Estimating Sediment Yield from Upland and Channel Erosion at A Watershed Scale Using SWAT

**Yongbo Liu · Wanhong Yang · Zhiqiang Yu ·
Ivana Lung · Bahram Gharabaghi**

Abstract Sediment discharge is one of the main water quality concerns in integrated watershed management. A proper identification of sediment sources is therefore important to the success of watershed conservation programs. Since water quality monitoring data collected at the mouth of the watershed alone are typically not sufficient for identifying key sediment sources distributed in the watershed, hydrologic models can be applied to prioritize Best Management Practices (BMPs) implementation for sediment control in a watershed. In this paper, the Soil and Water Assessment Tool (SWAT) is applied to the South Tobacco Creek (STC) watershed in Canada to identify sediment sources and to estimate the spatial distribution of sediment yield from both upland and channel erosion processes. The model is calibrated and validated against observed flow and sediment data measured at fourteen edge-of-field and mainstream stations based on 20 years of land management data. Modeling results show that approximately 60 and 40 % of the sediment discharge at the mouth of the watershed are originated from channel erosion and upland erosion respectively. A high spatial and temporal variation of sediment yield is found in the watershed depending on climate, topography, land use, and soil conditions. These findings will be helpful for understanding the runoff and erosion processes and evaluating the cost-effectiveness of soil and water conservation programs at a watershed scale.

Keywords Sediment yield · Upland erosion · Channel erosion · SWAT · South tobacco creek

1 Introduction

Prediction of soil and channel erosion is an important component in the assessment of land management strategies and in landscape studies where sediment is identified as a major cause

Y. Liu
State Key Laboratory of Environmental Information System, IGSNRR, CAS, Beijing 100101, China

Y. Liu (✉) · W. Yang · Z. Yu · I. Lung
Department of Geography, University of Guelph, Guelph, ON N1G2W1, Canada
e-mail: lyongbo@uoguelph.ca

B. Gharabaghi
School of Engineering, University of Guelph, Guelph, ON N1G2W1, Canada

of the ecosystem degradation. Studies have shown that soil and channel erosion can dramatically increase under certain climate, land use, and land management conditions (Ouyang et al. 2010). Continued upland soil erosion can result in degraded soil quality and ultimately reduced crop yields and profitability, while channel degradation can lead to the loss of agricultural land and channel hydraulic structures. Additionally, excessive erosion reduces water quality through increased turbidity and the transport of sediment-bound pollutants. Therefore, understanding the source of sediment and the spatial distribution of soil and channel erosion is the basis for effective implementation of beneficial management practices (BMPs) and water quality improvement at both field and watershed scales.

Field monitoring is an important measure for understanding hydrologic processes and erosion dynamics at a watershed scale. However, continuous flow and sediment monitoring is very expensive, time consuming, and spatially impractical. Mathematical modeling has therefore become an important method for analyzing erosion and its spatial and temporal distribution at the watershed scale. Watershed models that can be used to evaluate the effects of climate and land use, particularly agricultural practices, on runoff and sediment from both upland fields and stream channels are essential to analyze erosion dynamics in an agricultural watershed. Watershed-scale models have been used in the US Conservation Effects Assessment Project (CEAP) (Richardson et al. 2008) and the Canadian Watershed Evaluation of BMPs (WEBs) project (Yang et al. 2007) to support BMP management and program evaluation. Since measured data at stream or field stations are often insufficient to distinguish sources of sediment within a watershed, models can be used to trace sediment sources and delivery in a watershed, and provide assistance to decision making in watershed management.

The objective of this paper is to estimate and examine sediment yield from upland and channel erosion in the South Tobacco Creek (STC) watershed in southern Manitoba of Canada based on the Soil and Water Assessment Tool (SWAT) and extensive field monitoring data on climate, flow, sediment, and land management. Data collected at edge-of-field stations are used to calibrate upland erosion parameters, while data collected at main stream stations are used to calibrate channel erosion parameters. A spatial and temporal distribution of upland erosion and channel erosion is obtained based on the model simulation results.

