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Deriving a country-wide soils dataset from the Soil Landscapes of Canada (SLC) database for use in Soil and Water Assessment Tool (SWAT) Simulations

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Abstract

The Soil and Water Assessment Tool (SWAT) model has been commonly used in Canada for hydrological and water quality simulations. However, pre-processing of critical data such as soils information can be laborious and time-consuming. The objective of this work was to pre-process the Soil Landscapes of Canada (SLC) database to offer a country-level soils dataset in a format ready to be used in SWAT simulations. A two-level screening process was used to identify critical information required by SWAT and to remove records with information that could not be calculated or estimated. Out of the 14,063 unique soils in the SLC, 11,838 soils with complete information were included in the dataset presented here. Important variables for SWAT simulations that are not reported in the SLC database [e.g. hydrologic soils groups (HSGs) and erodibility factor (K)] were calculated from information contained within the SLC database. These calculations, in fact, represent a major contribution to enabling the present dataset to be

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used for hydrological simulations in Canada using SWAT and other comparable models. Analysis of those variables indicated that 21.3 %, 24.6 %, 39.0 %, and 15.1 % of the soils in Canada belong to HSGs 1, 2, 3, and 4, respectively. This suggests that almost two-thirds of the soils have a high (i.e., HSG 4) or relatively high (i.e., HSG 3) runoff generation potential. A spatial analysis indicated that 20.0, 26.8, 36.7 and 16.5 % of soil belonged to HSG 1, HSG 2, HSG 3, and HSG 4, respectively. Erosion potential, which is inherently linked to the erodibility factor (K), was associated with runoff potential in important agricultural areas such as southern Ontario and Nova Scotia. However, contrary to initial expectations, low or moderate erosion potential was found in areas with high runoff potential, such as regions in southern Manitoba (e.g. Red River Valley) and British Columbia (e.g. Peace River watershed). This dataset will be a unique resource to a variety of research communities including hydrological, agricultural and water quality modellers and are publicly available at doi:10.1594/PANGAEA.877298.

KEY WORDS: Modelling, SWAT, input datasets, soils, Canada.

1. Introduction

Integrated environmental modeling is inspired by modern environmental problems and enabled by transdisciplinary science and computer capabilities that allow the environment to be considered in a holistic way (Laniak et al., 2013). In an agricultural context, synthesis and quantification of multi-disciplinary knowledge via process-based modeling are essential to manage systems that can be adapted to continual change (Ahuja et al., 2007). The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is an example of such a process-based model. It has been developed over the past 30-years to evaluate the effects of alternative management decisions on water resources and nonpoint-source pollution in large river basins through the simulation of major processes including hydrology, soil temperature and properties, plant

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growth, nutrient and pesticides dynamics, bacteria and pathogens transport, and land management (Arnold et al., 2012; Douglas-Mankin et al., 2010). Furthermore, a weather generator is included in the model to fill gaps that may exist in meteorological records.

The SWAT model has been extensively tested around the world for a wide range of hydro-climatic conditions, water and land management practices, and time scales (Douglas-Mankin et al., 2010). The wide adoption of the SWAT model has been prompted by pre- and post-processing software tools such as a GIS interface, extensive user documentation (Arnold et al., 2012), as well as several linked databases for crops, soils, fertilizers, tillage, and pesticides (Santhi et al., 2005). Among these, soil properties are especially important as they are needed for the simulation of influential processes such as evapotranspiration, soil water balance, nutrient dynamics, and sediment transport (Neitsch et al., 2005). However, the existing built-in database is only valid for SWAT applications in the USA. Accordingly, studies outside the USA require the development of a soils dataset by pre-processing available soils data into a format readable by SWAT, a time consuming process as not all data required by SWAT is readily available for countries outside of the USA.

In Canada, the SWAT model has been used for hydrological simulations in most provinces, including Prince Edward Island (Edwards et al., 2000), New Brunswick (Chambers et al., 2011; Yang et al., 2009), Nova Scotia (Ahmad et al., 2011), Ontario (Asadzadeh et al., 2015; Rahman et al., 2012), Quebec (Lévsque et al., 2008), Manitoba (Yang et al., 2014), Saskatchewan (Mekonnen et al., 2016), Alberta (Mapfumo et al., 2004; Watson and Putz, 2014; Faramarzi et al., 2015), and British Columbia (Zhu et al., 2012). However, preparation of Canadian soils information in a consistent and usable format for SWAT is time consuming (Rahman et al., 2012), as information has to be collected from soil reports, cross-checked against GIS datasets,

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missing soil variables have to be calculated from other physical and hydraulic properties, and all parameters have to be attributed to specific soil grids or polygons.

Some of this pre-processing work can be alleviated by using publically available databases that contain most of the information required by SWAT. The Soil Landscapes of Canada (SLC) database published by Agriculture and Agri-Food Canada (Soil Landscapes of Canada Working Group, 2010) is an example, and has been used in SWAT applications in Ontario (Asadzadeh et al., 2015; Rahman et al., 2012), Saskatchewan (Mekonnen et al., 2016), Alberta (Faramarzi et al., 2015), and British Columbia (Zhu et al., 2012). The SLC contains a series of GIS dataset that provides information about the country's agricultural soils at the provincial and national levels. It was compiled at a scale of 1:1 million, and the information is organized according to a uniform national set of soil and landscape criteria based on permanent natural attributes (Soil Landscapes of Canada Working Group, 2010). The SLC encompasses the southern portions of the Provinces of Ontario and Quebec and a larger portion of the Prairies Provinces of Manitoba, Saskatchewan, and Alberta as far north as to the boreal shield. Coverage in the maritime provinces of New Brunswick, Nova Scotia, and Prince Edward Island is nearly complete (Fig. 1).

