and Martin 1975). The elevation of the watershed is about 877 m in its southwest region and 395 m in its central region near Burdick. The mean annual precipitation is 365 mm with an annual average air temperature of 4˚C (Environment Canada 2009). The predominant contribution to streamflow is snowmelt, which occurs in early spring. The watershed is also dominated by agriculture with 71 % in annual crops, 21 % in pasture and range grass, and 4 % in forest (Olthof *et al.* 2008). There are heavy clay soils in the east of the watershed and gravelly sandy soils in its western portions (SWA 2005).

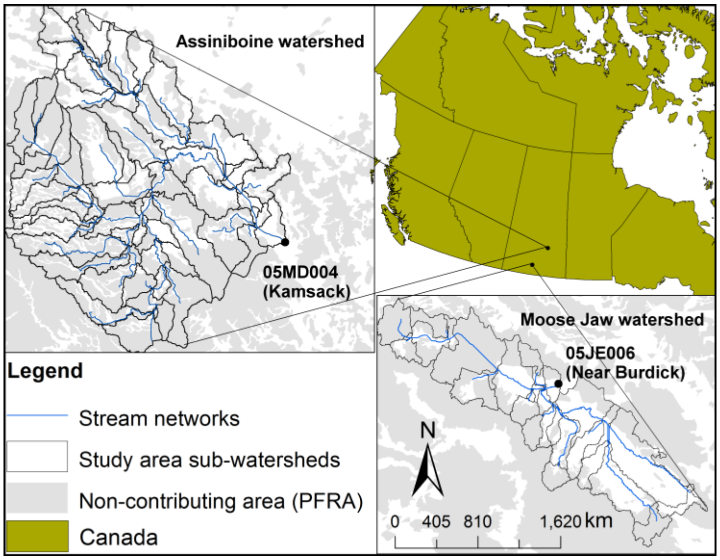

Figure 1: Map showing the studied Moose Jaw River and Assiniboine watersheds

3 MODIFICATIONS TO SWAT

3.1 Probability-Distribution Approach to Depression Storage

For the development of the probability distribution to describe storage in the depressions in the study watersheds, terrain analysis of DEM (Digital Elevation Model) data was performed using the ArcGIS 10 tool called "ArcHydro Tools" (Environmental Systems Research Institute 2011). Within ArcHydro Tools is a depression analysis routine. This was used to identify each landscape depression in the study watersheds and the associated area that drains to it, as well as its surface area (when full) and volume. Probability distributions were then fitted to the data in terms of the storage capacities of the depressions; storage capacity is defined as the volume of a depression divided by its surface area. It was found that both the exponential and Pareto distributions fit the data reasonably well. However, the exponential distribution was chosen because the distribution has fewer parameters and this is more computationally efficient to model. A comparison of the distributions to the storage capacity data for the study watersheds and the equation for the probability distribution are given in Mekonnen *et al.* (2016b).

For an individual depression, the water balance is described as follows. If the inputs of water to the depression exceed that which can be stored, runoff from the depression is equal to the inputs of water to the depression minus any losses and the storage in the depression. The inputs of water to a depression include precipitation and runoff from upland areas contributing to the depression. Losses from a depression include evapotranspiration and seepage. That stored within the depression is equal to the water storage capacity of the depression minus the water initially stored in the depression. For the work herein, all terms are written in terms of volume per surface area. If the inputs of water do not exceed the sum of the losses and capacity of the depression to store the water, there is no runoff.

The probability distributed model keeps track of the percentage of the depressions that are full to their capacity. With precipitation, the precipitation is distributed evenly to the potholes. Those that are full to their capacity contribute runoff. Those that are not full, collect precipitation until they are full per the water balance described above. This probability distributed model was coded into the SWAT Pond module. The details of the mathematics of this model and its integration into SWAT are given in Mekonnen *et al.* (2016a,b).

