Applying the Soil Water Assessment Tool to 5th Canadian Division Support Base Gagetown

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ABSTRACT

A hydrologic and water quality model is sought to establish an approach to land management decisions for a Canadian Army training base. Training areas are subjected to high levels of persistent activity creating unique land cover and land-use disturbances. Deforestation, complex road networks, off-road manoeuvres, and vehicle stream crossings are among major anthropogenic activities observed to affect these landscapes. Expanding, preserving and improving the quality of these areas to host training activities for future generations is critical to maintain operational effectiveness. Inclusive to this objective is minimizing resultant environmental degradation, principally in the form of hydrologic fluctuations, excess erosion, and sedimentation of aquatic environments. Application of the Soil Water Assessment Tool (SWAT) was assessed for its ability to simulate hydrologic and water quality conditions observed in military landscapes at 5th Canadian Division Support Base (5 CDSB) Gagetown, New Brunswick. Despite some limitations, this model adequately simulated three partial years of daily watershed outflow ($\text{NSE} = 0.47-0.79$, $R^2 = 0.50-0.88$) and adequately predicted suspended sediment yields during the observation periods (%$d = 6-47\%$) for one highly disturbed sub-watershed in Gagetown. Further development of this model may help guide decisions to develop or decommission training areas, guide land management practices and prioritize select landscape mitigation efforts.

Key words | erosion, hydrology, military, modelling, SWAT, water quality

INTRODUCTION

Developing an understanding of watershed hydrology and land cover is a critical component to the successful assessment of stream flow and water quality conditions. Landscape alterations can contribute significant non-point source pollutants to aquatic environments and markedly alter watershed hydrology (Winter et al. 1998; Stanley & Arp 2002; Culp et al. 2009). The principal objective of this study was to assess the effectiveness and suitability of a numerical model on a watershed used extensively for Army exercises. Should this prove successful, continued expansion and applications may then guide landscape alterations and mitigation efforts to achieve targeted water quantity and quality guidelines for aquatic environments.

Anthropogenic activities, such as agricultural cultivation, urban development and deforestation, can significantly impact watershed health. These activities may shift water yields, increase peak flows, degrade water quality and cause a variety of other detrimental impacts (Winter et al. 1998). Knowledge of hydrologic impacts and non-point source sediment pollution from military training grounds is relatively limited compared to more common and conventional landscapes across Canada. Increased surface runoff, decreased baseflow, elevated erosion rates, increased sediment yields and increased stresses to aquatic environments have been identified as watershed management issues at 5th Canadian Division Support Base (5 CDSB) Gagetown (Smith 2014). At this time, Gagetown is undertaking a multi-year, multi-million dollar project to address some of these issues under the Sediment and Erosion Control Plan.
Many environmental models have been recommended, developed or applied to assist land managers in mitigating detrimental watershed impacts on military lands. Regression equations have been developed to relate climate, land cover and land-use variables to stream water quality conditions at Fort Stewart, Georgia (Jager et al. 2011). Some tools rely on lumped geographic and climate variables to predict surface erosion, such as the empirical Universal Soil Loss Equation (USLE) and its derivatives. Various forms of this model have been applied to several military installations in the United States of America (USA) (Warren et al. 1989; Wigmosta et al. 2007; Dalton 2008). These studies typically establish an annual erosion estimate but do not always consider the redistribution of sediments across the landscape and transport within stream channels. Other, more process-based models, account for sediment transport and deposition patterns, as seen in the Unit Stream Power Erosion Deposition (USPED) model, EROSION 3-D and the Hillslope Erosion Model. These models have seen applications to military landscapes in Germany and the USA in order to predict general erosion and deposition trends or event-based water and sediment dynamics (Deinlein & Bohm 2000; Warren et al. 2005; Liu et al. 2007; Steichen et al. 2008). The Water Erosion Prediction Project (WEPP) is another modelling tool that has been used for military watersheds (Gaffer et al. 2008). WEPP has also been integrated into multi-spatial scale, hybrid modelling projects for military installations to quantify detailed processes, such as road erosion (Donigian et al. 2010). While these latter models primarily focus on surface runoff, the Distributed Hydrology Soil Vegetation Model (DHSVM), Hydrological Simulations Program-Fortran (HSPF) and Soil Water Assessment Tool (SWAT) have been used as more holistic watershed models for military lands in order to predict continuous stream flow and water quality conditions (Wigmosta et al. 2007; Dalton 2008; Donigian et al. 2010).