Although there are more detailed soil datasets available at provincial levels (e.g. AGRASID dataset in Alberta), selection of SLC for integration with SWAT was based on the fact that i) it covers all of Canada’s agricultural soils in a single dataset; ii) it has been used in regional studies in Canada, as described above; and iii) it is more easily applicable to large-scale national studies as broad-scale datasets require reduced resources to prepare and process data (Moriasi and Starks, 2010). Modelling studies comparing the performance of a single model (calibrated and un-calibrated) but using soil datasets with varying spatial resolution in the USA [i.e., the State Soil Geographic database (STATSGO) compiled at 1:250,000 scale, and the Soil Survey

Geographic database (SSURGO) with scales ranging from 1:12,000 to 1:63,360] also revealed that using either dataset produced comparable results (Mednick, 2008).

Due to the importance of the SWAT model for integrated environmental modeling in Canada, and the prominence of the SLC database as a potential input dataset for this model at a national level, the objective of this work was to offer a country-level soils dataset in a format ready to be used in SWAT simulations. The dataset was derived to provide over 20 parameter values for different soil types that are varied for each soil layer. It was prepared in a format suitable for use in the ArcSWAT version of the model, which is attributed to a grid or polygon-based soil map. Such a laborious pre-processing exercise is widely, but inconsistently adopted in SWAT simulations reported in the literature. Finally, deficiencies in the dataset are also presented and discussed.

2. SLC data structure

The SLC database (http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html) is structured as a component-based GIS layer, where a single polygon may contain several soil series. This structure is similar to that of the State Soil Geographic (STATSGO) database in the United States (Srinivasan et al., 2010). Such structure creates a one-to-many relationship where the multiple soil components of a polygon are not spatially defined. The actual soil information in the SLC database is stored in a number of tables linked together through intricate relationships (Soil Landscapes of Canada Working Group, 2010). Among these, four tables are relevant for developing a dataset for SWAT applications:

- the Polygon Attribute Table (PAT) provides the linkage between geographic locations (polygons in the SLC GIS coverage) and soil landscape attributes in the associated database tables (e.g. unique soil ID in the SNT and respective number of layers in the SLT);

- the Component Table (CMP) describes each of the individual soil and landscape features comprising the polygons. That is, it describes which soil(s) are present in each spatial unit (i.e., polygon) in the GIS layer;
- the Soil Name Table (SNT) describes the general physical and chemical characteristics for all of the soils identified in a geographic region;
- the Soil Layer Table (SLT) contains soil information that varies in the vertical direction (i.e., layered attributes).

The CMP table describes the proportion of each non-spatially defined soil component in a polygon if more than a soil component exists [the soil component(s) refer to the soil(s) element(s) that comprise each polygon]. The component numbering follows a sequence of decreasing proportion in a polygon (i.e., first component has the highest proportion; last component has the smallest proportion). This component-based structure of the SLC database does not affect the analysis since all the soils listed in the SNT table were processed to generate the present dataset. However, it has implications for the SWAT model user, who has to make a decision on how to handle the relationship between the polygon (spatially defined) and each non-spatially defined soil component in multi-component polygons (e.g. selecting the larger component in a polygon or generating a hybrid soil incorporating properties of each soil component).

3. SWAT soils data structure

The SWAT soils information is stored in the 'usersoil' table, located within the SWAT 2012 database in Microsoft Access format (i.e., SWAT2012.mdb). Each soil is stored as a new record

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(i.e., row) in the table. Specific soil variables (Table 1) comprise the 152 columns of the user soil table. The first column is an OBJECTID field assigning an unique identifier for each record. Columns two through six pertain to soil classification. The second column is the map unit identifier (MUID), which is used for mapping a collection of areas grouped by the same soil characteristics. A single MUID may describe different soil types, which are stored with a record counter in the third column (SEQN), while a soil identifying name (SNAM), a soil interpretation record (S5ID), and the percent of each soil component (CMPPCT) are recorded in the fourth, fifth, and sixth columns, respectively (Sheshukov et al., 2009). Columns seven through twelve describe major soil properties pertaining to the soil type, namely, the number of layers (NLAYERS), the hydrological soil group to which that soil belongs (HYDGRP), the maximum rooting depth of the soil profile (SOL_ZMX), the fraction of soil porosity from which anions are excluded (ANION_EXCL), the potential of maximum crack volume of the soil profile expressed as a fraction of the total soil volume (SOL_CRK), and the texture of the soil layer (TEXTURE).

The next 120 columns starting from column 13 (i.e., columns 13 to 132) describe the information for each layer of the soil profile. These columns are arranged in sets of 12 variables each for 10 possible soil layers. The variable NLAYERS indicates how many of these sets should be populated. Variables for any sets beyond NLAYERS should be assigned a value of zero. The variables included in each set of soil layers are the depth from soil surface to bottom of layer (SOL_Z), moist bulk density (SOL_BD), available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), organic carbon (SOL_CBN), clay (CLAY), silt (SILT), sand (SAND), and rock fragment (ROCK) contents, moist soil albedo (SOL_ALB), erodibility factor (USLE_K), and electrical conductivity (SOL_EC). Beyond the columns describing layered soil information, there are 20 columns (i.e., columns 133 to 152)

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describing two variables [i.e., soil $CaCO_3$ (SOL_CA) and soil pH (SOL_PH)] for 10 soil layers. These variables are not currently active in SWAT and are assigned a value of zero.