2 Study Area and Data Availability

2.1 The STC Watershed

The STC watershed is located about 150 km southwest of Winnipeg on the Manitoba Escarpment in central Canada. The STC has a drainage area of 74.6 km^2 which originates from the Pembina Hills of Manitoba. Water out of the STC watershed drains into the Tobacco Creek and then the Morris River and flows into the Red River eventually. The STC watershed has a terraced topography sloping from the west to the east. Elevation ranges from 306 m at the watershed outlet to 506 m at the hilltop. Differing from the Prairie watersheds in north-central Manitoba, two distinct tiers exist in the middle and upper part of the STC watershed extending from the northwest to the southeast. The average watershed slope is 5.6 % derived from a 3×3 m DEM. Approximately 71 % of the watershed area is under cultivation, and the remaining 29 % in the watershed are comprised of non-cultivated grasslands, trees, water bodies, and road allowances (Fig. 1). The cultivated soils in the STC watershed are largely Orthic-Dark-Gray loam and clay loam developed from a mixed till of shale, limestone and granite. Regosols are mainly found on steep slopes unsuitable for cultivation, where they support woodland vegetation (Hope et al. 2002).
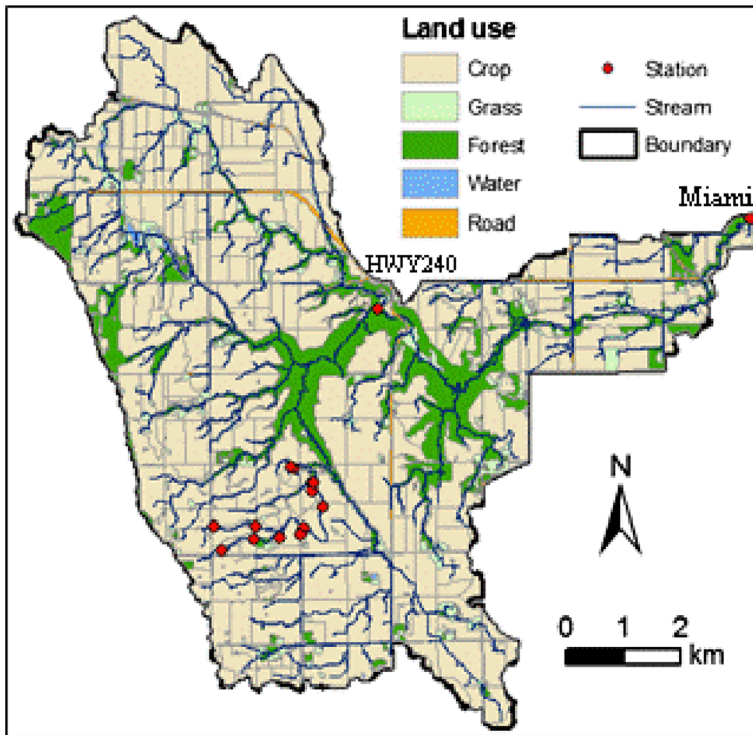
Fig. 1 Land use and hydrologic monitoring stations in the STC watershed

The watershed has a semi-arid climate with a pronounced seasonal variation. Differences in terrain result in a slight variation in average annual temperature of 2.0 to 4.0 °C and annual precipitation from 590 to 500 mm above and below the escarpment. About 75 % of this precipitation occurs as rainfall from April to October while the remainder falls as snow during winter months. The average annual daily discharge at the watershed outlet is 0.16 m^3/s ranging from 0.00 to 0.41 m^3/s based on the observation data from 1964 to 2010. The average annual runoff is 69.4 mm with an average runoff coefficient of 0.125. More than 80 % of this runoff and most of the annual peak discharges are observed in spring because of snowmelt. Base flow is a small portion of the total runoff (<10 %), which provides little contribution to the sediment transport.

Because of the activities of upland drainage, road construction, and land clearing for agricultural production, the STC watershed has suffered flooding and soil erosion problems during spring snowmelt and after heavy storms in the summer over the past years. In the Canadian AAFC WEBs project since 2004, the STC watershed has been selected as a pilot site to study the impact of BMPs such as conservation tillage and forage conversion on stream water quality improvement, including reduction of soil erosion and sediment transport. Therefore, understanding the partition of sediment yield from upland erosion and channel erosion has become a key component in the overall BMPs assessment in the STC watershed.

2.2 Data Availability

Three types of input data, i.e. geospatial, climate, and land management, are required for SWAT setup, while the monitoring data of flow and water quality are required for model

calibration and validation. The geospatial data, including a 1×1 m LiDAR DEM, a soil map with a Manitoba soil survey system, and a 2010 land use map for the STC watershed, are obtained from the Ministry of Agriculture and Agri-Food Canada (AAFC). The daily climate data at the Twin station (Fig. 1) managed by AAFC and at the Miami Orchard station close to the watershed outlet managed by Environment Canada (EC) for the period from 1991 to 2010 is available for model setup and verification. In addition, a detailed land management survey data at field scale from 1991 to 2010 is available from AAFC, including crop types, planting, harvest, rotation, tillage, fertilizer, manure, and straw management, as input for the SWAT model.

Fourteen flow and sediment monitoring stations, including two mainstream stations (Miami and HWY240) managed by EC and 12 edge-of-field stations in the Steppler and the Twin sub watersheds (Fig. 2) managed by AAFC, are available for the SWAT modeling in this study. Data at Miami, HWY240, Steppler, MS10, and MS11 are from 1991 to 2010, while other nine stations are from 2005 to 2010. The contribution areas of each monitoring station are listed in Table 2. Daily discharges at these stations are converted from observed hourly or 10-minute flow data using area-weighted average method to match with SWAT model output. Sediment data are grab samples taken during flood events.

Since 2009, a comprehensive study of the sources of sediments has been undertaken using sediment fingerprinting techniques. Suspended sediments are sampled using paired time-integrated samplers fixed to the stream bed. Samples are collected over the course of 3 years at several locations along the mainstream of the creek, with contribution area ranging 42 to 74.6 ha at the watershed outlet. Sediment samples are analyzed for caesium-137 content and the values are compared to those measured within the surface soil of field and riparian areas, and stream bank profiles. Analysis has shown that the majority of suspended sediments being exported from the watershed are coming from stream channels and not the soils of the uplands (Koiter et al. 2013). This preliminary analyzing result also serves as an important reference for the sediment modeling in this study.
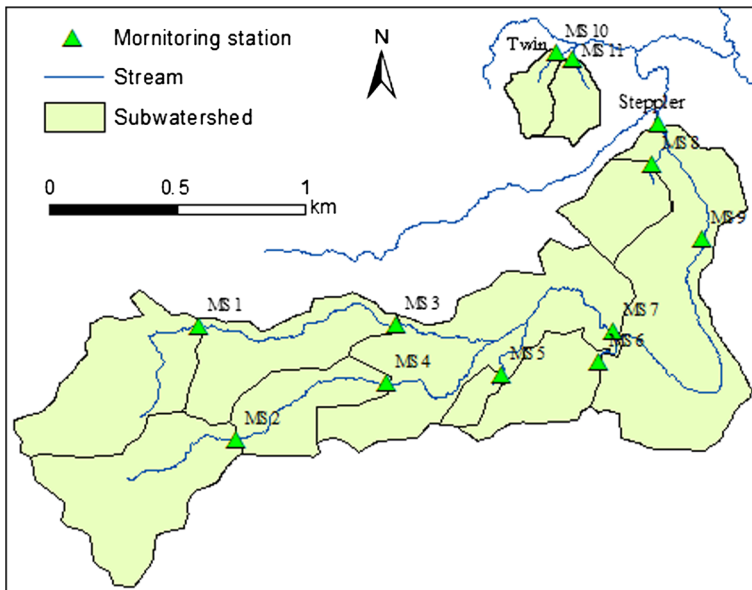