The classical USLE only accounts for lumped monthly or annual erosion rates. The USPED model enhances the USLE capabilities by accounting for distributed flow accumulation, profile curvature and transport-limited sediment deposition (Warren et al. 2005). Both these models lack detailed hydrological considerations and only focus on landscape processes. WEPP, while generally applied at the hillslope scale, accounts for more physically based dynamic conditions. This includes soil detachment from raindrops and flow shear stress, sediment deposition, soil physics, plant growth and management conditions (Flanagan et al. 2013). The previously mentioned models may be distributed but they do not consider variations in microtopography, such as vehicle ruts and road features. The Limburg Soil Erosion Model (LISEM) accounts for some of these limitations with sub-cell rut coverage and other features (Roo et al. 1996). WEPP can be modified to account for road features, such as cut-slopes, ditches and ruts. Detailed overland flow, ditch drainage and cut-slope water interception, can also be simulated in the DHSVM (Beckers et al. 2009).

Hydrology, erosion and water quality models vary in data requirements, conceptual framework, complexity and outputs. The simulated time-scale of watershed models can range from hours to decades with computational time-steps varying from seconds to years. Observed climate data, event-based design storms or stochastic weather generators can be used to drive model computations. Spatial distributions have included cells a few metres in size, field scale hillslope elements or relatively large sub-catchments. Agricultural watersheds can typically utilize lumped or semi-distributed landscape characteristics because of their natural homogeneity. Forested watersheds typically require more distributed representations due to the significant influences of forestry roads on sediment yields (Luce et al. 2001). Military training areas display characteristics from both these land-use categories and are recognized to require multiple spatial scales for watershed modelling assessments (Donigian et al. 2010).

SWAT, the model selected for this study, operates on a daily time-step and has a strong capacity to process decades of data. Watersheds are simulated with distributed subbasins and lumped hydrological response units (HRUs) composed of unique land cover, slope and soil conditions. Runoff is calculated with the Soil Conservation Service Curve Number (SCS CN) method, or Green and Ampt Infiltration method. There are several evapotranspiration (ET) options, including the Penman–Monteith method which accounts for daily temperature, relative humidity, wind speed and solar radiation. Vertical and lateral groundwater flow is calculated through multiple soil layers over one groundwater reservoir. Erosion is calculated with the
empirical Modified USLE and sediments, along with water, can be routed through a series of overland and channels structures.

Army training grounds are affected by intense off-road vehicle activity, as well as a variety of other operations and land management practices. Heavily utilized areas are often intermixed with relatively undisturbed, natural environments. Within the USA, many training areas are located in semi-arid locations and are generally subject to intense usage. Training activities and poor land management practices can cause vegetation and soil loss leading to substantial environmental degradation, reduced training effectiveness and costly rehabilitation efforts (Dalton 2008; Stevens et al. 2008).

The training area at 5 CDSB Gagetown has challenges that are both common and unique to bases in the USA from the previously referenced studies. Humid, wet conditions can make soils more susceptible to rutting, compaction and disturbances. Vegetation management (e.g. cutting, spraying or burning) is required to maintain manoeuvre corridors in a grassland or ‘old field’ state. Cold climate conditions have significant effects on watershed processes and training activity. Water quality and channel stability are also a concern, including point source sediment inputs from vehicle stream crossing activities and flow regime fluctuations from deforestation and land cover change.

Military vehicle traffic, and the effect it has on the landscape, has received considerable attention because the effects can directly influence watershed hydrology, erosion and water quality conditions. USLE cover-factors have been predicted based on vehicle manoeuvre impact miles per hectare at Camp Atterbury, Indiana (Dalton 2008). Cover-factors for manoeuvre lands have also been developed considering LANDSAT imagery and vegetation field surveys (Warren et al. 1989, 2005). Vegetation loss and rut depth from vehicle manoeuvres have been estimated with the Vehicle Dynamic Monitoring and Tracking System which considers detailed vehicle properties, movement tracking dynamics and soil properties (Koch et al. 2012). A field trafficability model has also been developed for 5 CDSB Gagetown, utilizing the Forest Hydrology Model, soil information and basic vehicle properties (Vega-Nieva et al. 2008). These tools have the potential to be integrated with broad-based hydrology and water quality models to maximize their effectiveness.

