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Long-term weather, hydrometric, and water chemistry datasets in high-temporal resolution at the La Salle River watershed in Manitoba, Canada

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Abstract

Lack of long-term datasets in fine temporal resolution hinders environmental studies and modelling efforts; to address this issue in the La Salle River watershed, in Canada, long-term weather (1990-2013), hydrometric (1990-2013 except years with no or poor data), and water chemistry (2009-2013) datasets were developed. The weather variables consisted of temperature, relative humidity, wind speed, solar radiation, and precipitation in an hourly time-step, which is required for physically-based modelling. The only hydrometric variable included in the dataset was stream discharge in a daily time-step, which is the usual time-frame for summarizing the results of long-term studies. The water chemistry data consisted of total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP) and total dissolved phosphorus (TDP). Samples were collected weekly during the open water season at the same site as they hydrometric gauging station (05OG008) starting in August 2009 until October 2012 with some gaps (i.e. Fall 2011, Spring 2012, September 2012). In 2013 the frequency of sampling was increased to daily or sub-daily during high stream discharge and weekly during low stream discharge. An overview of the data indicates that values and trends are within ranges reported in the literature for the region.

Mean annual, winter, and summer temperatures were 3.5 °C -10.7 °C and 17.2 °C, respectively. Annual relative humidity averaged 73.1 % but tended to be higher and more homogenous in cold seasons. Wind speed was very similar over the different seasons with annual average of 4.3 m/s. Solar radiation followed the typical curve reported for western Canada, with peak daily average values around 250 W/m^2 in July. The precipitation records were mostly comprised of dry hours and the characteristic precipitation pattern of the Canadian Prairies with high frequency of small precipitation events as observed, with 75.3% of the hourly precipitation being equal or less than 2 mm/h. The hydrometric characteristics of the dataset were also typical of the Canadian Prairies; the average peak discharge over the entire period was larger in April (2.3 m^3/s) due to large amounts of snowmelt runoff. The average concentrations of TN, TDN, TP and TDP of 1.54, 1.35, 0.56, and 0.49 mg/L, respectively, were in agreement with values found in previous studies at the same location. The datasets for weather (doi: 10.23684/ODI-2017-00957), discharge (doi: 10.23684/ODI-2017-00959) and water chemistry (doi: 10.23684/ODI-2017-00958) are accessible through the Government of Canada's Open Data portal (http://open.canada.ca).

KEY WORDS: Prairie hydrology; cold-region; modelling; input datasets, climatic, hydrometric, water chemistry.

1. Introduction

Lake Winnipeg, the 10th largest freshwater lake in the world, experienced rapid eutrophication in the last century due to increased nutrient input (McCullough et al., 2012), which prompted research efforts to identify nutrient sources and loads to the lake (Mayer and Wassenaar, 2012;Schindler et al., 2012). Due to the prominence of the Red River Basin as the primary source of increasing nutrient loading to Lake Winnipeg (Mayer and Wassenaar, 2012), recent hydrologic modelling efforts have focused on this Basin or that of its major tributary, the Assiniboine River. For example, the effects of climate change on hydrologic and nutrient fluxes has been simulated for sub-catchments of the Red River Basin and the Upper Assiniboine catchment in the Assiniboine River Basin using the Soil and Water Assessment Tool (SWAT) (Shrestha et al., 2012b, a). The effects of land management practices on hydrology and nutrient dynamics has also been simulated with SWAT in three pilot watersheds in both the Red River and the Assiniboine River basins (Yang et al., 2014).

While these modelling exercises represent an important step towards hydrological simulations in the Red-Assiniboine Basin, they were performed using a daily time-step, which is not adequate i) to represent the hydrology of small catchments because of their short storm response times (Beven, 2011) or ii) to force process-based hydrological models (Ellis et al., 2010;Fang and Pomeroy, 2008;Fang et al., 2013;Fang et al., 2010;Zhou et al., 2014;Skaggs et al., 2012). Thus, physically-based simulations of hydrological processes with focus on finer spatial scale require input data at sub-daily time-steps, which has been one of the major limitations for this type of modelling in this Basin.

Sub-daily weather data records have become more commonly available only with the relatively recent expansion of automated weather station networks (Meyer and Hubbard, 1992;Estévez et al., 2011;Fiebrich, 2009). As a result, long-term simulations using sub-daily time steps are often hindered due to lack of sub-daily data (Gaume et al., 2007). Even when sub-daily records can be obtained, data gaps are a frequent limitation (Kim and Pachepsky, 2010) due to loss of older paper records (e.g. fire, accidents) or interruption of automated stations due to calibrations, malfunctioning, or relocation (Simolo et al., 2010). This challenge is emphasized in regions where the weather station density is relatively sparse or where daily data is more widely available, which is the case in much of Canada (Hutchinson et al., 2009).

Hydrometric data comprise another important input for hydrological simulations. Streamflow information for a given watershed or region is crucial for hydrological studies (Mishra and Coulibaly, 2010). In Canada, daily hydrometric data such as stream discharge and stream level is usually available for gauged streams (Environment and Climate Change Canada, 2013). While daily data is usually adequate for long-term, process-based modelling due to simulation results being summarized at this time-step, hydrometric records in Canada are plagued by large data gaps (Mishra and Coulibaly, 2010). An inspection of the HYDAT database (Environment and Climate Change Canada, 2013) also indicates that most of the hydrometric stations located in the Canadian portion of the Lake Winnipeg Basin, whose largest area is comprised by the prairie provinces of Alberta, Saskatchewan, and Manitoba, operates only seasonally (i.e. from March to October) due to no-flow conditions caused by negligible discharge or river ice cover (e.g. Corriveau et al., 2013). Recent analysis during the flow period also indicates that the presence of in-channel control structures and river ice constitute an uncertainty factor for hydrologic simulations in the region (Cordeiro et al., 2016).

Water chemistry data is also of critical importance to identify nutrient sources and loads to Lake Winnipeg. Long-term monthly sampling has been carried out near the mouth of major rivers discharging to Lake Winnipeg (McCullough et al., 2012). In fact, long-term monitoring in some of the prairie provinces of the Lake Winnipeg Basin has only been carried out at the provincial borders (Environment and Climate Change Canada, 2015), while water chemistry sampling at lower-order streams is less frequent. For example, total nitrogen (TN) and total phosphorus (TP) were only available from 1994 in the La Salle, Little Morris, and Seine River systems (Corriveau et al., 2013).