Fig. 2 Flow and sediment monitoring stations in the Steppler-Twin sub watersheds

3 Methods

3.1 Description of the SWAT Model

The SWAT is a process based watershed model allowing the assessment of land management practice impacts on water, sediment, nutrient and other agricultural chemical yields in a watershed with varying soils, land use and management conditions over a long period of time. The model performs continuous simulations at a daily time step. Weather, soil properties, topography, vegetation, and land management practices are the main inputs to the SWAT model for simulating hydrologic and water quality processes in a watershed (Arnold et al. 1998). The model is intended for long term simulations and is not capable of conducting detailed single-event flood routing.

The SWAT divides a watershed into a number of sub watersheds, which are further divided into main channels and hydrologic response units (HRU) based on a unique combination of land use, soil, and slope classes within each sub watershed. Erosion and sediment yield are estimated for each HRU with a Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977) expressed in terms of runoff volume, peak flow, and Universal Soil Loss Equation (USLE) factors including rainfall erosion index, soil erodibility factor, cover and management factor, support practice factor, slope factor, and coarse fragment factor (Wischmeier and Smith 1978). Sediment routing in the channel is based on stream power concept (Bagnold 1977) and the modified equation for bed degradation and sediment transport (Williams 1980). Channel bed degradation is adjusted with USLE soil erodibility and cover factors, and deposition is based on particle fall velocity.

The SWAT model is selected in this study because of its ability to account for various land management practices and to simulate water balance and sediment transport dynamics at a watershed scale. According to Borah and Bera (2004), the SWAT has been found suitable for predicting long-term flow volumes, sediment and nutrient loads based on a literature review of seventeen SWAT applications. Despite the uncertainties associated with SWAT simulation results under variable climate and land management conditions, a number of recent sediment modeling studies, e.g. Chu et al. (2004), Gikas et al. (2006), Mishra et al. (2007), Mukundan et al. (2010), Setegn et al. (2010), Saghafian et al. (2012), Talebizadeh et al. (2010), and Woznicki and Nejadhashemi (2013) have demonstrated that the SWAT model can predict reasonably well the flow and sediment yield as well as their spatial distributions. However, these studies have not examined specifically the partition of sediment sources between upland and channel.

3.2 Model Setup

The 1×1 m LiDAR DEM is used for the STC watershed delineation in order to capture the fine details of the study area. A total of 58 culverts are detected through a field survey. Elevations at these culvert sites are then modified on the DEM so that a continuous stream network can be created within the watershed. In order to incorporate the data measured at those edge-of-field stations into the STC SWAT modelling, a threshold value of 1.5 ha is specified to delineate the stream network. Sub watershed outlets are then defined based on the location of monitoring sites, main tributaries, and (c) proposed channel evaluation sites. A total of 82 sub watersheds are divided in the STC watershed ranging from 2.88 to 325 ha with an average sub watershed area of 91 ha.

The HRU distribution is created based on the STC soil data and the land use data in 2010. With a total of 34 classified soil types, the user soil parameter database is created based on the

Manitoba soil survey data and the soil attribute data from the Canadian Soil Information Service (CanSIS). Major soil attributes include soil name, number of layers, hydrological group, maximum rooting depth, maximum crack volume, and depth, texture, moist bulk density, available water capacity, saturated hydraulic conductivity, organic carbon content, content of clay, silt, sand, and rock fragment, moist soil albedo, and USLE soil erodibility factor for each soil layer. The soil hydrologic group is one of the import properties to determine surface runoff. In this study, we use the final constant infiltration rate to classify the soil hydrologic group. The final infiltration rate is assumed to be equal to the saturated hydraulic conductivity. Other soil parameters are obtained or calculated based on the information from the CanSIS and Manitoba soil survey database. Based on the land cover and crop data of 2010, a total of 23 land cover types are reclassified into 15 categories with different hydrologic characteristics during model setup, which include major crops (spring wheat, winter wheat, barley, canola, oats, flax, and pea), others crops (Agriculture land – generic, row crops, and close-grown), pasture/hay, grassland, forest, road, and water. The crop land uses are changed annually in the SWAT HRU management files based on the actual land use data collected from 1991 to 2010 for the STC watershed, while those non-crop HRU land uses are unchanged over the simulation period. In order to limit the number of HRUs, 20 and 10 % threshold values are specified for land covers and soil types in the SWAT HRU distribution. Because the STC watershed is relatively flat where steep slopes are concentrated in riparian areas with forest land cover, the slope classes are not identified in the HRU distribution. A total of 348 HRUs are created with about 4 HRUs on average in each sub watershed. The HRU distribution is fixed after its construction. Multi-year land cover and land management changes within the HRU are characterized based on the land management data from 1991 to 2010. Lastly the climate data of daily precipitation and temperature recorded at the Twin sub watershed and the Miami Orchard station are prepared as the weather input to the STC SWAT model.