Study area

5 CDSB Gagetown is located in Southern New Brunswick and is one of the largest military training facilities in Canada, with an area of over 1,100 km² (Figure 1). This includes 21,000 ha of manoeuvre areas, 30,000 ha of ranges and impact areas, 829 km of roads, 362 km of off-road trails, more than 500 fords and 1,174 in-stream culverts and bridges. Primary land cover categories can be described as forested (66%), grasslands and early succession (18%), aquatic environments (10%) and barren areas (6%). Generally, grasslands are highly disturbed from off-road vehicle manoeuvres and include dense track networks. Barren areas include roads, recently devegetated areas being converted to grasslands and areas that are persistently barren with negligible vegetation due to repetitive vehicle traffic.

The base was established in the 1950s, which involved the expropriation of private lands including several communities, agricultural areas and forest harvest blocks. Additional land was deforested to create the manoeuvre fields, ranges and munition impact areas at this time. In the 1990s another 7,000 ha of forests were cleared in an attempt to create more manoeuvre areas; however, many of these areas were not used for years because of erosion and vegetation issues.

Annually, the Gagetown training area experiences the equivalent impact of 98,000 personnel training-days, including 800 tracked and 14,000 wheeled vehicle. Military service members generally train throughout the year. However, vehicle operations typically peak in the month of May, which accounts for about 20% of the annual training load, as tracked by the base Range Control office.

5 CDSB Gagetown is located within the Southern New Brunswick Uplands and Maritime Lowlands. The region receives approximately 885 mm of rainfall a year and 276 cm of snowfall, totalling 1,143 mm of annual precipitation. The daily average temperature is 5.3 °C, ranging from −9.8 °C in January to 19.3 °C in July (Marshall et al. 1999).

Within base boundaries there are 3,272 km of watercourses, 156 lakes and ponds, and 6,487 ha of wetlands. Poor water quality, suspended solids in particular, has
been recorded throughout the area (Hood 2013), along with potential stress to some benthic communities (Estrada et al. 2012). Atlantic salmon and brook trout are primary fish species of management interest (Smith 2014).

The Kerr Brook watershed (Figure 1) was selected to test the SWAT model. Centrally located in the base and within the mounted manoeuvre area, this watershed is highly disturbed, regularly used for military training and well documented with meteorological, geographic information system (GIS), hydrometric and water quality data. This 20 km² watershed is covered by mixed forests (26%), grasslands (32%), brush lands including young pioneer tree species (36%), and barren features including roads, tracks and highly disturbed manoeuvre areas (4%). Wetlands, beaver ponds and other water features are evident but cover less than 2% of the area. Surficial soils are primarily loams and gravelly sandy loams underlain by moderately shallow bedrock. Disturbances that are commonly observed in this area are vehicle ford crossings, dense vehicle rutting across manoeuvre grasslands and persistent barren areas created from repetitive vehicle traffic, demonstrated in Figure 2.

**METHODOLOGY**

This research approach involved a critical assessment of available information, selection of a suitable numerical tool, followed by model development and application. This
initial phase of work provides the framework for subsequent investigation that will focus on expansion of the simulation area, refinement of input parameters, improvements to modelling processes and evaluation of mitigation measures. The scope of this modelling effort excluded winter seasons, detailed vegetation conditions and complex stream channel processes due to data limitations and simulation complexities.

**Data assembly and analysis**

Meteorological data were primarily obtained from a 5 CDSB Gagetown meteorological station located approximately 4 km from the Kerr Brook watershed. A Thiessen polygon analysis indicated that this station provided a reasonable representation of the local climate, with 92% of Kerr Brook associated to this station. Hourly precipitation, temperature, wind speed and relative humidity data were available. Data gaps were supplemented using adjacent meteorological stations yielding a continuous climate data set from 2007–2012. There were several minor data gaps during winter periods; however, there are negligible flow and water quality observations during these periods. Climate data from 2007 and 2008 were used for the model warm-up period.