The objective of this work was to prepare a long-term dataset to be used as input data for hydrological simulations at hourly time-steps in a sub-catchment of the La Salle River watershed, which is a tributary of the Red River Basin. This watershed has been selected due to its importance as an object of recent hydrological simulations and its characteristics as an agriculturally-dominated tributary of the Red River, the primary nutrient source to Lake Winnipeg (McCullough et al., 2012;Yang et al., 2014;Corriveau et al., 2013). The dataset presented and discussed here is comprised of three major components: weather (1990-2013), hydrometric (1990-2013 except years with no or poor data), and water chemistry (2009-2013) data. Weather parameters included in the dataset are temperature, relative humidity (RH), wind speed (WS), precipitation (PPT), and solar radiation (SR). Since not all of these variables were available at weather stations within the La Salle River watershed and the record length available for them was not consistent, a “virtual station” was created by drawing data from different stations around the watershed (i.e. parent stations). The process of station selection is described in detail, along with the gap-filling strategy used for different weather variables. Precipitation was only available in a daily time-step; thus, a disaggregation technique was used to downscale the data to an hourly time-step. Hydrometric data include stream discharge, while water chemistry data included total dissolved phosphorus (TDP), total phosphorus (TP), total dissolved nitrogen (TDN), and total nitrogen (TN).

2. Study area

The data collection and analysis focused on a 189 km^2 sub-catchment of the La Salle River watershed (Fig. 1a). This watershed, located in the central plains region of Manitoba, Canada

(Graveline and Larter, 2006), is a tributary of the larger Red River. Thus, it is representative of the Red River Basin and ideal for long-term, physically-based simulation of cold region hydrological processes and nutrient dynamics. The surface geology consists of lacustrine clay deposited in glacial Lake Agassiz characterized by a lower, dark grey clay and a thinner upper unit of lighter coloured, calcareous silty clay, with surface texture being predominantly clayey (La Salle Redboine Conservation District, 2007). The watershed is located in the Prairie Ecozone, with mean annual temperature around 2.5°C, mean summer temperature of 16°C and mean winter temperature of -13°C; the mean annual precipitation is 560 mm, out of which around 25% takes place as snow, while the potential mean annual gross evapotranspiration is about 834 mm (La Salle Redboine Conservation District, 2007). The source weather data used to derive the hourly datasets described in section 3 was originated in the same stations selected for model simulations for the entire La Salle watershed (Yang et al., 2014). Thus, the weather data presented here, although in a finer time-step, could also be used at that spatial scale. However, the hydrometric and water chemistry datasets were only derived for the sub-catchment (Fig. 1 inset).

3. Weather dataset

3.1 Selection of parent stations

The closest weather stations with long-term records of sub-daily (i.e. hourly) data belonged to Environment Canada (EC) and Manitoba Agriculture, Food and Rural Development (MAFRD) (Table 1). The MAFRD station (Fig.1, station A) did not come into operation until the second quarter of 2007; thus, this station was not used in the analysis since it did not cover the period of interest (i.e. 1990-2013). The Portage La Prairie CDA (Canadian Department of Agriculture; Fig.1, station B) was also excluded because data was only available at a daily time-step. The Portage Southport Airport station (Fig.1, station D) was the source of temperature, relative humidity, and wind speed data since this was the closest station with hourly data available. The Winnipeg International Airport station (Fig.1, station F) was the only station measuring solar radiation and was selected for this weather element. The only stations equipped with both tipping buckets and weighing gauges capable of measuring precipitation in both liquid and solid forms were located at the Portage Southport Airport (Fig. 1, station D), at the University of Manitoba Research Station in Carman (Fig1., Station E), and at The Forks in Winnipeg (Fig.1, station G). However, none of these stations were selected because the records started either in 1999 (The Forks) or in 2004 (Portage Southport Airport and University of Manitoba Research Station). As a result, precipitation available in a daily time-step had to be disaggregated to an hourly time-step (sub-section 3.3). Among the candidate stations with daily precipitation, the Marquette station was selected due to the close proximity to the study area and measurement of precipitation as both rain and snow. Proximity was considered the most important criteria for selecting the weather station because of the inherent spatial variability of precipitation (Ramos-Calzado et al., 2008).

3.2 Gap-filling

The presence of gaps in meteorological time series is a very common problem for long term studies (Tardivo and Berti, 2014). The records for all the variables in the weather dataset had some gaps that had to be infilled. The temperature, relative humidity, wind speed, solar radiation and precipitation records had 27.3%, 29.8%, 27.4%, 37.0%, and 0.5% of missing data, respectively. The gaps in temperature and wind speed records were usually short (few hours) and distributed over the entire time series. Data gaps in RH records occurred systematically from 18:00 h to 3:00 h and during weekends until 1993, and then occurred only sporadically from

1994 onwards, indicating the beginning of automated measurements. Similarly to temperature and wind speed, gaps in solar radiation records were short. However, they were mostly concentrated between years 1992 and 2000. The low proportion of gaps in precipitation is due to the time-step used (i.e. daily). These gaps were distributed over the entire time series. Different gap-filling strategies were used to reconstruct the datasets, depending on the weather variable.

3.2.1 Temperature

Linear regression between the Portage Southport Airport station (target station to be gap-filled) and the Winnipeg International Airport and The Forks stations (data sources) was used to reconstruct the temperature. Regression-based techniques are usually used for reconstructing temperature records (Tardivo and Berti, 2014). The method was chosen because it is robust with regards to extreme events or local effects (Ramos-Calzado et al., 2008;Hutchinson et al., 2009). Potential problems with temperature lapse rate due to elevation changes (Henn et al., 2013) were negligible in this area due to its flat topography (Graveline and Larter, 2006). The coefficient of determination (R^2) between the Portage Southport Airport and either station in Winnipeg was 0.98. Due to the similarity in R^2, both neighboring stations in Winnipeg (which were 8.3 km apart from each other) were considered mutually equivalent. However, the station at the Winnipeg International Airport was given priority due to the shorter distance to the target station (Table 1). The proportion of missing temperature data in the target station was decreased from 27.3% to 1.1% using the Winnipeg International Airport. The remaining 1.1% f measurements were infilled using the regression between the target station and the station at The Forks to achieve a complete dataset.