3.2 Seasonally Adjusted Soil Erodibility Factors

Research conducted by McConkey *et al.* (1997) indicated for the nearby Swift Current watershed, soil erodibility varied by "season". They divided the year into four periods to define these seasons: Period 1 was November 1 to March 15; Period 2 was March 16 to March 31; Period 3 was April 1 to April 30; and

Period 4 was May 1 to October 31. These periods corresponded to varied conditions of runoff and whether the soil was frozen or partially-frozen. In Period 1, the ground is frozen and runoff is due to snowmelt. In Period 2, the soil is partially-frozen and runoff is due to snowmelt. In Period 3, the soil is either thawed if not covered by snow or partially-thawed if covered by snow. Finally, in Period 4, the soil is thawed and there is no snow. In field plot tests, McConkey *et al.* (1997) observed varied soil erodibility coefficients for the different periods.

To test whether the study watersheds were showing variations in erodibility during these periods, the observed daily sediment load was plotted against observed daily streamflow for each of the listed periods, as given in Mekonnen *et al*. (2016b). It was seen there is greatly varied slopes in this relationship between periods indicating that seasonal erodibility values should be considered. As such, soil erodibility values in SWAT were modified to vary K (see Eq. 1) for each of the listed periods. For this work, the ratio of the soil erodibility coefficient to its typical annualized value for each period suggested by McConkey *et al.* (1997) were used to adjust the annualized erodibility coefficient for the soils given in SWAT.

4 INPUT DATA REQUIREMENTS

The spatial data required for use in the model include land cover, topography, and soils data. The land cover data were obtained from the GeoBase Canada (2007) and was prepared through vectorization of raster-thematic data originating from classified Landsat 5 and Landsat 7 ortho-images. The land-cover data were available at a scale of 1:250,000. The DEM of the case study basins were obtained from the GeoBase Canada website at a scale of 1:50,000. Detailed soil data at a resolution of 1:1,000,000 along with soil properties used in the SWAT model (version 2009) were obtained from the Agriculture and Agri-Food Canada database (Soil Landscapes of Canada Working Group 2007).

Gridded daily temperature (minimum and maximum) and precipitation data was used as the meteorological input data for the SWAT model (version 2009). The gridded climate dataset for Canada (Hutchinson *et al.* 2009) was obtained from Agriculture and Agri-Food Canada. This dataset covers south of 60°N latitude in Canada for the period 1961–2003, and was prepared through interpolation of observations from Environment Canada using a thin-plate smoothing spline-surface fitting method at a 10 km spatial resolution. Choi *et al.* (2009) demonstrated the suitability of gridded climate data to calibrate a hydrologic model in a prairie environment.

5 MODEL CALIBRATION AND VALIDATION

Model calibration was carried out using the shuffled complex evolution-uncertainty analysis algorithm (SCE-UA). Flow parameters were adjusted first to best represent flow processes. Then sediment calibration parameters were optimized while keeping the flow parameters fixed. Details of the model calibration procedures and reasons for this two-step approach are given in Mekonnen *et al.* 2016b. Observed daily discharge data from the Assiniboine River at Kamsack and Moose Jaw River near Burdick hydrometric stations were used for the flow calibration. Four years of flow data (1992–1995) were used for model calibration, and another four years of flow data (1996–1999) for model validation at the Kamsack gauging station. Similarly, five years of flow data (1992–1997) were used for model calibration, and an additional five years of flow data (1998–2002) for model validation at the Moose Jaw River near Burdick gauging station. Furthermore, two years of model warm-up period were allowed prior to model calibration for both watersheds to reduce uncertainty associated with initial conditions.