4. Merging the two datasets

Despite its usefulness as a source of soil information for hydrological simulations, the SLC dataset is not assembled in a format readable by SWAT or other similar models. For example, SWAT stores all the properties for a specific soil in a single row in the the '*usersoil*' table, while this information is stored in the SLC as multiple rows in two different tables (i.e., SNT and SLT). Thus, the information contained in the SLT database has to be processed to satisfy SWAT's format requirements. In addition, all properties in the *usersoil* are spatially defined while those of SLC are often stored in a multi-polygon structure with no unique spatial identification. Variables required by SWAT and contained in the dataset presented here were either extracted from SNT and SLT, or calculated from the information therein. Some other variables were estimated from published values. Extraction or calculation of variables was done through an R code that imported both SNT and SLT, screened the data for missing records and missing SWAT-required information (data screening is described in section 5), and sequentially populated unique soil records in the database. This section describes how these variables were defined.

5. Data screening

5.1 Screening out incomplete soil information in the SNT

The use of the SNT is necessary as it links the soils information to the GIS coverage containing the PAT. However, a first screening was required to remove soils from the SNT that are not present in the SLT, as soil layer information is required by SWAT. The mismatch among

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soils in both tables can occur for a number of reasons. For example, there are soils in both tables that pedologists have identified but their properties have not yet been characterized. Also, soils listed in one table may be absent from another table due to changes in soil classification. Finally, soils listed as unclassified in the SNT (i.e., variable KIND=U) do not have any data associated with them in the SLT and do not occur on any published map.

Out of the 14,063 unique soils in the SNT, 489 soils were missing in the SLT and, therefore, removed from the analysis. These 489 soils correspond to around 3.5 % of the soils listed in the SNT. Most of the missing soils were reported as “unclassified” (305 soils; 62.2 %), suggesting that these soils have been identified, but their properties have not yet been characterized. Mineral soils corresponded to 29.4 % (144 soils) of the total, likely a reflection of changes in classification. The other two classes comprised non-true soils (e.g. mine tailings, urban land; 33 soils; 6.7 %) and organic soils (8 soils; 1.6 %). Also, only 58 of the 489 missing soils (11.0 %) could be mapped through linking with the CMP table, making it impossible to do any spatial analysis on the distribution of these soils across the country. However, since the SNT assigns a province for each soil, it is possible to identify where these missing records occur. Most of the missing soils were in British Columbia (167 soils; 34.2 %), Manitoba (151 soils; 30.9 %), and Saskatchewan (133 soils; 27.2 %), with smaller proportions in Yukon (13 soils; 2.7 %), Ontario (11 soils; 2.3 %), Nova Scotia (9 soils; 1.8 %) and Newfoundland (5 soils; 1.0 %).

5.2 SWAT requirements

The SWAT data requirements were used as a second level of screening to build the present dataset. The soil input variables in SWAT can be either required or optional (Table 2; Arnold et al., 2013). Required variables that could not be calculated or estimated (e.g., SOL_BD, SOL_K, SOL_CBN, CLAY, SILT, and SAND) were used to separate complete from incomplete records.

Soils in the SLT containing or allowing derivation of all the variables required by SWAT were compiled in a dataset comprising 11,838 unique soils that were importable into the model. Soils in the SLT with missing records (i.e., variables entered as -9 in the database) for the required SWAT variables (gray rows in Table 2) were removed from the analysis. These soils were compiled into a soils list provided as a reference.

As for the non-matching soils in the SNT and SLT, only 547 out of 1736 (i.e., 31.5 %) soils with missing information could be mapped through linking with the CMP table, which renders any spatial representation of these soils unmeaningful. However, the provinces where these soils occur could also be identified. The highest proportions of soils with incomplete information were in British Columbia (490 soils; 28.2 %), Manitoba (391 soils; 22.54 %). Ontario (182 soils; 10.5 %) and Alberta (180 soils; 10.4 %) had intermediate values, while Newfoundland (123 soils; 7.1 %), Saskatchewan (102 soils; 5.9 %), New Brunswick (93 soils; 5.4 %), the Northwest Territories (80 soils; 4.6 %), Nova Scotia (47 soils; 2.7 %), Quebec (30 soils; 1.7 %), and Yukon (17 soils; 1.0 %) had less than 10 % of the soils missing information.

6. Populating the user soil table in SWAT

The variables in SWAT's 'usersoil' table refer to record indexing and soil classification, as well as soil properties pertaining to the entire profile or specific layers. The variables in each of these groups are described in the following sub-sections. The 'usersoil' table starts with a number of columns that define the database and soil classification variables, followed by soil profile and layer information, and inactive soil properties (Table 2).

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6.1 Database and soil classification variables

The SWAT soil classification variables include the OBJECTID (general listing number), MUID (map unit identifier), SEQN (sequence number), SNAM (soil name), S5ID (Soils5-ID number for USDA soil series data) and CMPPCT (percentage of the soil component in the MUID). A numbering system used for the OBJECTID variable was chosen to avoid conflicts with existing soils in the user soil table. The SWAT model comes with more than 200 soils in a built-in database that cannot be easily overwritten, and any soils imported into the database with the same OBJECTID as existing soils will not be imported. Thus, the OBJECTID field was populated sequentially from 1001 to the number of unique soils in the SLC database plus 1000 (i.e., OBJECTID ends in 12,838 in the case of the COMPLETE dataset, which has 11,838 unique soils). The map unit ID (MUID) was assigned the SOIL_ID code in the SLC dataset, which is a concatenation of the province code (two digits), a soil code (three digits), a modifier code (five digits), and a profile code (one digit). The sequence number (SEQN) variable was assigned the same value as the OBJECTID variable. This process created a unique SEQN for each recurrence in the SLC dataset.