3.2.2 Relative humidity

Similarly to temperature, gaps in the RH records were infilled using linear regression between the Portage Southport Airport station and the Winnipeg International Airport or The Forks stations. The coefficient of determination R^2 between the target station and both stations in Winnipeg was 0.71, which was deemed satisfactory for calculating the missing values of relative humidity since this parameter does not present large spatial variability when compared to other weather elements such as precipitation. Using the station at the Winnipeg International Airport in the first gap-filling step, the missing records decreased from 29.8% to 0.03%. The remaining missing records were infilled using the station at The Forks.

3.2.3 Wind speed

Linear regression was also employed to reconstruct the wind speed dataset using the same stations used for temperature and relative humidity. However, the correlation between those stations for wind speed was weaker than those found for temperature and relative humidity (i.e. R^2=0.48 between Portage Southport Airport and the Winnipeg International Airport; R^2=0.34 between Portage Southport Airport and The Forks station). Despite the weaker correlations, this method was preferred over the typical approach used to address missing data in weather records which is to transplant data from a nearby region to the area of interest (Pomeroy et al., 2013;Liu et al., 2013). The missing records decreased from 27.4% to 1.2% after the infilling using the Winnipeg International Airport. The dataset was completed by gap-filling the remaining missing records using the station at The Forks.

3.2.4 Solar radiation

Since the station at the Winnipeg International Airport was the only location with long-term measurement of solar radiation, data used for gap-filling had to be acquired from a research station located at The Point in the University of Manitoba. This station is located 13.7 km from the Winnipeg International Airport. The missing data was replaced directly with data from the station at The Point due to proximity (Pomeroy et al., 2013;Liu et al., 2013). After gap-filling, there were 6% of the records still missing, which were replaced with the long term average (1990-2013) for that particular Julian day. This approach was preferred over more complex gap-filling methodologies for solar radiation that rely on derivation of coefficients as well as temperature and precipitation information (Hunt et al., 1998). The long-term average was deemed suitable due to the small proportion of the dataset left to be infilled.

3.2.5 Precipitation

The proportion of missing records in the precipitation dataset (i.e. 0.5%) was much smaller than those for the other weather variables since precipitation was in a daily time-step. These gaps were infilled using data from Portage Southport Airport. Once complete, the dataset was used for disaggregation from daily to an hourly time-step.

3.3 Precipitation disaggregation

Disaggregation of precipitation to an hourly time-step was performed using HyetosR (Kossieris et al., 2013), which is an R package for the temporal stochastic simulation of rainfall process at fine time scales based on Bartlett-Lewis rectangular pulses rainfall model (Koutsoyiannis and Onof, 2001). Poisson-cluster models such as the Bartlett-Lewis can be used for point-precipitation simulation while keeping the statistical properties of the process through a wide range of aggregation levels (Velghe et al., 1994). A detailed description of the model including its parameters is given by Velghe et al. (1994) and Koutsoyiannis and Onof (2001).

The parameters needed for model disaggregation have to be estimated from hourly records. A six-parameter model was used for disaggregation (the model can also be run using seven parameters). Since the Marquette weather station did not have precipitation records in an hourly time-step, the hourly records from the Portage Southport Airport station were used for parameter estimation. This station was selected because it was the closest station with available data. Monthly parameters were estimated using the evalutionary annealing-simplex method in HyetosR. Once estimated, these parameters were used as inputs to the DisagSimul function in HyetosR to disaggregate the daily precipitation records into an hourly time-step.

4. Hydrometric data

Daily streamflow observations between 1990 and 2013 were obtained from the hydrometric data (HYDAT) database (Environment and Climate Change Canada, 2013) for the Water Survey of Canada (WSC) gauging station 05OG008 (La Salle River near Elie; Fig.1) located at the outlet of the watershed's sub-catchment. Data collection at this location was seasonal from 1990 to 1996, and has been continuous from 2002 to present. Only flow data is available from HYDAT for the period prior to 1996, while flow and water level were both recorded from 2002 onwards. The annual monitoring period for this station spans from March 1st to October 31st, with no data available during winter months. A gap in available flow data exists between flooding in 1997 and instrument replacement in 2001. Notes in the HYDAT metadata pertaining to 2004 and 2008 indicate equipment malfunctions resulting in loss of data. For this reason, the periods from 1997-2001, 2004, and 2008 are not included in the dataset presented here.

5. Water chemistry data

Prior to the initiation of sampling at higher temporal frequency in 2013 water samples were collected weekly with rope and bucket from a water control structure located at the hydrometric gauging site for the watershed. In 2013 samples were collected during snowmelt and storm events at a higher frequency using an auto sampler (Sigma 900). Timing of sample collection from 2009 to 2012 was designed to provide seasonal coverage (multiple samples monthly) with some higher frequency sample collection during periods of elevated flow. Frequency was increased in 2013 to provide coverage of each runoff event hydrograph with samples on rising, falling, and near peak.

From 2009 to 2012, grab samples were collected, placed on ice, and shipped to the Environment Canada National Laboratory for Environmental Testing (NLET) in Saskatoon, Saskatchewan for analysis using standard analytical techniques at this accredited laboratory. Samples were filtered (0.45µm pore size) on arrival at the laboratory (within 4 days of collection) to create a subsample with particulate material removed for analysis of dissolved N and P. Resulting filtered and unfiltered samples were kept refrigerated until being analyzed for P (within 28 days of collection) and N (within 20 days of collection). Total and dissolved N were determined at NLET as nitrate in solution following alkaline potassium persulphate digestion. Total and dissolved P were measured as orthophosphate in solution following sulphuric acid/persulfate digestion.

Samples collected in 2013 were kept on ice until filtered (0.7µm pore size) and frozen as filtered or unfiltered aliquots within 48 hours of sample collection. Water samples were analyzed in the AAFC hydrology laboratory at the Brandon Research and Development Centre in Brandon Manitoba. Comparison of dissolved N and P for a variety of samples filtered to 0.45µm and

0.7µm indicated no significant difference (unpublished data). Analyses for TP were completed by sulfuric acid/ persulfate digestion followed by colorimetric analysis using the ascorbic acid method. TN calculated as the sum of particulate and dissolved N. Analyses for dissolved N were completed by the combustion method using a Shimadzu TOC-VCSH analyzer and of particulate N by combustion using a Thermo Scientific Flash 2000 CHNS/O elemental analyzer. Coefficient of variation for replicates with each analysis for TP, dissolved N, and particulate N was generally less than 5%, internal check standards created over the range of observed concentrations were within 10% of expected values, and external quality control standards are run periodically in the AAFC laboratory to ensure values fall within range stated on certificate of analysis.