3.3 Model Calibration and Validation

A manual calibration and validation is conducted in this study for improving model predictions at the 14 monitoring stations (Tables 1 and 2). Model calibration is performed at Miami, HWY240, Steppler, MS10, and MS11 for the period of 2001–2010 under existing climate and land management condition, and validation is performed at above stations for the period of 1991–2000, and stations MS1-MS9 for the period of 2005–2010. Flow calibration and validation are focused on daily and monthly predictions, while sediment calibration and validation are performed by comparing model output with grab sampling data at each monitoring station.

A sensitivity analysis is conducted using the SWAT extension program. 23 sensitive parameters are detected for the STC watershed associated with snowmelt, runoff generation, flow routing, upland erosion, and channel erosion. These parameters are adjusted by comparing model outputs with field observations, while other parameters retain their default values during calibration process. The final parameter values after model calibration and validation are given in Table 1.

For flow simulation, model performance is evaluated graphically together with two statistical measures: model bias (BIAS) (Moriasi et al. 2007) and the Nash–Suttcliffe coefficient (NSC) (Nash and Sutcliffe 1970) at daily, monthly and yearly time steps. Model bias can be expressed as the relative mean difference between predicted and observed stream flows, reflecting the ability of reproducing water balance. A lower bias value indicates a better fit. The NSC describes how well the stream flows are simulated by the model. The NSC value can range from a negative value to 1, with one indicating a perfect fit between the simulated and

Table 1 Runoff and sediement parameters adjusted in the SWAT model for the STC watershed

Parameter	Definition	Value
SMTMP	Snowmelt base temperature (°C)	2.0
SMFMX	Melt factor for snow on June 21 (mm/d)	6.5
SMFMN	Melt factor for snow on December 21 (mm/d)	2.5
TIMP	Snow pack temperature lag factor	1.0
SURLAG	Surface runoff lag coefficient	0.5
CANMX	Maximum canopy storage (mm)	5.0
ESCO	Soil evaporation compensation factor	0.96
CN2	SCS curve number under moisture condition II	0.00[*]
SOL_K	Saturated hydraulic conductivity (mm/hr)	−0.05[*]
SOL_AWC	Soil available water content	−0.03[*]
SOL_CRK	Maximum potential crack fraction	0.05
SLOPE	Average slope steepness (m/m)	−0.05[*]
SLSUBBSN	Average slope length (m)	−0.15[*]
USLE_K	USLE soil erodibility factor	0.01[*]
USLE_P	USLE support practice factor	0.65
USLE_C	USLE minimum crop factor	−0.10[*]
SPCON	Linear factor for channel sediment routing	0.01
ADJ_PKR	Subbasin peak sediment adjustment factor	1.0
PRF	Main channel peak sediment adjustment factor	2.0
CH_N2	Main channel Manning's roughness coefficient	0.04
CH_K2	Main channel hydraulic conductivity (mm/hr)	10
CH_EDOR	Channel erodibility factor	0.20
CH_COV	Channel cover factor	0.80

[*] ratio of relative change

observed hydrographs. Sediment predictions are evaluated graphically together with two statistical measures: root mean square error (RMSE) (Moriasi et al. 2007) and the determination coefficient (R^2) (Moriasi et al. 2007). The RMSE is a measure of the differences between values predicted by the model and the values observed. R^2 is a measure of the linear relationship between two random variables. A higher R^2 indicates a higher correlation between observed and simulated values. The calibration objective for flow is to maximize the NSC and to reduce the BIAS, while for sediment is to reduce RMSE and to increase R^2 simultaneously. A summary of SWAT model performance for the 14 monitoring stations at daily, monthly and yearly time scale are provided in Table 2. A graphical comparison between observed and simulated monthly discharge from 1991 to 2010 at the STC watershed outlet is shown in Fig. 3. Figures 4 and 5 show the comparisons between the simulated and observed daily sediment load at the MS1 and the Miami outlet station in 2009 respectively.

The evaluation results summarized in Table 2 show that the SWAT reproduces flow and sediment very well for the two main stream stations in both calibration and validation periods. Model bias on flow at the Miami station over the simulation period 1991–2010 is 0.03, while the NSC values are 0.69, 0.77, and 0.85 respectively on daily, monthly and yearly basis. The R^2 on sediment loading at the Miami station is 0.82 over the entire simulation period indicating a good agreement between simulated and observed values. However, model performances on flow and sediment loading are less satisfactory at those edge-of-field stations with small