For the calibration for sediment, the challenge for the study watersheds was the limited frequency of sediment load measurements and period of coverage. For instance, Water Survey of Canada had terminated sediment data collection in the study watersheds in 1983. Consequently, sediment data are available only in the period of 1970–1983, and limited to spring and summer time. Calibration and validation were performed by comparing the simulated sediment load with observations corresponding to the dates when observation data were available (mostly available for the spring and summer periods). A total of 980 observations of sediment loading over four years (1972–1975) and 979 observations over four years (1976–1979) were used for calibration and validation, respectively, for the Assiniboine River watershed (Kamsack gauging station). Similarly, sediment data consisting of 1,238 observations over the years 1972–1977 were used to calibrate the model for the Moose Jaw River watershed. Additional sediment data consisting of 385 observations over the years 1978–1983 were used to validate the model for the Moose Jaw River watershed. Prior to the model calibration and validation periods, two years of model input data and warm-up period were allowed to reduce uncertainty associated with initial conditions. Therefore, because of data limitations, the flow and sediment calibrations were performed over different periods. A similar methodology had to be implemented by Santhi *et al.* (2006) while calibrating SWAT for a large river basin in the United States (Bosque River Watershed). Thus, the model's performance at simulating streamflow was assessed for the sediment calibration and validation periods. Results show that the model had good performance during these periods.

Performance of the model was judged by graphical means and several statistical parameters including the Nash-Sutcliffe efficiency (NSE) and the root mean square error (RMSE). The Nash-Sutcliffe Efficiency, NSE, is:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (\widehat{Q}_i - Q_i)^2}{\sum_{i=1}^{n} (\bar{Q} - Q_i)^2} \qquad [2]$$

where n is the number of data points; $\widehat{Q}_I$, is the simulated value at time i; Q_i is the observed value at time i; and $\bar{Q}$ is the averaged observed streamflow. According to van Liew et al. (2003), a model can be rated as "good" for an NSE greater than 0.75, satisfactory for an NSE value between 0.36 and 0.75, and unsatisfactory if NSE less than or equal to 0.36. The root mean square error is calculated by:

$$RSME = \sqrt{\sum_{i=1}^{n} (Q_i - \widehat{Q}_i)^2} \qquad [4]$$

For the model, the calibrated parameters for streamflow were the curve number, soil evaporation compensation factor, surface runoff lag coefficient, baseflow factor, snowfall temperature, snowmelt base temperature, maximum melt factor, minimum melt factor, snowpack temperature lag factor, areal snow coverage threshold at 100 %, areal snow coverage threshold at 50 %, depression maximum storage capacity, and Manning's n for the main channel. The calibrated parameters for predictions of sediment yield in the study watersheds are the peak rate adjustment factor for sediment, linear parameter for maximum sediment re-entrained, exponent parameter for sediment re-entrained, USLE support practice factor, channel erodibility factor, and channel cover factor. Details of the calibration results are given in Mekonnen *et al.* 2016b.

6 RESULTS AND DISCUSSION

6.1 Streamflow Simulations

First, the probability distributed approach (SWAT-PDLD) was evaluated for the two study watersheds for the prediction of streamflow. The results from SWAT-PDLD were compared to those from SWAT assuming no depressions in the watershed and SWAT with the lumped approach in the existing POND module. Figures 2 and 3 give the simulated *vs.* observed data for the calibration and validation periods for the average monthly streamflows during the calibration and validation periods, with the associated statistical parameters given in Table 1. Additional daily streamflow simulation results and duration curves are given in Mekonnen *et al.* (2016a).

It is seen that the application of SWAT considering no-depressions (all drainage areas contributing) gave poor model performance, where SWAT consistently overestimated streamflow. The assumption of lumping all depressions into one for each sub-basin, which is done in the SWAT Pond Module, did significantly improve model performance as compared to the no depression case. However, this modelling approach tended to underestimate peak flows, which was also observed by Wang *et al.* (2008). Further improvement in modelling results did occur with the probability distributed approach to storage, as evidenced by increased NSE values and reduced RMSE as shown in Table 1.