6. Dataset overview

6.1 Weather data

6.1.1 Temperature

The overall temperature distribution followed the expected range of the Canadian Prairies (Fig.2a). The seasonal temperature values for the 1990-2013 period were also in general agreement with published values for the La Salle River watershed (La Salle Redboine Conservation District, 2007). However, there seems to be a slight trend towards warmer temperatures when the data is analysed annually and seasonally. The reported mean annual temperature is around 2.5 °C, while this value for the present dataset was 3.5 °C. Similarly, reported mean annual temperatures during winter and summer were, respectively, -13 °C and 16 °C , while those values calculated from the dataset were -10.7 °C and 17.2 °C, respectively. The annual average temperature seemed to have increased in the yearly part of the period (fig.2b) mostly driven by an increasing trend in the annual minimum (Fig.2c), while the annual maximum remained relatively stable (Fig.2d). As the annual minimum tended to decrease and leveled off after the 2000's, annual averages tended to decrease. These results are consistent with long-term analysis of temperature in Canada that reports an increase in the number of cold events (days and nights) and a decrease in the number of warm events in the Canadian Prairies (Vincent and Mekis, 2006). Despite the apparent trend, Mann-Kendall tests performed using the R package Kendall (McLeod, 2011) indicated no trend in either annual minimum (p=0.5852), annual maximum (p=0.4566), or annual average (p=0.6024) temperatures, possibly due to the short period analyzed that contrasts to the longer period analyzed by Vincent and Mekis (2006) (i.e. 1950-2003 and 1900-2003).

6.1.2 Relative humidity

Relative humidity averaged 73.1 % (standard deviation = 16.8%) over the 1990-2013 period. Seasonally, RH tends to be higher and more homogenous (i.e. narrower range) in cold seasons (Table 2) due to cold temperatures that lower the saturation capacity of the atmosphere. For example, 46.8% of the RH values in cold seasons (i.e. winter and fall) were above 80%, while only 36.6% of the values were above this threshold in warm seasons (i.e. spring and summer). The boxplot of the annual RH average for different seasons illustrate this difference, with the seasonal RH average being the lowest in the spring, increasing in the summer to reach its maximum at fall and winter (Fig. 3). When all the seasons are considered, the median of the yearly average resembles that of the summer season but with a much narrower range since only the annual averages were used to compute the boxplot (Fig. 3).

6.1.3 Wind speed

Wind speed is one of the key parameters for estimating reference evapotranspiration (Aladenola and Madramootoo, 2013), which is one of the major components of the water budget in the Canadian Prairies (Satchithanantham and Sri Ranjan, 2015). It is also a critical parameter for cold-region hydrological processes such as snow transport and sublimation (Pomeroy et al., 2007). The statistical properties of wind speed were quite similar over the different seasons (Fig. 4a). The annual average wind speed was 4.3 m/s, while it was 4.5 m/s during the winter, spring, and fall but dropped to 3.9 m/s during the summer. The Mann-Kendall test indicated no trend in annual average wind speed (p=0.6733; Fig. 4b), although studies in the Canadian Prairies indicated decreasing trends in most station between April and October (Burn and Hesch, 2007), which is in agreement with other studies that also suggest a decrease in annual wind speed in the region (Hugenholtz and Wolfe, 2005). Restricting the present analysis to those months only also resulted in no trend despite a decrease in p value (p=0.2059). Wind direction was not included in this analysis since it is not usually required for modelling or environmental studies.

6.1.4 Solar radiation

Historic estimates of daily global solar irradiation are often required for climatic impact studies (Barr et al., 1996). However, very few stations in the Canadian Prairies measure this weather variable (Jong and Stewart, 1993). In Manitoba for example, only 4 out of 110 weather stations measure solar radiation (Aladenola and Madramootoo, 2013). The long-term trend of solar radiation data followed the typical curve reported for Western Canada (Hare, 1997), with peak daily average daily values around 250 W/m^2 in July (Fig. 5). However, hourly solar radiation reached values as high as 1003 W/m^2. During the winter, values ranged from 40 to 50 W/m^2, which is in agreement with trends for southern Canada between 30 and 50 W/m^2 (Hare, 1997).

6.1.5 Precipitation

The majority of the 210,383 records (i.e. 95.0%) registered no precipitation (i.e. dry hours). These records were removed from the dataset and statistics for the dataset were computed. Investigations of precipitation trends in the Canadian Prairies have defined wet days as those with precipitation above 1 mm/day (Shook and Pomeroy, 2012), although values of 0.5 mm/day have also been used (Akinremi et al., 1999). In the present study, a threshold of 1 mm/day or 0.042 mm/h was used to select rain events used in the statistical calculations. The characteristic precipitation pattern of the Canadian Prairies with high frequency of small precipitation events (Shook and Pomeroy, 2012;Akinremi et al., 1999) was observed in the dataset, with 75.3% of the hourly precipitation being equal or less than 2 mm/h (Fig. 6a). The average precipitation was 1.36 mm, while the median was 0.55 mm (Fig. 6b). Out of 9,660 wet hours, only 137 and 17 events were larger than 10 and 20 mm, respectively. The Mann-Kendall test indicated a decreasing trend in precipitation amounts ($p<0.05$), as suggested by the smoothed precipitation plot (Fig. 6c). This result is consistent with other studies in the Canadian Prairies that report an increase in the number of low-intensity events (Akinremi et al., 1999).

6.2 Hydrometric data

The hydrometric characteristics of the dataset were typical of the Canadian Prairies with peak discharge during the spring due to snowmelt runoff (Shook and Pomeroy, 2010). Peak discharges occurred in April in 12 out of 17 years with good data (Table 3). The average discharge between 1990 and 2013 for years with good data is also higher in April (i.e. 2.3 m^3/s; Fig. 7a). Two peak discharges occurred in May, while one peak discharge occurred in March and one in June. An odd peak discharge occurred in July, which is not typical for this region. Inspection of the hydrometric data in July of 2005 suggests an anomaly in the hydrograph, with a very sharp rise and a "flat top", which resembles a culvert outflow hydrograph or some other form of upstream flow restriction (Fig. 7b). This type of behaviour is not expected and indicates potential issues with the hydrometric data since years with larger peak flows such as 2006 did not show these anomalies (Fig. 7c). Removing the year of 2005 from the dataset results in an average monthly hydrograph that resembles the expected trend in the prairies, where peak flow occurs in April and lower flows occur over the summer months (fig. 7a). This anomaly in July of 2005 actually represented disinformation for model assessment (Beven, 2011) and was removed from model assessments in the sub-catchment (Cordeiro et al., 2016). Since the datasets presented here were specifically developed for forcing and assessing hydrological modelling, the period between June 28th and July 31st has been removed from the hydrometric dataset. This period has been flagged as 'Removed' in the respective dataset accompanying this manuscript. Readers interested on the complete hydrometric time-series are referred to the HYDAT database (Environment and Climate Change Canada, 2013).