GIS data, including a 10 m digital elevation model, surficial soil coverage, and land cover inventories, were provided by the Gagetown Geocell. Surficial soil data were supplemented by various soil survey reports to assist with parameterization of soil conditions (Colpitts et al. 1995; Castonguay & Arp 2002; Fahmy et al. 2010). Land cover information included a land cover inventory, road/track vector data and bare soil raster data classified from Colour Infrared Imagery.

Hourly stream stage data were collected during late spring, summer and fall from 2009–2012 at an upstream and downstream monitoring location in Kerr Brook. Stage-discharge curves were constructed and calibrated to eight discharge measurements throughout this monitoring period.

Simulating erosion, sediment transport and sediment yields is difficult considering the common lack of available sediment data. In order to overcome this limitation, continuous suspended solids information was approximated using a regression approach for comparison to SWAT results (Rasmussen et al. 2011). This multi-linear regression (MLR) model was developed from eight partial storm monitoring events including turbidity, stream flow and total suspended solids (TSS). Other parameters suspected of influencing TSS loading conditions were incorporated into this analysis, including antecedent dry days, cumulative antecedent vehicle activity and rising/falling hydrograph conditions. Variables were selected based on their significance and their ability to significantly improve results. This regression model was applied to an event-flow threshold value, selected from a flow-duration curve. The final model was also applied to all flow conditions and automatically set to a zero TSS load for zero turbidity readings to compare results.

A Water Quality Index (WQI) was computed for the Kerr Brook watershed to assess general water quality conditions. This WQI integrated National Agri-Environmental Standards Initiative-Ideal Performance Standards for TSS and turbidity (Culp et al. 2009), Canadian Council of Ministers of the Environment (CCME) guidelines for pH and water temperature recommendations for brook trout (Birtwell 1999). Average and median daily values were both considered in this analysis. Data were also trimmed with the mirrored 5th percentile to reduce inappropriate deflation of the WQI by low frequency events (Kilgour et al. 2013).

Vehicle water crossing operations have the potential to impair water quality in local streams. Grab samples from ford crossings indicate that this activity can be responsible for turbidity and TSS loadings as high as 1,000 NTU and 1,000 mg L$^{-1}$, respectively, immediately downstream of crossing sites. Daily turbidity statistics from the upstream and downstream monitoring locations, including the hourly minimum, 1st quartile, median, 3rd quartile and maximum, were correlated to the daily total vehicle load operating within the Kerr Brook watershed. This analysis was conducted to provide a general indication of whether or not documented vehicle loads impacted observed water quality conditions.

**Model selection**

Appropriate model selection is an important aspect of any environmental simulation project.

There are a variety of models which are appropriate for military land, as previously discussed. The new generation of
eroded models focuses on highly distributed, physically based processes which require substantial amounts of input data for small, field-scale applications. While this additional complexity can enhance simulation capabilities, it becomes increasingly cumbersome to apply for large areas and complex models are not always recommended for practical management applications (Grayson et al. 1992). With 5 CDSB Gagetown covering over 1,100 km², models can be effectively applied to large areas are preferable. Available data can be used for calibration and validation of continuous stream flow conditions, giving preference to such models as oppose to event-based or stochastic climate models. SWAT and HSPF are both well supported and commonly applied hydrology-water quality models meeting this criteria. However, HSPF is commonly reported to require substantial parameterization efforts and is not generally considered to be user-friendly (Beckers et al. 2009). Alternatively, SWAT has a relatively straightforward user-interface and is integrated within a simple GIS framework. SWAT was also designed for application in large, ungauged agricultural watersheds requiring minimal parameterization (Neitsch et al. 2011).

SWAT was selected for this study because of its capacity to effectively process and simulate lumped hydrological processes, which can be calibrated and validated with available data. Erosion and overland flow processes are simplified in this model; however, these simplifications make large-scale applications efficient.

Model development

The Kerr Brook watershed was delineated within ArcSWAT with streams defined at a resolution of 66 ha contributing area. Outlets were located at an upstream and downstream monitoring location in addition to two other tributaries. HRUs were defined with a 20% soil threshold and 20% slope threshold, resulting in two soil groups and three slope categories. Land cover categories include forest, grass, brush and barren areas. Barren areas were delineated by buffering and merging roads and tracks with bare soils. Other land cover categories were predefined. A 1% land cover threshold was selected to adequately capture barren areas, which is substantially smaller than the common recommendation of 20% (Winchell et al. 2007).

