Advances in the simulation of nutrient dynamics in cold climate agricultural basins: developing new N and P modules for the Cold Regions Hydrological Modelling Platform

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Abstract

Excess nutrients in aquatic ecosystems is a major water quality problem globally. Worsening eutrophication issues are notable in cold temperate areas, with pervasive problems in many agriculturally dominated catchments. Predicting nutrient export to rivers and lakes is particularly difficult in cold agricultural environments because of challenges in modelling snow, soil, frozen ground, climate, and anthropogenic controls. Previous research has shown that the use of many popular small basin nutrient models can be problematic in cold regions due to poor representation of cold region hydrology. In this study, the Cold Regions Hydrological Modelling Platform (CRHM), a modular modelling system, which has been widely deployed across Canada and cold regions worldwide, was used to address this problem. CRHM was extended to simulate biogeochemical and transport processes for nitrogen and phosphorus through a complex of new process-based modules

that represent physicochemical processes in snow, soil and freshwater. Agricultural practices such as tillage and fertilizer application, which strongly impact the availability and release of soil nutrients, can be explicitly represented in the model. A test case in an agricultural basin draining towards Lake Winnipeg shows that the model can capture the extreme hydrology and nutrient load variability of small agricultural basins at hourly time steps. It was demonstrated that fine temporal resolutions are an essential modelling requisite to capture strong concentration changes in agricultural tributaries in cold agricultural environments. Within these ephemeral and intermittent streams, on average, 30%, 31%, 20%, and 16% of the total annual load of NO_3, NH_4, SRP and partP occurred during the episodic snowmelt freshet (~9 days, accounting for 21% of the annual flow), but shows extreme temporal variation. The new nutrient modules are critical tools for predicting nutrient export from small agricultural drainage basins in cold climates via better representation of key hydrological processes, and a temporal resolution more suited to capture dynamics of ephemeral and intermittent streams.
Keywords: Catchment Nutrients, hydrology, cold regions, simulation, management

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1. Introduction

Reducing nutrient losses from agricultural fields has been a major priority worldwide for many years due to increasing concerns with enhanced aquatic productivity and algal blooms. Water quality models for both basin and in-stream studies have been widely used to support nutrient management, but have often been problematic in seasonally cold regions such as Canada and the northern United States due to deficiencies in the representation of key processes specific to these regions. Cold regions hydrology cannot be represented by the classical concepts of rainfall-runoff models due to water storage by the seasonal snowcover, snow redistribution by wind, radiation-driven snowmelt, infiltration to and runoff over seasonally frozen ground, poorly defined drainage due to glacial geomorphology, and highly episodic runoff events (Pomeroy et al., 2007). Regional biogeochemistry in soils an runoff is challenging to model due to cold temperatures and seasonal soil freezing that influence nutrient release from soil-plant systems, plant uptake and microbial activity, which in combination with management practices (including fertilizer applications, tillage practices and wetland drainage) affect the hydrochemistry of soils and runoff (Baulch et al., 2019; Costa et al., 2020a; Irvine et al., 2019; Van Esbroeck et al., 2017; Macrae et al., 2007).

The dynamics of nutrient storage and release in cold climates are strongly affected by various cold regions hydrological processes and conditions (Deelstra et al., 2009). Snowpacks collect and transform chemicals during winter and rapidly release them during snowmelt (Pomeroy et al., 2005), with a significant portion of the nutrients contained in runoff being transformed and retained in topographical depressions (Neely and Baker, 1989; Crumpton and Isenhart, 1993; Birgand et al., 2007). Spring snowmelt is the largest runoff event of the year in cold regions such as the Northern Great Plains of North America (Gray et al., 1970), and accounts for most of the annual nutrient export (Baulch et al., 2019). The magnitude of peak flows furing spring freshet depends not only on overwinter snow accumulation but also on the antecedent soil moisture and basal snowpack and ground ice conditions

(Gray et al., 1986; Pomeroy et al., 2007). Except for runoff from intensive convective rainfall events, summer flows are often small (Gray et al., 1970; Pomeroy et al., 2007).