Another feature of the hydrometric data is the strong correlation between peak discharge and annual discharge. The overall correlation between these two variables (including the year of 2005) is very good (R^2=0.68). When the year of 2005 is excluded, the correlation improves even more (R^2=0.90), indicating that most of the annual discharge occurs during spring and is associated with snowmelt runoff. Assessment of water yield for different years confirms these results (fig. 7d; July 2005 removed). The water yield during snowmelt corresponds to most (in some years to all) of the annual water yield in the study area. The exception to this trend would be dry years (e.g. 1994, 20012) and years with excessively wet summers (e.g. 2010). The average water yield in the study area is 64 mm, out of which 72% occurs during snowmelt.

6.3 Water chemistry data

The average concentrations of TN, TDN, TP and TDP between 2009 and 2013 were, respectively, 1.54, 1.35, 0.56, and 0.49 mg/L. The TN and TP concentrations were in agreement with values found in previous studies at the same location (WSC gauging station 05OG008) between 1995 and 1996, which report annual TN concentrations of 1.67 mg/L and annual TP concentrations of 0.56 mg/L (Corriveau et al., 2013). On average, 88% and 84% of the total nitrogen and phosphorus were in dissolved form, which explains the similar temporal trend between total and dissolved forms of both nitrogen and phosphorus (Fig. 8). High proportion of dissolved forms of nutrient is in agreement with water chemistry results published for the La Salle River and other watersheds in Manitoba. The TDP/TP ratio in the La Salle watershed ranged from 0.25 to 0.99 (Corriveau et al., 2013), although values in the higher end of the spectrum were more frequent. McCullough et al. (2012) also report TDP corresponding to 81% of TP in the lower reaches of the main stem of the La Salle River over the course of a large snowmelt flood event in April–June 2009.

The plot of the concentrations over the monitoring period (Fig.8) indicates that concentrations of all analytes increased in wet years (2010 and 2011) and decreased in dry years (2012). When considered across years, a wide range of TN and TP concentrations were observed for lower flows, but concentrations at high flow were generally elevated, indicating that seasonal variation in the C-Q relationship likely exists. Peak values in 2009 were missed since monitoring started in August, after the spring snowmelt. Smoothed curves support the increase in concentration during wet years and decrease in dry years (Fig. 8), although trend analysis was not performed due to the short monitoring period. The monthly trends show that concentration of TN peak in March (3.3 mg/L), increasing from lower values in October (1.32 mg/L; Fig. 9a).

When streamflow discharge is at its peak in April, TN concentrations are already decreasing (2.6 mg/L). Concentrations of TP are also lower in October (0.37 mg/L) than in March (0.71 mg/L) and start to decrease by the time of peak discharge (0.54 mg/L). However, different that TN concentrations that peaks in March, TP concentrations peak in June (0.72 mg/L), remain relatively stable until July (0.68 mg/L), and start to decrease towards the fall.

The relationship between concentration and discharge (C-Q) has long been recognized in the literature (Hall, 1970, 1971). In the present dataset, however, this relationship was not very distinct (Fig. 9b, c). Although investigation of concentration-discharge relationships in the dataset is out of the scope of this work, in-stream processes controlling water chemistry such as nutrient uptake and release from sediment are likely of amplified importance in this slow moving and productive ecosystem (Mulholland and Hill, 1997). The seasonality observed in concentrations is in-line with this hypothesis.

7. Data availability

The data can be accessed through the Government of Canada's Open Data portal (http://open.canada.ca) under the following data titles and digital object identifiers:

- La Salle River Watershed 05OG008 Hourly Weather 1990 to 2013, DOI: 10.23684/ODI-2017-00957
- La Salle River Near Elie 05OG008 Daily Discharge 1990 – 2013, DOI: 10.23684/ODI-2017-00959
- La Salle River 05OG008 Water Chemistry 2009 – 2015, DOI: 10.23684/ODI-2017-00958

8. Conclusions

The high-frequency weather, hydrometric, and water chemistry datasets presented and discussed in this work represent an effort to develop a long term records not usually available in the Canadian Prairies, where the monitoring networks are sparse and records contain frequent gaps. Such an effort is significant for long-term environmental studies of climate change, land use management, hydrology, and limnology. An example of the applicability of the dataset is found in Cordeiro et al. (2016), who used the dataset to simulate cold-region hydrology in the sub-catchment of the La Salle River watershed using the Cold Regions Hydrological Modelling platform. Such long-term simulations using a physically-based model would not be possible without the datasets presented here. The methodology used to develop complete datasets consisted of drawing the best data available for specific weather elements from the closest stations. However, data gaps comprised a large proportion of the records, which ranged from 27.3% to 37% for the five weather elements analyzed. The gap-filling techniques used to address this issue were linear regression and direct transplantation from close-by stations. Due to the lack of hourly data that met the quality criteria, hourly precipitation had to be disaggregated using a Poisson-cluster model. Hydrometric data was only available in a daily time-step and no attempt was made to develop records in an hourly time-step since results of long-term environmental and modelling studies are usually summarized at this time scale or coarser. Overall, the hydrometric data was much more consistent than the weather data, but entire years were missing in the records due to no data collection. Years with data of dubious quality were also removed from the dataset due to the uncertainty created for long-term environmental and modelling studies. The water chemistry dataset represents an effort made by Agriculture and Agri-Food Canada and Environment and Climate Change Canada to address the chronic lack of data in the area.

Although short in length compared to weather and hydrometric data (i.e. 1990-2013 vs. 2009-2013), these records represent an important source of data for modelling studies with focus on nutrient export and impact to downstream water bodies in a region where eutrophication is of significant environmental concern.

Author contributions

All authors provided input in the planning of data collection and acquisition for this dataset. M.R.C. Cordeiro led in the preparation of the manuscript with input from J. Vanrobaeys and H. F. Wilson. M.R.C.Cordeiro acquired the weather and hydrometric data and performed analysis. J. Vanrobaeys planned, coordinated and implemented the water chemistry monitoring. H.F. Wilson coordinated analysis of water chemistry data in 2013.