Similar to the MUID variable, the soil name variable (SNAM) was also assigned the SOIL_ID code in the SLC, despite the soil name being in the database, so as to link the soil information to the GIS layer. The S5ID variable was created as a concatenation between the acronym “SLC” and the province two-digit abbreviation code. For example, all the soils in the province of Alberta have S5ID equal to “SLCAB”. The CMPPCT variable was assigned a value of 100, meaning that the soil comprises 100 % of this component. As stated in section 2, the user has to make a decision on how to handle multipart polygons in the pre-processing of the SLC GIS dataset since the soils in multi-component polygons are not spatially defined.

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6.2 Soil profile information

The following six variables in the dataset (i.e., columns 7 to 12) pertain to soil profile information. The number of layer variables (NLAYERS) was defined according to the soil layers in the SLT below the soil surface. The SLT table also contains information for layers above the soil surface as is the case of litter, which have negative values for upper and lower depths (i.e., the ground surface corresponded to the zero depth, while above surface and below surface layers have negative and positive values, respectively). Above-surface layers were removed from the dataset prior to analysis through filtering layers with lower depth above the soil surface (i.e., lower depth less than or equal to zero).

The hydrologic soil group (HSG) variable (HYDGRP) is an influential parameter for estimation of runoff using the SCS-Curve Number method and, consequently, for hydrological simulations in SWAT (Gao et al., 2012; Neitsch et al., 2005). The HSGs were calculated according to the method outlined by USDA-NRCS (1993), which is based on depth to the impermeable layer (e.g., bedrock), depth from soil surface to shallowest water table during the year, hydraulic conductivity of the least conductive layer of the soil profile, and depth range of the hydraulic conductivity. The specific criteria used are provided in tabular form as supplementary material. Soils in the dual HSG classes were assigned to the less restrictive class since most agricultural soils in Canada exhibit some degree of drainage (e.g., municipal drainage network, surface drains, or tile drainage). SWAT translates HSG alphabetical classification into a numeric system, where HSGs A, B, C, and D, are interpreted as 1, 2, 3, and 4, respectively. The runoff potential increases with increasing numeric designations.

The depth to the impermeable layer is not reported in the SLC database and was estimated based on the soil layers available in the SLT. When a bedrock layer or specific soil horizons

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were present [i.e., fragipan; duripan; petrocalcic; orstein; petrogypsic; cemented horizon; densic material; placic; bedrock, paralithic; bedrock, lithic; bedrock, densic; or permafrost; USDA-NRCS (1993)], its upper depth was used as the depth to impermeable layer. When a bedrock layer was absent, the lower depth of the deepest mineral soil layer was used as an alternative. The shallowest annual depth to water table is also not reported and was estimated based on drainage class reported in the SNT. Very poorly drained, poorly drained, imperfectly drained, moderately well drained, and well drained (or better) soils were assigned water table depths of 0 , 25 , 75, 100, and 125 cm, respectively. The variables pertaining to hydraulic conductivity of the least conductive layer of the soil profile and depth range of the hydraulic conductivity were both calculated using information from the SLT.

Out of the 11,838 soils in the generated dataset, 21.3, 24.6, 39.0, and 15.1 % belonged to HSGs 1, 2, 3 and 4, respectively. These results suggest that more than half of the soils in Canada have a relatively high or high runoff generation potential (i.e., HSGs 3 and 4, respectively). A spatial analysis indicated that 20.0, 26.8, 36.7, and 16.5% of the areal extend of the soils belonged to HSGs 1, 2, 3, and 4, respectively. Much of the soils with higher potential for runoff generation are in the humid regions of Ontario, Quebec, and the Maritimes (Fig. 2). Not surprisingly, this region has extensively adopted measures to address excess moisture in agricultural soils, such as tile drainage (Stonehouse, 1995; Rasouli et al., 2014). Excess moisture is also a problem in areas of Canadian Prairies, such as the Red River Valley in Manitoba, where surface drainage (Bower, 2007) and a growing use of tile drainage (Cordeiro and Sri Ranjan, 2012, 2015) have been used to address this problem. Conversely, soils with low potential for runoff generation are located in Saskatchewan and Southeastern Alberta (along the Saskatchewan border), which are among the most arid regions in Canada (Wolfe, 1997).

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The maximum rooting depth of the soil profile (SOL_ZMX) was assumed to be the lower depth of the deepest layer in the SLC soil profile. The fraction of soil porosity from which anions are excluded (ANION_EXCL) was not available in the SLC database and was set to the default value of 0.5 in SWAT (Arnold et al., 2013). This variable affects the concentration of nitrate in the mobile water fraction, which is directly related to nitrate leaching. The potential of maximum crack volume of the soil profile expressed as a fraction of the total soil volume (SOL_CRK) can be calculated by the FLOCR model using 30-yr weather data (Bronswijk, 1989). However, due to the fact that the model is not readily available for download and the unreasonable time required to run the model for such a large number of soil types, as well as the fact that SOL_CRK is optional in SWAT, its value was set of 0.5. In large scale studies this value is further adjusted through a spatially explicit calibration scheme (Whittaker et al., 2010). The SOL_CRK variable controls the potential crack volume for the soil profile. This value was selected based on the fact that all of the built-in soils in the SWAT soils database have the SOL_CRK variable set to 0.5. The TEXTURE variable, although not required for simulations with the SWAT model, was estimated for reference using the 'TT.points.in.classes' function from the 'soiltexture' R package (Moeys, 2016). The Canadian soil texture classification system was used as a reference.