Table 2 SWAT model performance for the STC watershed

Station	Area (km^2)	Period	Years	Flow				Sediment	
				BIAS	Daily NSC	Monthly NSC	Yearly NSC	RMSE	R^2
Miami	74.6	Calibration	2001–2010	−0.04	0.74	0.81	0.87	273	0.84
		Validation	1991–2000	0.09	0.63	0.75	0.82	201	0.81
HWY240	33.7	Calibration	2001–2010	−0.06	0.79	0.83	0.90	158	0.76
		Validation	1991–2000	0.11	0.60	0.70	0.79	134	0.72
Steppler	2.06	Calibration	2001–2010	−0.16	0.62	0.71	0.80	-	-
		Validation	1991–2000	−0.22	0.51	0.62	0.69	-	-
MS1	0.284	Validation	2005–2010	−0.05	0.59	0.68	0.76	0.21	0.64
MS2	0.280	Validation	2005–2010	−0.20	0.52	0.62	0.70	0.26	0.58
MS3	0.488	Validation	2005–2010	0.01	0.65	0.74	0.80	0.44	0.68
MS4	0.420	Validation	2005–2010	−0.21	0.67	0.75	0.82	0.39	0.70
MS5	0.025	Validation	2005–2010	0.06	0.32	0.56	0.62	0.05	0.35
MS6	0.127	Validation	2005–2010	0.02	0.43	0.52	0.58	0.12	0.37
MS7	1.35	Validation	2005–2010	0.04	0.68	0.75	0.81	1.45	0.73
MS8	0.102	Validation	2005–2010	0.18	0.35	0.45	0.52	0.12	0.40
MS9	1.87	Validation	2005–2010	−0.13	0.65	0.72	0.78	1.72	0.66
MS10	0.044	Calibration	2001–2010	0.16	0.34	0.47	0.56	0.04	0.36
		Validation	1993–2000	0.20	0.24	0.38	0.45	0.05	0.38
MS11	0.056	Calibration	2001–2010	0.15	0.23	0.36	0.47	0.04	0.40
		Validation	1993–2000	0.10	0.32	0.44	0.51	0.04	0.37

contribution areas, e.g. the MS5, MS10, and MS11 stations. The daily NSC values on flow are less than 0.35, and R^2 values are less 0.4 for these 3 stations. These may be caused by errors associated with drainage area delineation and poor simulations of snowmelt runoff and flow routing in those small sub watersheds. Figure 4 and 5 show a good agreement between simulated and observed sediment loadings at the two stations in 2009. The peak sediment rates are over estimated at station MS1 and under estimated at station Miami for the flood events in April 2009 but still in a reasonable magnitude. However, poor predictions also exist at other stations, e.g. MS10 and MS11, and other years, e.g. 2001 and 2006. Considering the 14 flow and sediment stations that are used in the model calibration in the study, the overall model performance for the STC watershed is found to be quite satisfactory.

4 Results and Discussion

4.1 Simulation Results

The calculated average annual precipitation in the STC watershed is 534.6 mm, of which 125.6 mm (23.5 %) is snow occurring from late October to April. The total calculated average annual PET is 774.5 mm for the watershed using the Hargreaves method, while the actual average annual evapotranspiration is 422.8 mm and is 79.1 % of the annual precipitation. The calculated total average annual runoff is 75.2 mm (14.1 %) of which 60.8 mm (11.4 %) is from
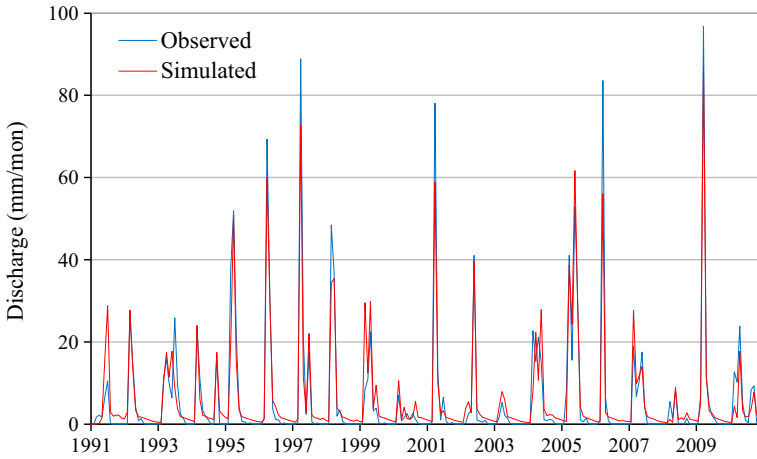
Fig. 3 Observed and simulated monthly discharge from 1991 to 2010 at the STC watershed outlet

land surface and 14.9 mm (2.78 %) is from subsurface flow. Precipitation is more concentrated in summer months, and small in other months (Fig. 6). High evapotranspiration occurs in the summer period from May to August because of the high air temperature, while high flow occurs in spring (March and April) from snowmelt runoff. Summer runoff is much smaller than spring runoff because of the high evapotranspiration and low soil moisture. The average yearly water yields exhibit considerable spatial variations, with higher water yields above average in areas with higher slopes and lower than average water yields in flat areas at sub watershed scale.

The calculated average annual sediment yield before streams is 0.45 t/ha for the watershed, of which high erosion occurs in March and April because of snowmelt flooding. Sediment yield from overland is relatively small from May to July because of the low rate of surface runoff. Figure 7 shows the spatial distribution of sediment yield from upland erosion and from channel erosion. The overland erosion rate varies from 0.05 t/ha to 1.86 t/ha at a sub watershed
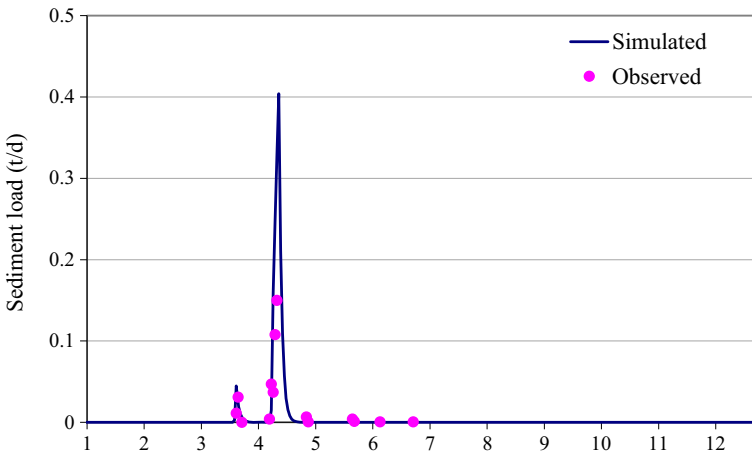