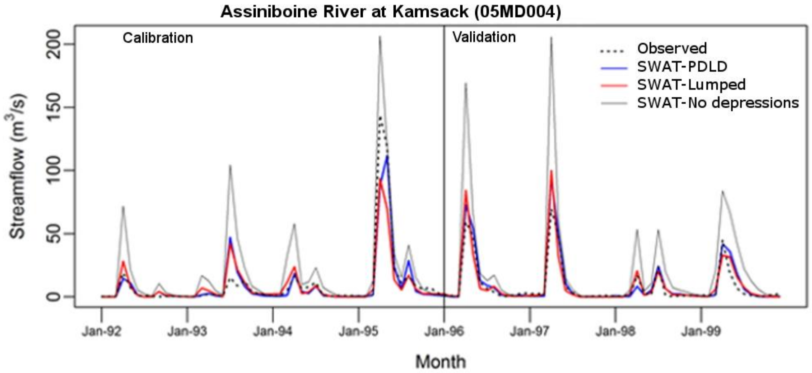

Figure 2: Average monthly hydrographs for Assiniboine River at Kamsack during the calibration and validation periods for the three SWAT configurations (adapted from Mekonnen *et al.* 2016a)

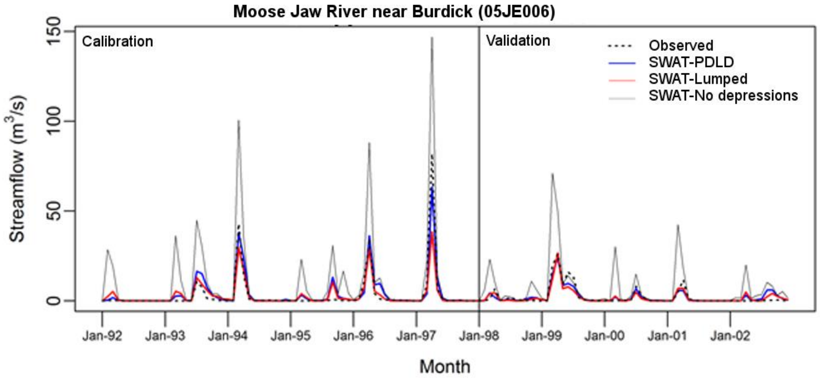

Figure 3: Average monthly hydrographs for Moose Jaw River at Burdick during the calibration and validation periods for the three test SWAT configurations (adapted from Mekonnen *et al.* 2016a)

Table 1: Statistical performance measures for monthly streamflow simulations

	Model Performance of Monthly Streamflow: Calibration (Validation)			
Model	Location	NSE	RMSE	NSE Model Performance Rating
SWAT - No depressions	Kamsack	0.37(-2.0)	26.93 (28.98)	Unsatisfactory
	Burdick	-0.80 (-2.10)	15.58 (12.77)	Unsatisfactory
SWAT lumped	Kamsack	0.81 (0.80)	10.82 (7.40)	Good
	Burdick	0.76 (0.84)	5.74 (2.94)	Good
SWAT with PDLD	Kamsack	0.86 (0.89)	8.84 (5.60)	Good
	Burdick	0.90 (0.89)	3.67 (2.46)	Good

6.2 Sediment Export Simulations with the Probability Distribution Approach for Landscape Depression Storage

The SWAT model with the probability approach to storage was then used to test the model for sediment export simulation for the study watersheds. The model was tested in two cases: (1) using annual values of soil erodibility; and (2) using seasonally adjusted erodibility values as defined above. The graphical results of the simulations for the Assiniboine River at Kamsack for these cases are given in Figures 4 and 5. The model performance results for simulating the mean daily sediment year (in tons per day) is given in Table 2 for both watersheds. The results show improved sediment export prediction using the seasonal soil erodibility values, however sediment export was still under predicted. This is especially true for the prediction of spring peak values. It is thought that some of this under prediction by the model may be due to unaccounted for management practices in these agricultural watersheds. The model assumed a cover crop in agricultural areas in all years. However, it has been common practice to leave some agricultural fields as fallow in some years (van Kooten et al. 1989) and this is known to result in increased erosion (van Kooten and Furtan 1987).