Plant growth parameters were adjusted to provide a constant Leaf Area Index; detailed vegetation conditions were unavailable and outside the scope of this study. Water impoundments were neglected in the initial model due to limited land coverage, but integrated in the sensitivity and calibration analysis. Sediment reduction structures, such as grassed waterways and filter strips, were not included due to data limitations.

Sensitivity analysis and calibration

A sensitivity analysis and calibration was conducted to improve model parameterization and reduce prediction uncertainty. A combination of manual and automated approaches was used during calibration with both objective and subjective target criteria, as described in Figure 3. From initial parameterization, automated calibration was conducted in the SWAT-CUP interface using generalized likelihood estimation (GLUE) (Abbaspour 2003). GLUE was selected because it was observed to produce more reasonable parameter ranges during trial runs, compared to SUFI2. It was also selected for further analysis because of its simplistic methodology. GLUE established parameter sensitivity and gave the first iteration of an auto-calibrated model. Several iterations were conducted considering different objective function thresholds, downstream and upstream observations or just downstream observations. The initial model was then manually calibrated by targeting annual observed water yields, followed by balancing surface and groundwater ratios. Finally, parameters were calibrated by optimizing the annual Nash-Sutcliffe Efficiency (NSE) and coefficient of determination ($R^2$) for daily flow conditions. This manually calibrated model was then passed through another iteration of auto-calibration. This procedure is outlined in Figure 3. Sediment yields from the regression model were compared to the simulation results, and not used for calibration of parameters affecting sediment yields.

Parameter identifiability issues affecting groundwater and surface runoff contributions were highlighted during the initial automated sensitivity and calibration analysis. To alleviate this issue, a two-parameter digital filter was used to split stream flow into surface flow and groundwater flow for manual calibration (Eckhardt 2005). Surface erosion is driven by surface runoff making these filter parameters a
critical target for calibration. Filter parameters were judged based on the literature (Eckhardt 2005), geological conditions and graphical baseflow separation. Two sets of filter parameters were used to assess their effect on parameter calibration. One baseflow filter parameter set was used to disaggregate groundwater into shallow aquifer and hard rock aquifer contributions. Observed flows could then be adjusted to neglect hard rock aquifer contributions, as the SWAT model was expected to inadequately simulate these results due to its single aquifer framework. The other baseflow filter set only predicted shallow aquifer contributions, resulting in both high post-event groundwater flow and extended baseflow.

RESULTS AND DISCUSSION

Preliminary data analysis

The TSS regression model was developed to consider only turbidity and stream flow. Other variables were discarded based on marginal improvement to the MLR relationship and their insignificance. The threshold confidence level applied for variable consideration was 10% (α = 0.1). Intra-storm event observations were utilized for this analysis due to data limitations (n = 41), even though this created concerns about data independence. The finalized regression model is provided below in Equation (1):

\[
TSS = 2.61 + 0.41(T) + 18.00(Q)
\]  

In Equation (1), TSS is total suspended solids (mg L\(^{-1}\)), T is turbidity (NTU) and Q is discharge (m\(^3\) s\(^{-1}\)). The model has a standard error of 41% and an adjusted \(R^2\) of 0.61. Also, the model and all coefficients are significant except the intercept. This regression model was applied to flows exceeding 0.35 m\(^3\) s\(^{-1}\), corresponding to the 20th percentile exceedance probability where the semi-logarithmic flow-duration curve exhibits a significant change in slope. The model was also applied to all flow conditions for a comparative analysis, which increased annual sediment loads by about 2%. Results from observed data using this regression model are summarized in Table 1.

Water quality analysis, using the CCME WQI, indicated that water quality in Kerr Brook is marginal; the WQI score ranged from 48–57. This range was established by utilizing combinations of daily median, average and trimmed data for turbidity, modelled TSS, temperature and pH. The addition of more variables is suspected to improve this score as other sources of pollution, such as metals and
nutrients, are anticipated to be minimal. There is no deterministic interval established for these calculations; however, conventional applications use discontinuous, daily data collected during relatively steady-state conditions (CCME 2001). The continuous, daily data used in this analysis, and inclusion of storm-event responses, may be deflating these results in comparison to conventional applications.