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Table 1. Weather stations surrounding the La Salle River watershed shown in Figure 1.

Station	WMO[†] ID	Network[‡]	Location	Distance[¶] (km)
A	N/A	MAFRD	Portage La Prairie East	24.9
B	N/A	EC	Canadian Dept. of Agric., Portage La Prairie	26.0
C	N/A	EC	Marquette	9.9
D	71851	EC	Southport Airport, Portage La Prairie	26.6
E	71147	EC	University of Manitoba Research Station, Carman	51.0
F	71852	EC	International Airport, Winnipeg	47.9
G	71579	EC	The Forks, Winnipeg	56.1

[†] World Meteorological Organization; N/A= not available. [‡] EC= Environment Canada; MAFRD= Manitoba Agriculture, Food and Rural Development. [¶] Distances measured from the geometric center of the study area.

Table 2. Statistical properties of relative humidity.

Season	Relative Humidity (%)		
	Mean (S.D)	Range	n
Winter	75.8 (12.8)	80	51983
Spring	67.0 (20.1)	86	52416
Summer	72.2 (17.4)	86	52992
Fall	77.2 (14.6)	84	52992

Table 3. Streamflow characteristics of the study area.

	Discharge			
Year	Annual[†] (m^3)	Peak (m^3 s^{-1})	Peak Date	Ice conditions
1990	5.32×10^6	2.4	April 4th	March 1st – April 21st
1991	5.91×10^6	2.1	April 7th	March 1st – April 13th
1992	1.21×10^7	6.7	April 10th	March 1st – April 12th
1993	1.25×10^7	5.6	April 07th	March 1st – April 10th
1994	3.33×10^6	0.7	April 10th	March 1st – April 16th
1995	1.15×10^7	5.0	March 31st	March 1st – April 15th
1996	1.87×10^7	13.5	April 29th	March 1st – April 28th
2002	1.94×10^6	1.6	April 16th	March 1st – April 16th
2003	3.49×10^6	2.1	April 2nd	March 1st – April 09th
2005	3.96×10^7	11.1	July 1st	March 1st – April 04th
2006	2.18×10^7	16.5	April 10th	March 1st – April 07th
2007	7.26×10^6	4.6	April 12th	March 1st – April 05th
2009	1.69×10^7	13.3	April 17th	March 1st – April 16th
2010	2.09×10^7	10.7	June 1st	March 1st – April 05th
2011	2.84×10^7	15.7	April 13th	March 1st – April 13th
2012	4.89×10^6	2.5	May 29th	March 1st – March 24th
2013	1.44×10^7	9.4	May 04th	March 1st – May 1st

Total flow from March 1st to October 31st.

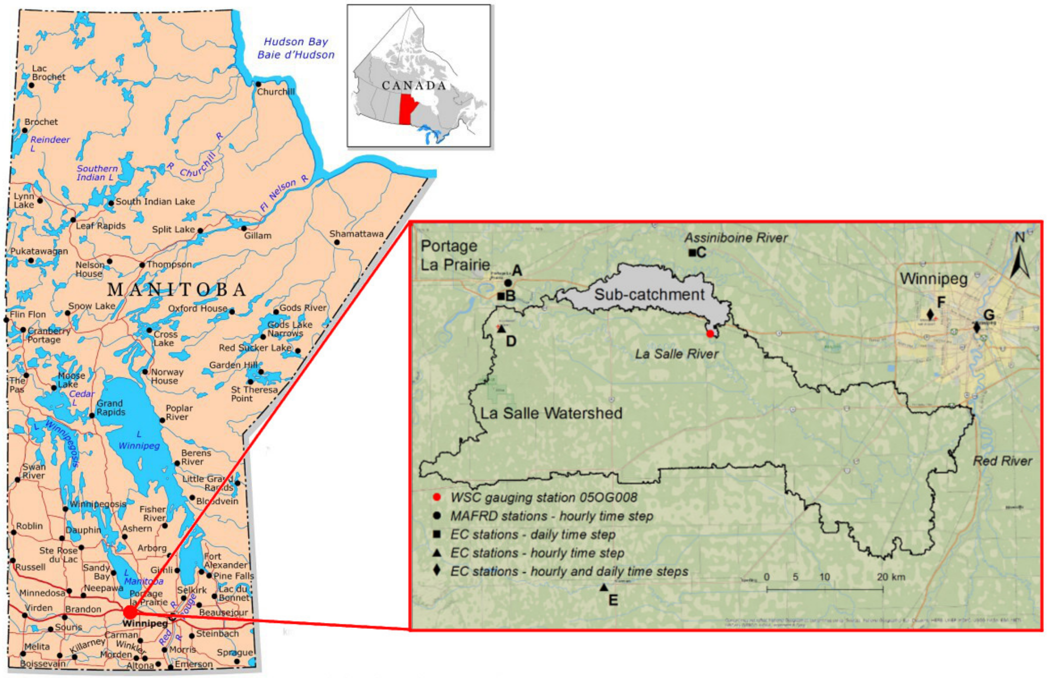

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Figure 1. Weather stations in closest proximity to the sub-catchment of the La Salle watershed used as the study area. Triangles, squares, and circles represent stations belonging to Environment Canada (EC) and Manitoba Agriculture, Food and Rural Development (MAFRD) networks in different time steps.

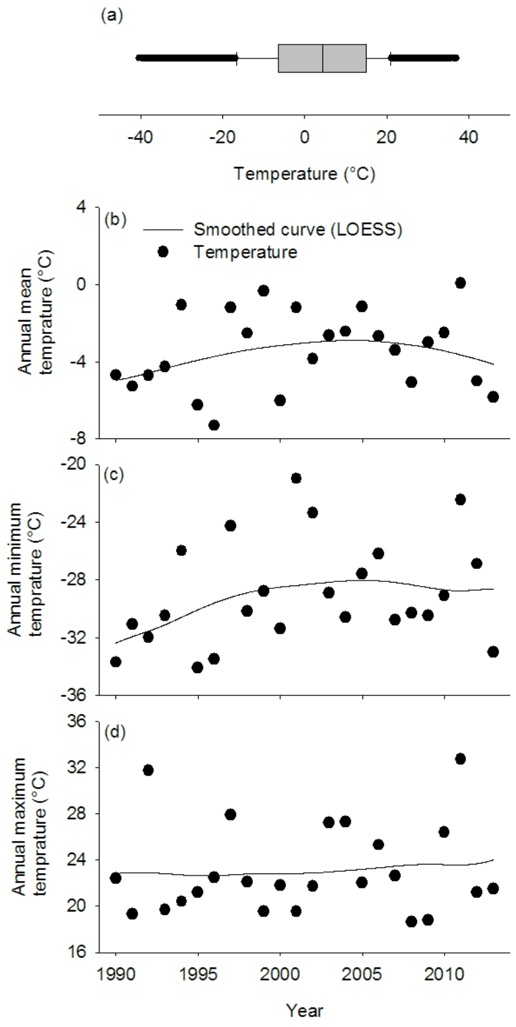


Figure 2. Graphical description of the temperature dataset showing the boxplot of temperature values between 1990 and 2013 (a), annual mean temperature (b), annual minimum temperature (c), and annual maximum temperature (d).