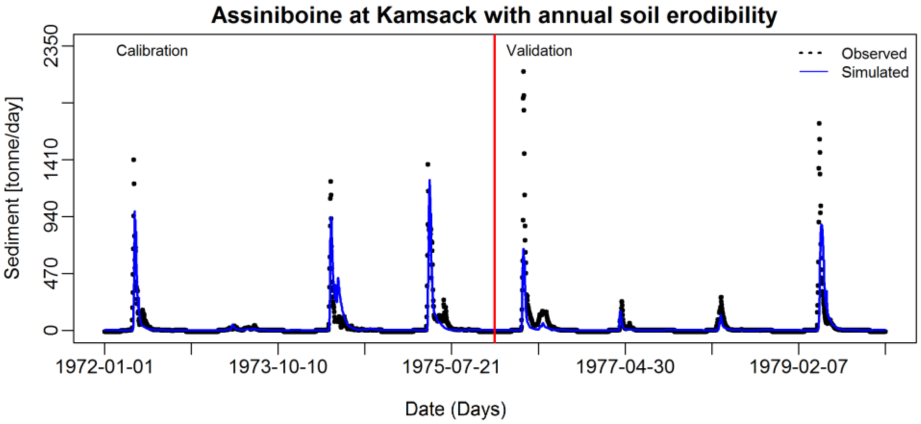

Figure 4: Observed and simulated daily sediment export for the Assiniboine River at Kamsack with SWAT-PDLD and an annual value of soil erodibility (K) (adapted from Mekonnen et al. 2016b)

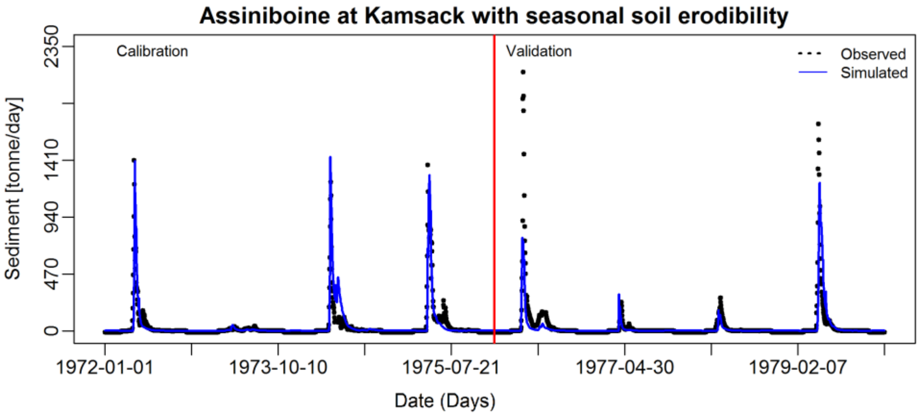

Figure 5: Observed and simulated daily sediment export for the Assiniboine River at Kamsack with SWAT-PDLD and a seasonally varying value of soil erodibility (K) (adapted from Mekonnen et al. 2016b)

Table 2: Sediment export simulation results as compared to observed values (*No observed data)

			Mean daily sediment yield (tons per day)		
Season	Months	Location	Observed	Model (annual K)	Model (seasonal K)
Fall	September, October, and November	Kamsack	0.94	0.76	0.77
		Burdick	0.73	0.46	0.48
Winter	December, January, and February	Kamsack	*	0.10	0.10
		Burdick	*	0.03	0.03
Spring	March, April, and May	Kamsack	127.4	102.3	120.0
		Burdick	750.3	279.8	486.9
Summer	June, July and August	Kamsack	22.9	13.6	13.8
		Burdick	26.9	12.9	15.5

7 CONCLUSIONS

Canadian prairie region watersheds are dominated by depression storage in millions of potholes of varied size that have a significant impact on streamflow generation in the region. In modelling streamflow within the region using SWAT, it was found that incorporation of dynamic contributions to streamflow from depression storage, herein using a probability distributed approach, significantly improves modelling results. Further, in modelling sediment export in these watersheds, seasonal adjustments for soil erodibility were found also to be important, as erodibility changes when the soil is frozen, partially-frozen or thawed.

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