Daily vehicle loads within the Kerr Brook watershed were not observed to significantly affect water quality at the watershed outlet; daily turbidity statistics were not strongly correlated to daily vehicle loads. Filtering high flow events and turbidity outliers did not significantly improve this correlation. The only mild correlation was observed for the maximum daily turbidity at the upstream monitoring location ($r = 0.22$). Vehicle load data used in this analysis are insufficient to conclude that vehicle stream crossing activity does not affect watershed water quality. Enhanced monitoring of specific timing and location of stream crossing activity would be required for such a conclusion. However, considering the available data and this analysis, point source sediment contributions from vehicle crossing activities were neglected in modelling efforts.

### Modelling results

The procedure for sensitivity, calibration and uncertainty analysis followed in this study provided an effective means to become familiar with the SWAT model, assess parameter sensitivity, optimize simulation performance and identify problems and limitations of this research approach. Initial sensitivity analysis and auto-calibration achieved reasonably strong statistics for daily flow simulations. Auto-calibration iterations achieved $P$-factors in the order of 0.83 and $R$-factors ranging from 0.46–0.53. For these iterations, the $NSE$ ranged from 0.78–0.79 and $R^2$ ranged from 0.70 to 0.82. However, these results were achieved over a significant parameter range and included a large number of parameters (18). Over 2,000 of the 10,000 simulation runs achieved satisfactory statistics ($NSE > 0.65$). The manner in which this exercise was conducted may have limited its value since a significant number of parameters were included in this analysis over a substantial parameter range. However, this identified the unfortunate issue of equifinality confronted by many models, where many different parameter combinations are able to achieve similar and realistic results (Jetten & Maneta 2011). The flashy nature of this watershed is also suspected to exacerbate the issue of equifinality, with extremely high storm event responses and low baseflow conditions. Parameter sensitivity, identified by t-stat ranking (Abbaspour 2013), also varied between iterations, which may be attributable to the significant degrees of freedom in this initial analysis. Common parameters that were sensitive in different iterations ($P < 0.1$) were percolation rates (DEP_IMP), the SCS CN adjustment factor (CNCOEF), groundwater delay (GW_DELAY), soil profile depth (SOL_Z), canopy storage (CANMX), surface runoff lag and SCS CNs.

This initial sensitivity analysis identified several limitations of this model. Extended baseflow conditions were poorly simulated, likely due to the single aquifer concept in the SWAT model. Flow timing parameters also displayed limited ability to align some event peaks; peak runoff events were occasionally simulated one day in advance of that observed. This is likely due to the daily time-step used in the SWAT model compounded by the flashy nature of the watershed.

The final accepted model from manual calibration achieved a total water yield with a percentage difference of approximately 2% during calibration years. Surface runoff, groundwater flow and deep aquifer recharge
contributions were generally predicted within 10% relative difference of the water balance derived from the baseflow filter analysis. Annual statistics for daily flow simulations were also strong (NSE = 0.73–0.79 and $R^2 = 0.86–0.88$). Upstream conditions were not as effectively simulated. Water balance components were consistently underestimated and typically ranged between 10–40%; however, daily flow statistics were still strong (NSE = 0.81–0.83 and $R^2 = 0.83–0.84$).

Manual calibration identified several key hydrological characteristics. Flatland drainage conditions and select soil types may be poorly simulated with this model. The upstream drainage area is relatively flat and primarily consists of Tracy Loams. Poor parameterization of these conditions may have resulted in the poor upstream predictions. Wetlands were also introduced in the watershed to mitigate peak flows and reduce total water yields. Wetland parameters were largely estimated; however, surface area and contributing area were approximated from Wet Area Mapping (WAM). Several wetlands were identified by WAM but only one sub-basin wetland significantly improved results. Wetlands were observed in the upstream drainage area but not integrated into the model due to undersimulated water yields. Many wetlands in this area are also observed to be influenced by beaver ponds, and beaver pond hydrology may be poorly simulated in SWAT.