Fig. 4 A comparison between simulated and observed daily sediment loads at the MS1 station in 2009
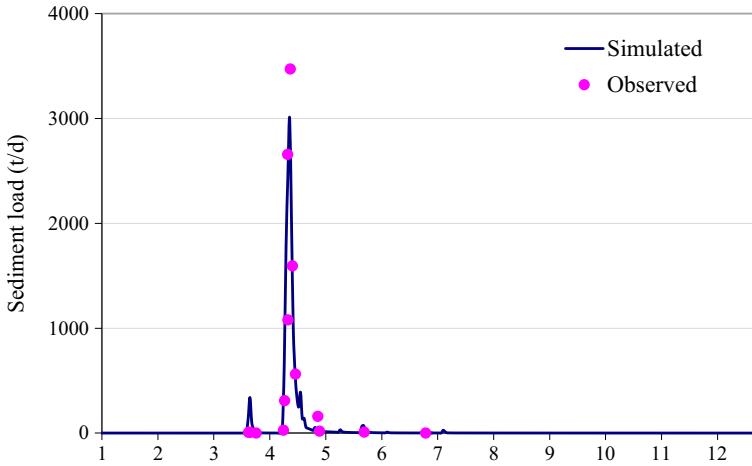
Fig. 5 A comparison between simulated and observed daily sediment loads at the Miami station in 2009

scale. High upland erosion occurs in those crop areas with relatively steep slope, while low upland erosion occurs in those flat areas with near zero surface slope (Fig. 7). The simulated average annual total sediment load at the watershed outlet is 8,483 t (1.14 t/ha), of which 3,393 t (0.45 t/ha) is from overland erosion and 5,090 t (0.68 t/ha) is from channel erosion (Table 3). The average overland erosion rate is calculated by the estimated sediment yield before streams divided by the watershed area, while the average channel erosion rate is calculated by the estimated channel sediment load divided by the total channel length. Most channel erosion is in the middle and lower reaches of the mainstream (Fig. 7). Sediment at the STC watershed outlet is approximately 60 % from channels and 40 % from upland fields. The average channel and ditch degradation has significant variations. In some reaches in upland sub watersheds, the calculated average annual channel erosion rate is less than zero indicating sediment deposition in those reaches. The middle mainstream has the highest channel erosion rate (100–200 t/km) because of the steep slopes.
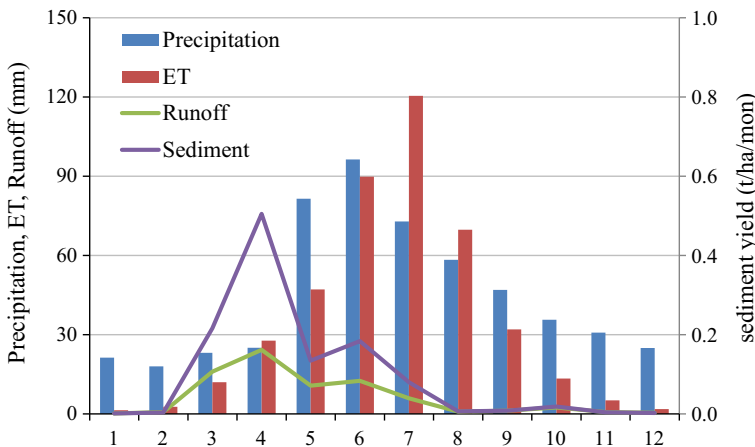

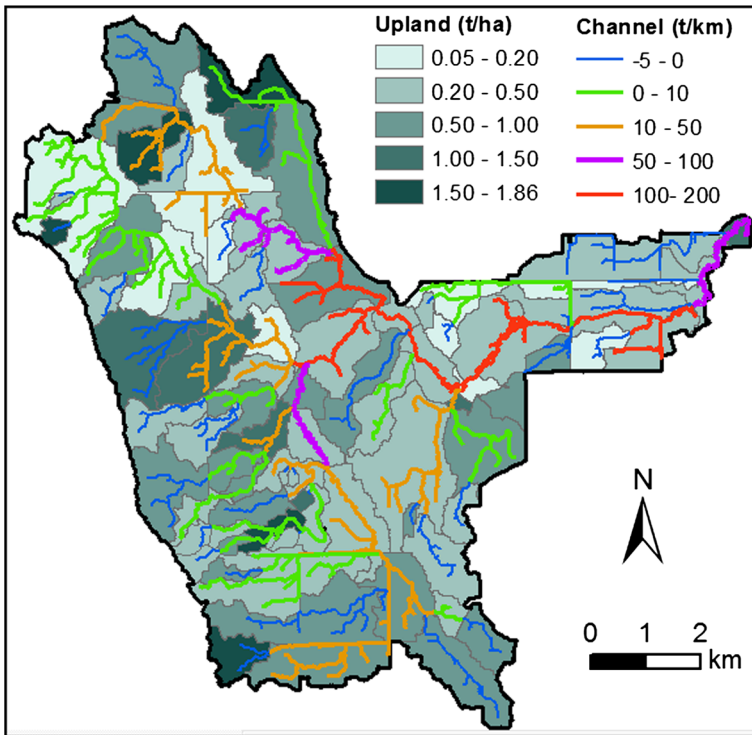**Fig. 6** Simulated average monthly precipitation, ET, run-off, and sediment yield in the STC watershed