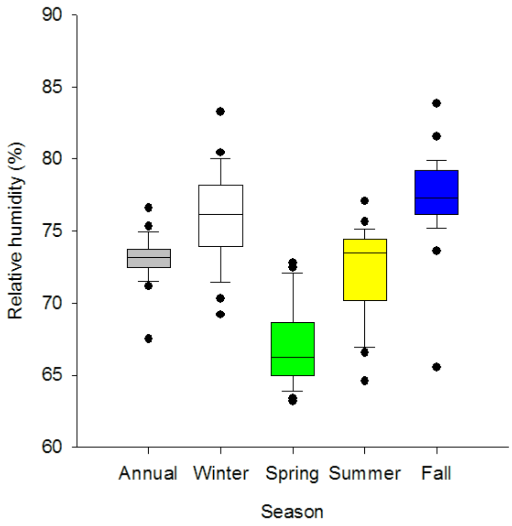


Figure 3. Statistical properties of relative humidity showing the boxplots of annual and seasonal values.

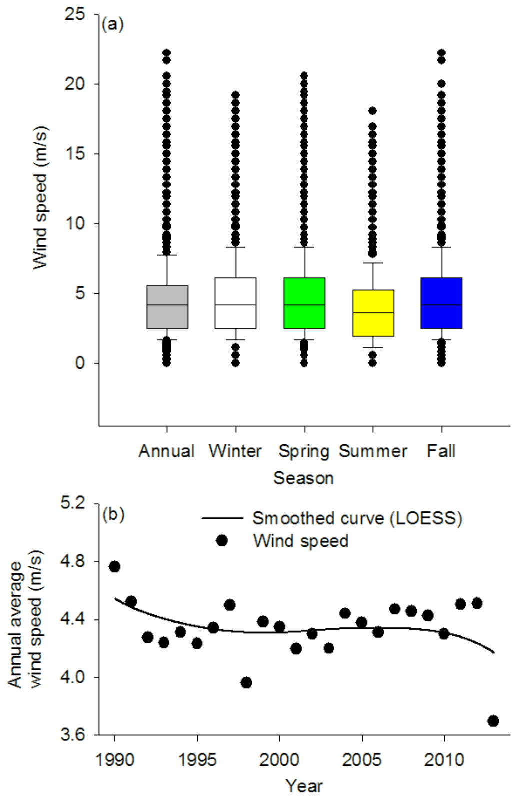
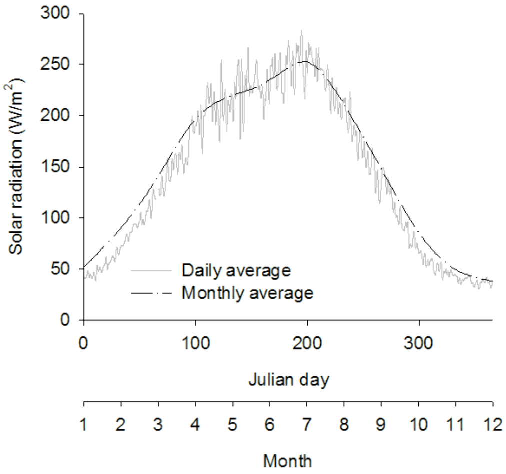


Figure 4. Graphical description of the wind speed dataset showing the annual and seasonal statistical properties (a) and the trend in annual average (b) of this variable.



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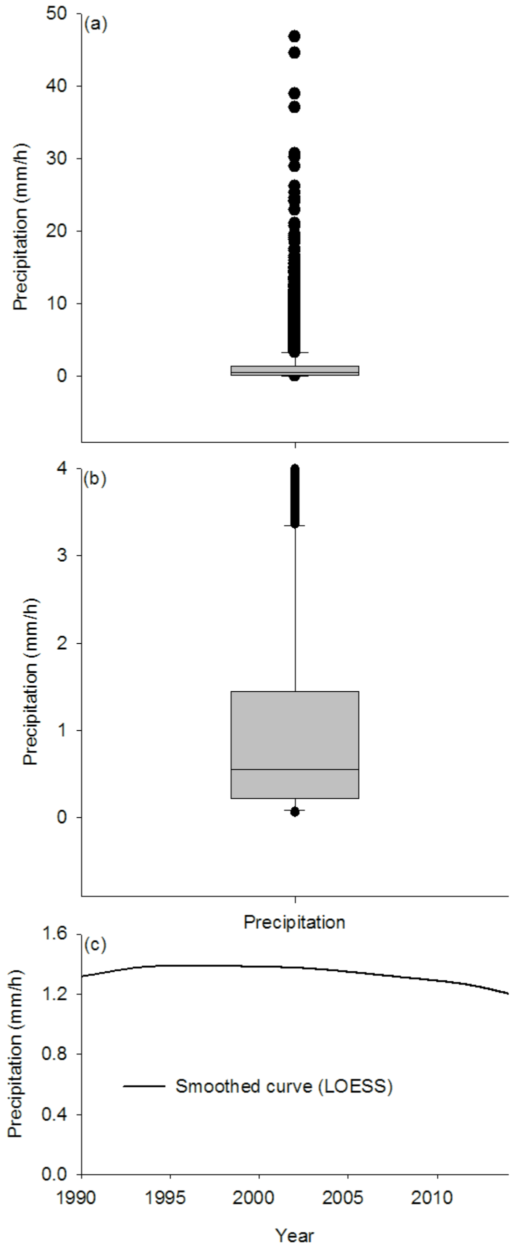
637 Figure 5.Annual variation of the long-term average of solar radiation.