Meteorological station REM02 was the only station applied to the Kerr Brook model. Adjacent meteorological stations, no more than 15 km away, displayed significant variability in rainfall patterns during select, intense storms. These storms generally resulted in overestimation of peak flows in the SWAT model. The daily rainfall values for these storms varied up to 75% or 30 mm between adjacent meteorological stations. Adjusting these rainfall values in the SWAT model proved to be an effective approach to align some of the simulated peak flows. There is potential that the simple meteorological station assignment to Kerr Brook used in this approach does not adequately represent local climate patterns.

Final auto-calibration, utilizing the GLUE program, did not significantly improve results. The number of parameters and parameter ranges were reduced based on knowledge gained during manual calibration. The SCS CN adjustment factor (CNCOEF) and maximum wetland volume (WET_MXVOL) were the only variables that converged to a significant value. Due to limited parameters and parameter ranges, $P$-factors were very poor (<0.2), emphasizing the requirement to accept exceptional uncertainty for this hydrological model. Manual calibration results were retained due to limited improvement of simulation results from this automated approach.

Simulations during the validation period were not as effective compared to the calibration period. Relative percentage differences for the total water yield in validation simulations ranged from 2% in 2009 to 73% in 2012. Other water balance components, derived from baseflow filtration, ranged from 6–96%. Annual statistics for daily flow simulations were also poor (NSE = −0.46–0.47 and $R^2 = 0.5–0.64$). Upstream simulations were more agreeable, with simulated water yields ranging from 12–34% and water balance components ranging from 2–66%. Annual statistics for upstream daily flow simulations were better than downstream simulations, but still generally poor (NSE = 0.47–0.54 and $R^2 = 0.5–0.62$). Simulated and observed daily downstream discharge values are displayed in Figure 4. Land cover SCS CNs for these results were 70, 82, 76 and 86 for forests, grasslands, brush and barren areas, respectively. The average annual precipitation of 1,170 mm saw 57% contribute to ET, 18% to surface runoff, 14% to shallow groundwater flow and 8% to deep groundwater flow. Alternative baseflow filter parameters could see these annual groundwater and surface runoff contributions shifting in the order of 30–90%.

The model consistently overestimated autumn stream flow in 2012. The first storm in the autumn of 2012 saw the largest daily rainfall event in the simulated time period of 118 mm. It is suspected that this error may be attributed to a disturbance that this storm event caused to the stream channel or data level logger, disrupting the stage-discharge relationship of the monitoring site. However, this error may also be attributable to a poorly simulated storage component in the SWAT model, such as soil, surface or wetland storage, but this is less likely.

Annual downstream sediment yields were generally adequate compared to the regression model from 2009–2011 (%$d = 6–47\%$). 2012 sediment yields were overestimated by 217% primarily due to poorly simulated and/or observed flow conditions. Monthly sediment yields from the SWAT
model and regression model are displayed in Figure 5. Simulated annual average sediment yields were in the order of 700 t yr\(^{-1}\). This annual yield can be compared to the Black Brook watershed in New Brunswick, which is 14.5 km\(^2\) covered by 10% urban areas, 25% forests and the remainder agricultural crops. The observed annual sediment yields for this watershed have ranged from 1,526–8,092 t yr\(^{-1}\), with 39% of the load generally occurring during the April snow-melt period (Yang et al. 2014). Simulated erosion rates ranged up to 6 t ha\(^{-1}\) and 11 t ha\(^{-1}\) for grasslands and barren areas, respectively. This corresponds to a low erosion class; however, most simulated HRU erosion rates were less than 6 t ha\(^{-1}\), which fall into the lowest, tolerable erosion class (Wall et al. 2002). Many sediment reduction processes are not simulated in this model, due to model and data limitations. Erosion rates are likely underestimated in the SWAT model; however, surface and aquatic deposition rates are also likely underestimated.

Simulated upstream sediment yields were consistently overestimated compared to those estimated from the regression model (%\(d = 76–384\%\)). This error is suspected to be attributable to the flat topography of the upstream drainage area, which would impact sediment transport and deposition patterns across the landscape. Low order streams...
are also thoroughly buffered with forested areas in the upstream sub-basin, raising conceptual model issues with filter strip definition and inter-HRU interactions. Wetlands and beaver ponds may also be attributable to low sediment yields. However, wetlands were not integrated into the upstream drainage area because water yields and peak flow were generally underestimated, and wetland integration would only exacerbate this issue. Land cover area ratios between the upstream and downstream contributing areas are relatively the same, so cover characteristics were not suspected to be the source of this error.