6.3 Soil layer information

The soil profile variables are followed by 10 sets of 12 variables (i.e., columns 13 to 132) pertaining to layered soil information. The lower depth of each soil layer in the SLT was used as the depth from soil surface to the bottom layer (SOL_Z). The soil bulk density (SOL_BD) was extracted directly from the SLT. The available water capacity of the soil layer (SOL_AWC) was calculated from the water retention of the soil reported in the SLT at different matric potentials.

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The water moisture content at -33 and -1500 kPa were assumed to represent the soil moisture at field capacity (FC) and permanent wilting point (PWP), respectively (Givi et al., 2004). The SOL_AWC was calculated as the difference between FC and PWP (Hillel, 1998). Soil moisture content at -33 kPa was not available for 2,658 layer records (i.e., 4.3% of the 61905 original records in the SLT table), which would result in the variable SOL_AWC not being calculated and the loss of more soils from the dataset. To avoid this, the moisture content at -10 kPa was used to replace that at -33 kPa. On average, the soil moisture content in the soil profile was around 6 mm larger at -10 kPa than that at -33 kPa (Table 3), indicating an overestimation of SOL_AWC in these soils. Larger differences between soil moisture content at -10 kPa and -33 kPa in the top soil layers were likely driven by lower bulk densities, which increase the water holding capacity of the soil (Table 3).

The variables saturated hydraulic conductivity (SOL_K) and soil organic carbon content (SOL_CBN), as well as the clay (CLAY), silt (SILT), sand (SAND), and rock fragment (ROCK) contents, were extracted directly from the SLT. The moist soil albedo (SOL_ALB) variable was only required for the top layer as subsequent layers were assigned a value of zero. Since this variable is not reported in the SLC database, it was estimated as the average (i.e., 0.10) of the range reported by Maidment (1993) for moist, dark, plowed fields (i.e., 0.05-0.15). Again, this value was selected since the SLC version 3.2 focuses on agricultural areas, which is also the major domain simulated by SWAT.

Another important variable for SWAT is the erodibility factor (USLE_K), used as an input to the Universal Soil Loss Equation (USLE). This equation is used to calculate soil erosion, which is inherently linked to sediment and nutrient transport (Sharpley et al., 1992; He et al., 1995; Sharpley et al., 2002; Aksoy and Kavvas, 2005; Koiter et al., 2013) and therefore, critical for

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simulations of non-point sources of pollution. The erodibility factor was calculated using the method presented by Sharpley and Williams (1990), which is based on the sand, silt, clay, and organic carbon content of the soil (Eq. 1):

$$K = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \cdot \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \cdot \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp\left[3.72 - 2.95 \cdot orgC\right]}\right) \cdot \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51\_22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}\right) \quad (1)$$

where K is the erodibility factor [0.01 (ton·acre·hr)/(acre ft-ton in)], m_s is the sand content (percent), m_{silt} is the silt content (percent), m_c is the clay content (percent), and $orgC$ is the organic carbon content (%) of the respective soil layer.

As for SOL_ALB, USLE_K is only required for the top layer and subsequent layers were also assigned a value of zero. When converted from Imperial to SI units (Foster et al., 1981), the range of calculated values (Table 4) generally agrees with the ranges reported for Canada (Wall et al., 2002), taking into consideration that K values may vary, depending on particle size distribution, organic matter, structure and permeability of individual soils (Wall et al., 2002). However, the units in the dataset presented here were kept in Imperial units for consistency with the SWAT input format. The spatial distribution of the erodibility factor (Fig. 3) was anticipated to align with HSG, which was the case in areas of low erosion potential in Saskatchewan where sandy soils prevail and in areas where runoff potential is high such as in southern Ontario. However, the spatial distribution of USLE_K somewhat contrasted to that of HSG in some areas of Manitoba and British Columbia, where low sediment transport potential was predicted in areas with high runoff potential. This contrast was likely due to other factors reducing the potential for

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sediment transport, such as soils with high clay to silt ratios or high organic carbon contents (Sharpley and Williams, 1990).

The soil electrical conductivity (SOL_EC) information was extracted directly from the SLT. The last twenty columns of the dataset (i.e., columns 133 to 152), which correspond to SOL_CAL for the 10 soil layers followed by SOL_PH for the same layers, were all populated with zeros since these variables are not currently active in SWAT. These variables also had values of zero for all the pre-existing soils in the built-in database in the model.

7. Importing the SLC dataset into SWAT database

Although the SWAT database is in a proprietary format (i.e., Microsoft Access), the present soils dataset has been published in a non-proprietary format [i.e., comma-separated values (CSV) file] that can be opened in a variety of software packages. However, the dataset can be easily imported into the SWAT soils database using an automated import routine in Microsoft Access. This import process consists of opening the SWAT2012 database and using the ‘Import Text File’ tool under the ‘Import & Link’ section of the ‘External Data’ tab to read the CSV file. This action will prompt a window where the user can select the path to where the present dataset is stored and specify how and where the data is stored in the database. The option ‘Append a copy of the record to the table’ should be selected, which activates a drop-down menu from which the ‘usersoil’ table should be highlighted. Once these options have been processed, an ‘Import Text Wizard’ window will be prompted, where the option ‘Delimited – Characters such as comma or tab separate each field’ should be selected. Processing of this selection will prompt another window where the option ‘comma’ should be automatically selected by the wizard. However, the user should activate the box ‘First Row Contains Field Names’ since the first row of the present

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dataset contains the variable labels. Confirming the processing of the next windows should finalize the import process, and the data should be ready to be used in SWAT predictions.