Fig. 7 Simulated annual average upland and channel erosion rate in the STC watershed

4.2 Discussion

The STC watershed has a very rich dataset including LiDAR DEM, detailed land management data, as well as flow and sediment data at different monitoring stations. This has benefited greatly the SWAT setup, model calibration, and validation. Comparison of modeling results with detailed management data and with coarse management data indicates that the detailed land management data can improve model performance greatly. This is also important for capturing information at a fine scale for BMPs assessment.

Moreover, the SWAT model was able to reproduce flow and sediment very well at the mainstream stations (Miami and HWY240). However, model performance at edge-of-field stations such as the MS10 and MS11 is still less than desirable. This indicates that SWAT is suitable for medium and large watershed simulations, but is difficult for small-sized watershed simulation. The calibration and validation results also show that the monthly and yearly performances are better than daily performance. This indicates that the SWAT model is suitable for long-term simulation of hydrologic processes and evaluation of BMPs at a watershed scale.

Table 3 Simulated average annual sediment yield at the STC watershed outlet over the period 1991–2010

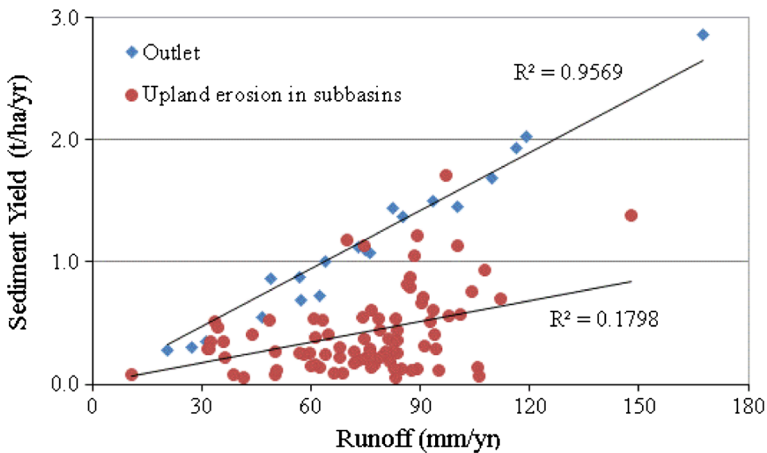| Sediment	Amount (t)	Rate (kg/ha)	Percent (%)
Upland erosion	3,393	450	40
Channel erosion	5,090	680	60
Total	8,483	1,140	100

Fig. 8 Relationship between runoff and sediment yield at the STC watershed outlet and in sub watersheds

The SWAT model predicts that 60 % of sediment yield is from within channel erosion processes and 40 % from upland runoff contributing areas sheet and rill erosion processes in the STC watershed. In a 2009–2011 sediment source fingerprinting study in the STC watershed, the results showed that the relative contributions of topsoil, stream banks, and shale bedrock across the watershed were on average 18–42 %, 33–59 %, and 12–33 %, respectively. (Koiter et al. 2013). This modeled partition of upland versus within stream contribution to sediment discharge at the outlet of the watershed is in agreement with the caesium-137 tracer experimental result that the majority of sediment is originated from stream channels rather than the upland fields.

This implies that channel management practices, such as channel bed and bank stabilization, installation of within stream energy dissipaters following natural channel design guidelines (Doll et al. 2003) and riparian management in critical stream segments, will play an important role in reducing sediment yield in the STC watershed. In addition to the estimation of sediment sources, the SWAT model has capabilities in predicting spatial distribution of sediment yield in upland fields and stream channels. The identification of the most erosion prone areas will help to plan and implement appropriate erosion control BMPs in the STC watershed.

Figure 8 shows that there is a clear linear relationship between runoff and sediment yield at the STC watershed outlet ($R^2=0.96$) based on the 20-year model simulation indicating that the climate is the main driving force for the total sediment yield in the STC watershed. However, no clear linear relationship is found between runoff and upland sediment yield at sub watershed scale in the STC watershed ($R^2=0.18$) based on the model simulation results. This indicates that sediment yield is a complex process in the study area depending on many factors such as contribution area, snow properties (e.g. accumulation and redistribution), land use composition (e.g. fraction of impervious area and open water), and in particular the land management practices (e.g. crop management and riparian management). More studies with respect to mechanics and processes of runoff generation, soil erosion, and sediment yield at different spatial scales are necessary in the study watershed.

Despite the general agreement between simulated and observed flow and sediment loadings at the 14 monitoring stations, uncertainties still exist in the modeling results. These

uncertainties are mainly associated with: (1) model structure - the SWAT model is designed for simulating hydrologic processes at a daily time step in a large river basin, and therefore some modelling algorithms may not be appropriate (e.g. flow routing and sediment transport) in small sub watersheds such as those edge-of-field sub watersheds in this study; (2) contribution area - the contribution areas of those edge-of-field stations are derived from the DEM, for which small area differences may cause large relative errors in the modeling output; (3) climate data - the climate data used as model input in this study may not represent accurately for those edge-of-field sub watersheds during model calibration; (4) sediment data - the grab sampling sediment data obtained during flood events were used for model calibration may not represent accurately the daily average to compare with SWAT output; and (5) model parameters. The modeling results with respect to runoff and sediment yield distributions will be improved after limiting above uncertainties in future research.