High runoff baseflow filter parameters achieved better sediment results than low runoff filter parameters. Also, adjusting parameters, such as slope length, cover-factors, and filter strip, were capable of significantly affecting total sediment yields. Considering the uncertainty associated with runoff quantity and these other sediment parameters, there would be a considerable number of parameter sets able to achieve reasonable sediment yield results. Improved characterization of surface runoff quantity, cover-factors and sediment reduction parameters would greatly increase confidence in model results. Additional investigation into key hydrological parameters, such as wetland coverage, flatland drainage and soil moisture conditions, could potentially improve model results and prediction uncertainty. The final results reported for this model did not include filter parameters, slope adjustments or cover adjustments because a proper calibration exercise would not consider TSS regression model results as a valid calibration target.

**CONCLUSION AND RECOMMENDATIONS**

The Kerr Brook SWAT model effectively simulated stream flow conditions for three out of four years of observation. Sediment yields during these three years were generally agreeable with TSS regression model results. The best simulation predicted acceptable total water yields, excellent daily flow conditions and acceptable monthly sediment loads. This is not to say the model confidently simulated the natural hydrological and sediment cycle within Kerr Brook. Uncertainties associated with surface runoff and baseflow ratios, soil storage, wetland storage and deep aquifer loss may be significant. Parameters for these key hydrological characteristics could be refined, with additional information, to produce more reliable model outputs. Many parameter combinations were capable of achieving satisfactory statistics during automated approaches. Subjective baseflow filtration, along with manual calibration, was the most effective means to achieve a unique solution in this application.

Further advancements in this research are recommended as follows:

- The SWAT model could be expanded to include a larger area at 5 CDSB Gagetown for immediate, practical application. This should include a time-series extension which would preferably capture well documented land cover changes.
- An expanded data collection effort could be implemented to facilitate parameter refinement for improvement of confidence in the model. This effort could include tracer tests for baseflow separation (Klaus & McDonnell 2013) and sediment fingerprinting (Mukundan et al. 2012) to provide additional insight into watershed hydrology and sedimentation processes.
- Continued monitoring of event-based turbidity, flow and TSS could be used to improve the TSS regression analysis. This would enable the implementation of daily observed values or daily regression results to increase the accuracy of sediment observations for model calibration and validation.
- Remote sensing techniques, supported by field survey quality control data, could be applied to refine plant and cover parameters, improve characterization of wetlands and parameterize surface features, such as filter strips.
- Lastly, enhancements in numerical simulations could enhance this field of study. This could see the application of more distributed, process-based models, such as WEPP or LISEM. Improvements to the SWAT model could also be conducted, such as the addition of multiple groundwater reservoirs or consideration of variable source areas (Easton et al. 2008). Other natural processes could also be studied, modelled and integrated into a watershed level context. This could include detailed consideration of road erosion or channel erosion processes.

This work has demonstrated that the SWAT model is a potentially capable tool for simulating large-scale hydrological
and erosion processes. With continued research, hydrological and water quality impacts from select military activities and landscape alterations may be assessed with this model. Management practices, such as mulching, wetland construction and tillage operations, also have the potential to be simulated in this model in order to guide land management decisions. Land managers at 5 CDSB Gagetown have limited, quantitative understanding of watershed processes and how they are affected by the diverse and unique conditions of military training grounds. The scale of this area and the ability to affect significant change across the landscape instil significant cause to objectively manage detrimental impacts to the hydrological and sediment cycle. SWAT holds potential to guide the design of landscape alterations and mitigation efforts, and with continued research, could be an effective tool for this application.

ACKNOWLEDGEMENTS

Many organizations provided critical data and support for this study. The Department of Fisheries and Oceans collected most hydrometric and water quality data used in this research, including stage-discharge analysis. The Meteorological and Geocell Sections at 5 CDSB Gagetown provided most climate and GIS data, respectively. The Royal Military College Environmental Science Group and Environmental Services Branch at 5 CDSB Gagetown also provided valuable support and guidance throughout this study. The efforts of all those involved is greatly appreciated.

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First received 31 March 2014; accepted in revised form 11 June 2014. Available online 23 June 2014