8. Data access

PANGAEA, an open access library to archive, publish and distribute georeferenced data, supports database-dependent research. Therefore, the entire dataset is published and archived in the PANGAEA database (https://doi.pangaea.de/10.1594/PANGAEA.877298) under Creative Commons Attribution 3.0 Unported, where the user must give appropriate credit, provide a link to the license and indicate if changes are made.

9. Conclusions

The soils dataset presented and discussed in this work represent an effort to facilitate hydrological simulations using the SWAT model in Canada. The dataset consists of a compilation of 11,838 different soils from the SLC database with all the information required by SWAT and is ready to be imported into the model's soils database. A two-level data screening procedure removed 489 soils with missing layered information (i.e., not present in the SLT), while 1,736 soils were removed due to the lack of critical information required by SWAT, such as soil bulk density or saturated hydraulic conductivity. Among the major contributions of this dataset, the calculation and/or estimation of variables not reported in the SLC database are of special importance. The hydrologic soil groups (HSGs) calculated from SLC database suggests that about half of the soils in Canada belong to classes with higher potential to generate runoff (i.e., HSG classes 3 and 4). Occurrence of soils in HSG 3 and 4 agree with management practices aimed at addressing excess moisture conditions in agricultural fields, such as subsurface drainage in southern Ontario and Manitoba. The erodibility factor, which is another important variable for SWAT simulations of non-point source pollution, suggest a relationship with runoff potential in portions of southern Ontario and Nova Scotia. However, low erodibility potential likely driven by high clay to silt ratios or high organic carbon content were found in areas with higher runoff potential in Manitoba and British Columbia.

Author contribution

M.R.C Cordeiro and R. Kroebel developed the concept for development of the dataset. G. Lelyk interpreted the soil information contained in the SLC database. M.R.C Cordeiro and G. Lelyk developed the methodology for deriving the soil variables. M.R.C Cordeiro developed the code using R programming language to process the SLC dataset and performed data analysis. All the authors revised the dataset and participated in manuscript preparation.

Acknowledgements

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Table 1. Description of variables in SWAT's 'usersoil' table.

Variable Group	Column number in 'usersoil' table	Variables[a]
Database indexing	1	OBJECTID
Soil classification	2 through to 6	MUID; SEQN; SNAM; S5ID; CMPPCT
Soil properties		
Profile	7 trough to 12	NLAYERS; HYDGRP; SOL_ZMX; ANION_EXCL; SOL_CRK; TEXTURE
Layers	13 through to 132 (12 variables for 10 soil layers)	SOL_Z_x; SOL_BD_x; SOL_AWC_x; SOL_K_x; SOL_CBN_x; $CLAY_x$; $SILT_x$; $SAND_x$; $ROCK_x$; SOL_ALB_x; $USLE\_K_x$; SOL_EC_x
Inactive	133 through to 152	SOL_CAL_x; SOL_PH_x

[a] Subscript x corresponds to soil layer from 1 to 10.

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Table 2. Variables included in the SWAT user soil table.

Column	Variable[a]	Description	Units	Status
1	OBJECTID	Object identifier	–	Optional
2	MUID	Mapping unit identifier	–	Optional
3	SEQN	Record counter calculated by SWAT	–	Optional
4	SNAM	Soil identifying name	–	Optional
5	S5ID	Soil interpretation record	–	Optional
6	CMPPCT	Soil component percent	–	Optional
7	NLAYERS[†]	Number of layers	–	Required
8	HYDGRP	Hydrologic Soil Group	–	Required
9	SOL_ZMX	Maximum rooting depth of the soil profile	mm	Required
10	ANION_EXCL	Fraction of soil porosity from which anions are excluded	–	Optional
11	SOL_CRK	Potential of maximum crack volume of the soil profile expressed as a fraction of the total soil volume	mm^3 mm^{-3}	Optional
12	TEXTURE	Texture of soil layer	–	Optional
13	SOL_Z_x	Depth from soil surface to bottom of layer	mm	Required
14	SOL_BD_x	Moist bulk density	Mg m^{-3} or g cm^{-3}	Required
15	SOL_AWC_x	Available water capacity of the soil layer	mm mm^{-3}	Required
16	SOL_K_x	Saturated hydraulic conductivity	mm h^{-1}	Required
17	SOL_CBN_x	Organic carbon content	% (w/w)	Required
18	$CLAY_x$	Clay content	% (w/w)	Required
19	$SILT_x$	Silt content	% (w/w)	Required
20	$SAND_x$	Sand content	% (w/w)	Required
21	$ROCK_x$	Rock fragment content	% (w/w)	Required
22	SOL_ALB_x	Moist soil albedo	–	Required
23	$USLE\_K_x$	Erodibility factor (K)	0.01 (ton·acre·hr)/(acre ft-ton in)	Required
24	SOL_EC_x	Electrical conductivity	dS m^{-1}	Optional

Adapted from Arnold et al. (2013) and Sheshukov et al. (2009). [a] Subscript x corresponds to soil layer from 1 to 10. The variables SOL_CAL_x and SOL_PH_x are present in the user soil table after all the columns listed above for all the 10 pre-existing layers. These variables refer to soil $CaCO_3$ and soil pH, respectively, and are not currently active in the model. Thus, their records are entered zero in the SWAT 2012 database. [†]The number of layers defines how many entries will be required in the layered information, signalled by the subscript x. For example, a soil with NLAYERS=4 should have subscript x corresponding to soil layer variables from 1 to 4. As a result, the records extend to column 60 in the user soil table. (i.e., 4 layers×12 variables + 12 preceding variables=60).