5 Conclusions

In this study, the SWAT model is applied to the 74.6 km^2 STC watershed in southern Manitoba of Canada. The daily measured flow and sediment sampling data at 5 stations from 1991 to 2010 and 9 stations from 2005 to 2010 are used for calibration and validation. The results of flow and sediment simulations are acceptable with respect to evaluation criteria of BIAS, NSC, RMSE, and R2, respectively. Based on the model simulation results, sediment yields from upland and channel erosion as well as their spatial distributions is determined. Approximately 60 % of sediment is from channel erosion mainly in the middle and lower reaches with high longitudinal channel slopes in the STC watershed, and 40 % from upland runoff contributing fields. This implies that channel management practices, such as channel bed and bank stabilization, installation of within stream energy dissipaters following natural channel design guidelines, and riparian management in critical stream segments, will play an important role in reducing sediment yield in the STC watershed.

In comparing to previous SWAT applications on sediment modelling, this study demonstrates that the SWAT model can be applied to estimate sediment yield from upland fields and from channels, and to identify critical areas and channel segments in a Canadian Prairie agricultural watershed after an intensive calibration effort. The data recorded at edge-of-field stations are important in controlling upland erosion parameters in the model, while data recorded at main stream stations can be used to adjust channel erosion and sediment transport parameters. A large source of uncertainty exist when calibrating the SWAT model based on only an outlet water quality monitoring station data in a watershed, for which the relative sediment contributions from the upland runoff contributing fields and from within channel erosion processes may be estimated inaccurately. As a result, model evaluation of BMPs associated with upland erosion or riparian buffer sediment controls may not represent the actual condition, and consequently induces a misleading optimum watershed specific soil and water conservation practices guidance.

References

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment. J Am Water Resour As 34(1):73–89

Bagnold RA (1977) Bedload transport in natural rivers. Water Resour Res 13(2):303–312

Borah DK, Bera M (2004) Watershed-scale hydrologic and nonpoint-source pollution models: review of applications. Trans ASAE 47(3):789–803

Chu TW, Shirmohammadi A, Montas H, Sadeghi A (2004) Evaluation of the SWAT model's sediment and nutrient components in the Piedmont physiographic region of Maryland. Trans ASAE 47(5):1523–1538

Doll BA, Grabow GL, Hall KR, Halley J, Harman WA, Jennings GD, Wise DE (2003) Stream Restoration: A Natural Channel Design Handbook. NC Stream Restoration Institute, NC State University. 128 pp.

Gikas GD, Yiannakopoulou T, Tsihrintzis VA (2006) Modeling of non-point source pollution in a Mediterranean drainage basin. Environ Model Assess 11(3):219–233

Hope J, Harker DB, Townley SL (2002) Long term land use trends for water quality protection, ten years of monitoring in the South tobacco creek watershed. Agriculture and Agri-Food Canada – PFRA, Regina

Koiter AJ, Lobb DA, Owens PN, PEtticrew EL, Tiessen KHD, Li S (2013) Investigating the role of connectivity and scale in assessing the sources of sediment in an agricultural watershed in the Canadian prairies using sediment source fingerprinting. J Soils Sediments 13:1676–1691

Mishra A, Kar S, Singh VP (2007) Prioritizing structural management by quantifying the effect of land use and land cover on watershed runoff and sediment yield. Water Resour Manag 21(11):1899–1913

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASAE 50(3):885–900

Mukundan R, Radcliffe DE, Risse LM (2010) Spatial resolution of soil data and channel erosion effects on SWAT model predictions of flow and sediment. J Soil Water Conserv 65(2):92–104

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual model. J Hydrol 10(3):282–290

Ouyang W, Skidmore AK, Hao FH, Wang TJ (2010) Soil erosion dynamics response to landscape pattern. Sci Total Enviro 408:1358–1366

Richardson CW, Bucks DA, Sadler EJ (2008) The conservation effects assessment project benchmark watersheds: synthesis of preliminary findings. J Soil Water Conserv 63(6):590–604

Saghafian B, Sima S, Sadeghi S, Jeirani F (2012) Application of unit response approach for spatial prioritization of runoff and sediment sources. Agr Water Manage 109:36–45

Setegn SG, Dargahi B, Srinivasan R, Melesse AM (2010) Modeling of sediment yield from Anjeni-gauged watershed, Ethiopia using SWAT model. J Am Water Resour Assoc 46(3):514–526

Talebizadeh M, Morid S, Ayyoubzadeh SA, Ghasemzadeh M (2010) Uncertainty analysis in sediment load modeling using ANN and SWAT model. Water Resour Manag 24(9):1747–1761

Williams JR (1980) SPNM, a model for predicting sediment, phosphorus, and nitrogen yield from agricultural basins. Water Resour Bull 16(5):842–848

Williams JR, Berndt HD (1977) Sediment yield prediction based on watershed hydrology. Trans ASAE 20(6): 1100–1104

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook 282, USDA-ARS.

Woznicki SA, Nejadhashemi AP (2013) Spatial and temporal variabilities of sediment delivery ratio. Water Resour Manag 27(7):2483–2499

Yang W, Rousseau A, Boxall P (2007) An integrated economic-hydrologic modeling framework for the watershed evaluation of beneficial management practices. J Soil Water Conserv 62(6):423–432