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639 Figure 6. Graphical description of the precipitation dataset showing the statistical

640 properties (a) and the trend in annual average (b) of this variable.

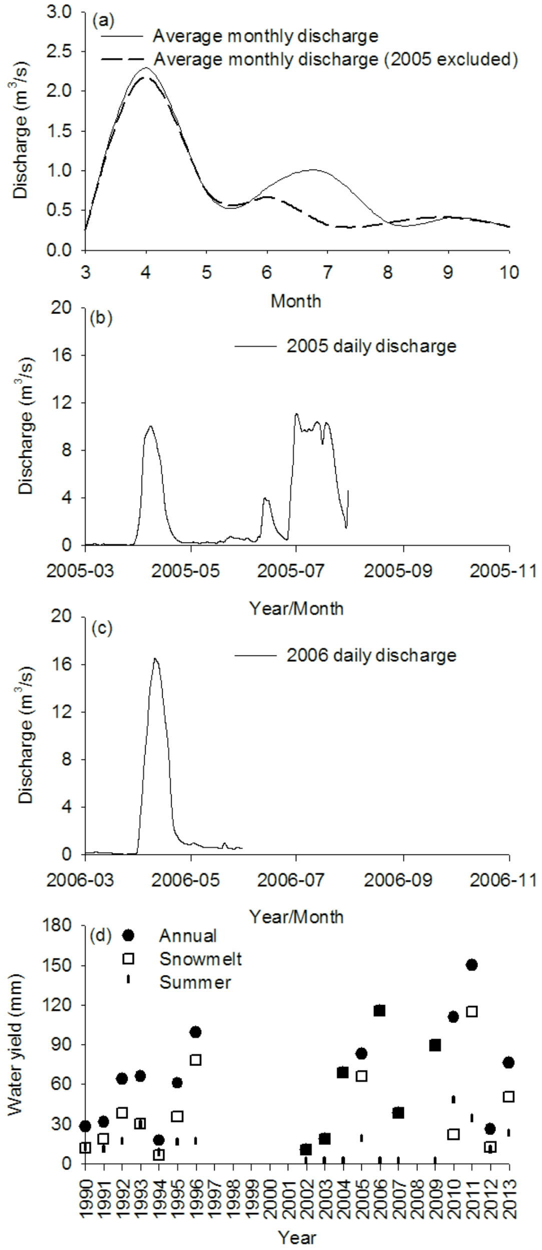
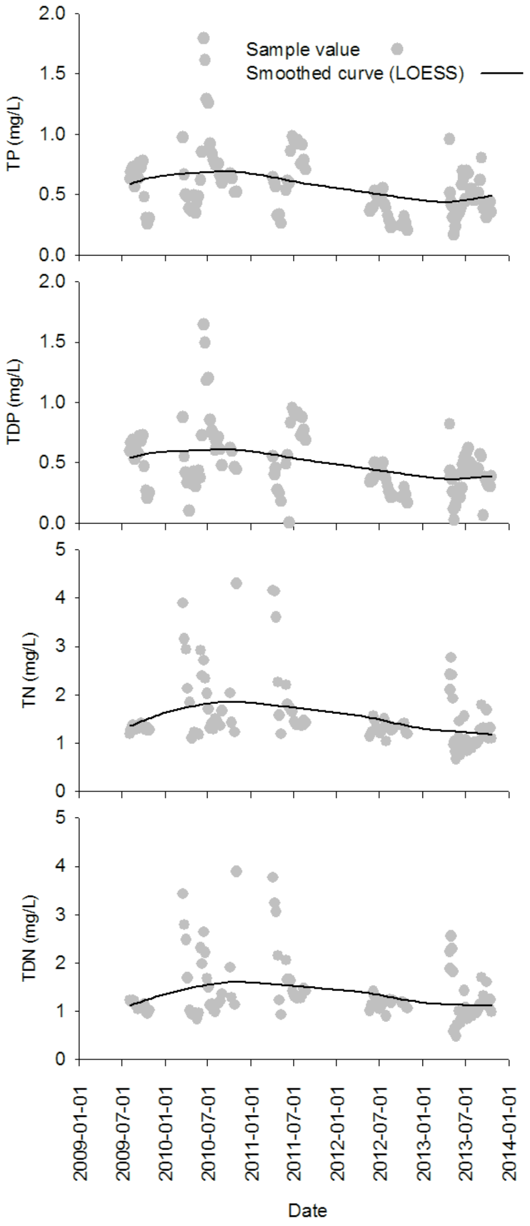


Figure 7. Graphical description of stream discharge showing the long-term monthly average (a), the 2005 daily discharge (b), the 2006 daily discharge (c), and annual and seasonal water yield (d).



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646 Figure 8. Scatter plot of sample concentrations of total phosphorus (TP; a), total dissolved phosphorus (TDP; b), total nitrogen (TN; c), and total dissolved nitrogen (TDN; d) between 2009 and 2013.

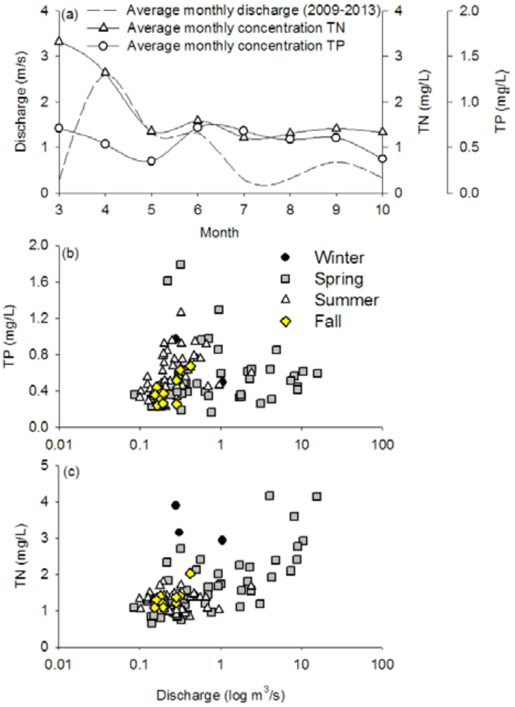

Figure 9. Graphical description of the relationship between total phosphorus (TP) and total nitrogen (TN) concentrations and stream discharge showing the variation of monthly averages of TP and TP variation of concentrations with monthly discharge (a), variation of sample values of TP (b) and TN (c) with daily stream discharge.