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Table 3. Average soil moisture content at matric potentials -10 kPa and -33kPa and average soil bulk density for discrete layers of the soil profile. The average was calculated for all soils in the dataset. Each layer could have different depths for individual soils used in the average.

Layer	$\bar{\theta}\, at - 10kPa$	$\bar{\theta}\, at - 33kPa$	Difference (mm)	Average soil bulk density (g cm^{-3})
1	36.8	29.67	7.13	1.13
2	33.65	26.72	6.93	1.27
3	31.99	25.36	6.63	1.38
4	29.48	23.32	6.16	1.47
5	28.1	22.17	5.93	1.50
6	27.26	21.53	5.73	1.52
7	27.03	21.42	5.61	1.54
8	26.98	21.17	5.81	1.54
9	25.05	18.86	6.19	1.55
AVERAGE	29.59	23.36	6.24	1.43

$\bar{\theta}$ = average soil moisture content (mm).

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Table 4. Comparison between the average erodibility factor (K) calculated for each soil textural class in the SWAT dataset and values reported in the literature.

Soil Textural Class	Acronym	Calculated average K	Reported K range[†]
Loam	L	0.14	0.23 – 0.30
Heavy clay	HCl	0.18	0.05 – 0.23
Silty clay loam	SiClLo	0.22	0.30 – 0.38
Clay loam	ClLo	0.14	0.23 – 0.30
Silt loam	SiLo	0.22	0.30 – 0.38
Sand	Sa	0.04	< 0.05
Sandy loam	SaLo	0.11	0.05 – 0.23
Clay	Cl	0.14	0.23 – 0.30
Silty clay	SiCl	0.22	0.23 – 0.30
Loamy sand	LoSa	0.07	< 0.05
Sandy clay loam	SaClLo	0.10	0.23 – 0.30
Silt	Si	0.55	0.30 – 0.38[¶]
Sandy clay	SaCl	0.09	0.05 – 0.23[#]

[†]Adapted from Wall et al. (2002). [¶]Range not reported; value from SiLo used. [#] Range not reported; value from SaLo used.

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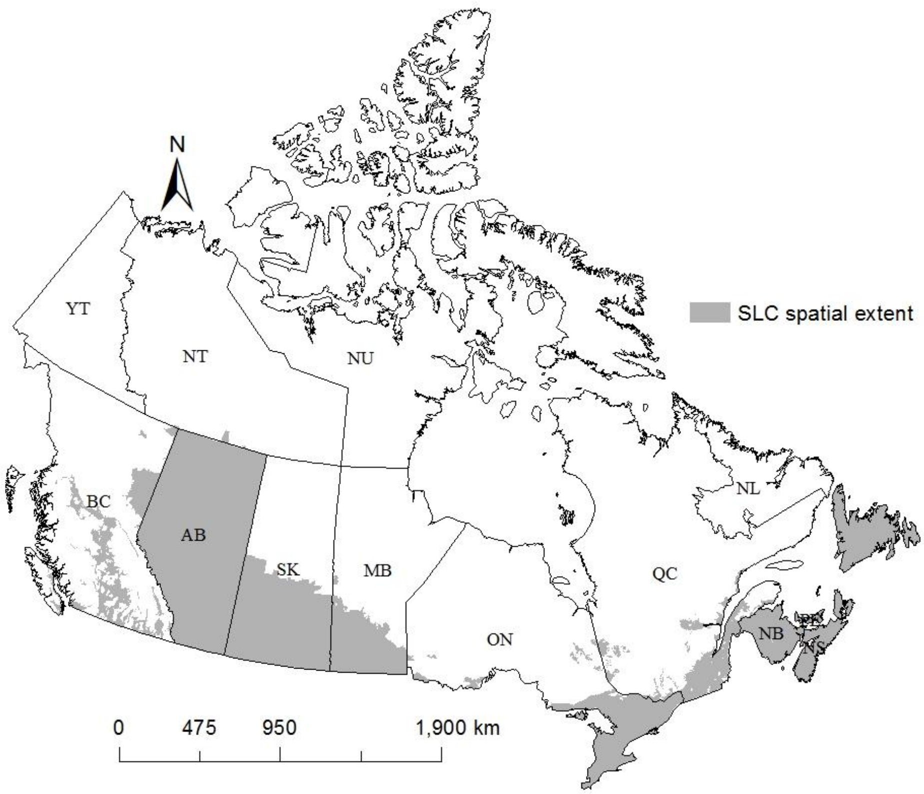

578
579 Figure 1. Spatial extent of the Soil Landscapes of Canada (SLC) database showing coverage in the Provinces of
580 Newfoundland and Labrador (NL), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec
581 (QC), Ontario (ON), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC), as well as the
582 Northwest Territories (NT).

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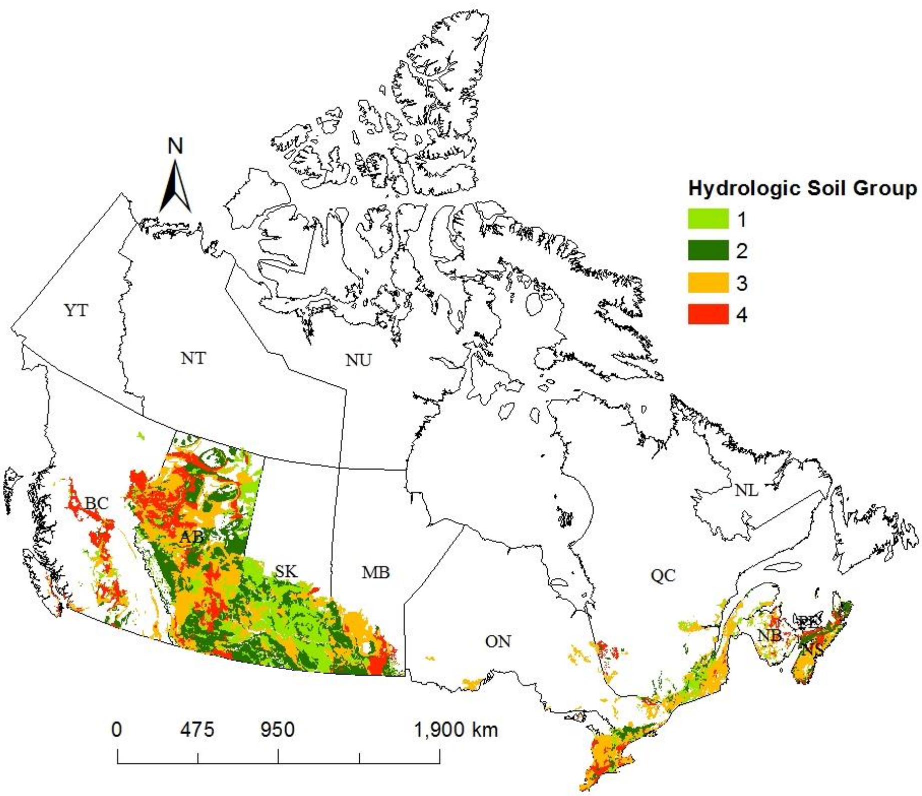

Figure 2. Spatial distribution of the hydrologic soil groups (HYDGRP) variable calculated for the Soil Landscapes of Canada (SLC) database. HSG A=1, HSG B=2, HSG C=3, and HSG D=4 shown for the Provinces of Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (ON), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). Some HSG could not be mapped [e.g. Province of Newfoundland and Labrador (NL)] due to missing records in the PAT of the GIS layer or being part of the soils with missing data in the SLT.

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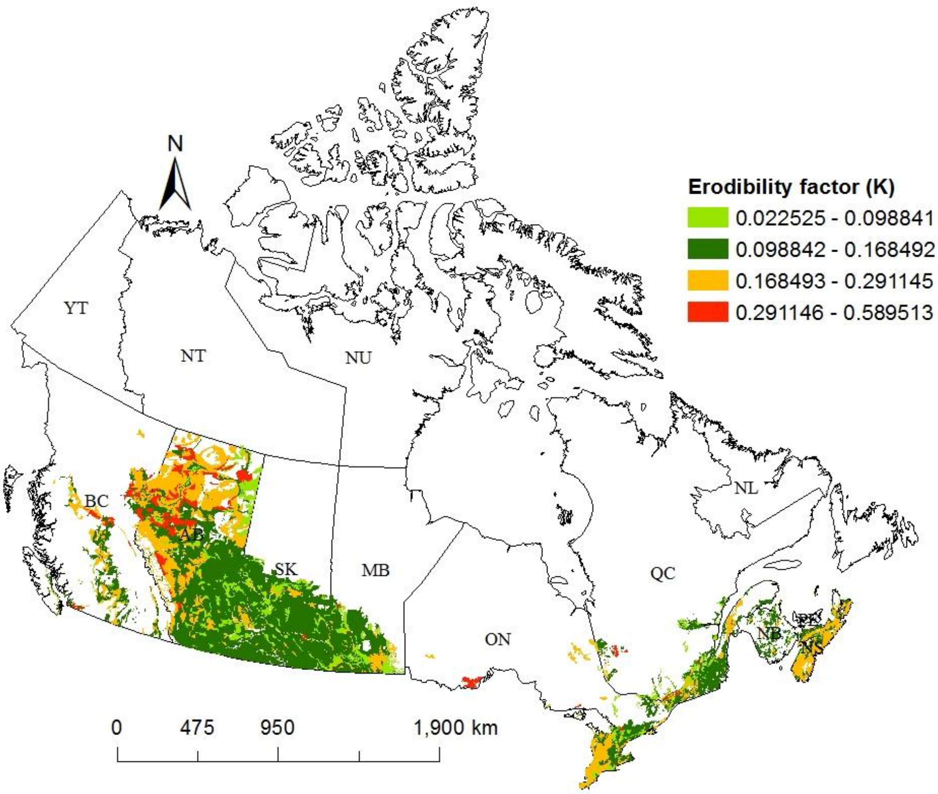

Figure 3. Spatial distribution of the erodibility factor (K) calculated for the Soil Landscapes of Canada (SLC) database (Imperial units). The K factor shown for the Provinces of Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (ON), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). Some HSG could not be mapped [e.g. Province of Newfoundland and Labrador (NL)] due to missing records in the PAT of the GIS layer or being part of the soils with missing data in the SLT.