Nitrogen (N) and phosphorus (P) transported via cold regions agricultural runoff originate in soil, vegetation, or to a lesser extent, the snowpack. The soil N pool is highly dynamic with weathering of soil parent material and decomposition of soil organic matter providing sources of mineral N (NO_3-N and NH_4-N) at rates depending on soil type and climate. Additional N enters the landscape through fertilizer application, plant residues, and atmospheric deposition. Transformations between labile and recalcitrant forms of N are generally biologically-driven with N lost to the atmosphere (through denitrification and volatilization) or to depth as soils drain (Baulch et al., 2011; Madramootoo et al., 2007). P exists in soils in both organic and inorganic forms, the latter derived from weathering of apatite. Like N, P enters the landscape through fertilizers, plant residues, and atmospheric deposition but is generally regarded to be less available due to soil sorption processes that are dependent on factors such as pH, temperature, and organic carbon content (Holtan et al., 1988). Phosphorus can be lost in runoff water, especially when concentrations exceed the sorption capacity of the soil, or when particulate P is transported along with soil through erosion processes. Soil frost can increase nutrient export by decreasing infiltration and increasing surface runoff where P concentrations are largest (Cade-Menun et al., 2013). Additionally, freeze-thaw cycles disrupt plant cells and increase nutrient leaching from residues and other vegetation (White, 1973; Liu et al., 2013a; Costa et al., 2019a; Liu et al., 2019), which can become an important additional source of nutrients during snowmelt, particularly in the presence of young and actively growing plants (Cober et al., 2018; Elliott, 2013). The impact of tillage practices on nutrient export is complex. Conservation tillage can cause the accumulation of plant residue on farm fields, which can release nutrients to snowmelt runoff (Timmons et al., 1970; Miller et al., 1994; Ulén, 1997). In addition, by decreasing the mixing of the applied fertilizer, reduced tillage increases nutrient soil stratification and can lead to higher nutrient concentrations in surficial soils, which can be readily mobilized by runoff.

More reliable predictions of nutrient transport in cold agricultural basins have long been seen as a crucial to support nutrient management in Canada (Costa et al., 2020a; Baulch et al., 2019; Costa et al., 2019b). (Mekonnen, 2016) identified 74 models of water quality worldwide, but it has been noted that application of many of these models can be problematic in cold climates due to inadequate representation of many cold regions processes (Han et al., 2010). Costa et al. (2020a) reviewed the suitability of five prominent catchment nutrient models for application in cold climates: SWAT (Arnold et al., 1998), INCA (Whitehead et al., 1998; Wade et al., 2002), HYPE (Lindström et al., 2010; Arheimer et al., 2012), HSPF (Bicknell et al., 1997, 2005; Duda et al., 2012), and AnnAGNPS (Bosch et al., 1998). They identified inadequate representation of cold climate hydrology and daily time steps to be some of the features most commonly limiting the utility of these models in cold regions. They noted that most of these models have rarely been applied to cold regions, with the exception of SWAT and HYPE. They also found that some models allowed limited soil vertical resolution (i.e., maximum number of soil layers) that could reduce their performance in heavily stratified soils. Erosion remains a major challenge and meaningful model structures based on observable and transferable parameters were recommended to reduce the often high number of parameters for controlling biogeochemical transformations (leading to parameter identifiability). It was also highlighted that representations of accumulation of immobile nitrogen and phosphorus organic pools were often limited in their ability to represent legacy N and P for long-term simulations.

The meteorological data typically used to force hydrological models (e.g. solar radiation, air temperature, precipitation and wind speed) are often measured on a daily basis. This may limit the temporal resolution of model simulations and compromise their ability to capture hydrological and transport-biogeochemical processes that may be subject to significant diurnal variations (e.g. wind redistribution of snow and radiation-driven snowmelt) and episodic oscillations (e.g., sediment erosion and soil nutrient release). Unfortunately, in cold regions, hydro-biogeochemical processes activated during spring snowmelt and convective storms are often responsible for most of the annual nutrient export (Baulch et al., 2019; Kokulan et al., 2019). Thus, long-term simulations must also capture short-term runoff events, meaning that daily timestep models are insufficient. For example, the HSPF model is one of the few nutrient models identified that are often run at (default) hourly time intervals for long-term simulations. However, like many other models, HSPF does not explicitly account for some critical cold regions processes such as blowing snow and infiltration to and runoff over frozen soils, and uses the daily time step empirical degree-day method to estimate snowmelt, a method that has long been found to be inadequate in many cold regions (Walter et al., 2005; Gray and Landine, 1988).

There is a need to investigate alternative modelling approaches that are more applicable to cold agricultural basins, better reflecting cold regions hydrological and biogeochemical processes, which have a crucial impact on timing, concentration and load of nutrients. For this purpose, a complex of new hydro-biogeochemical modules was developed for the flexible, modular Cold Regions Hydrological Modelling platform (CRHM). CRHM has been created specifically to improve the simulation of cold regions hydrology (Pomeroy et al., 2007) and has been applied successfully to agricultural basins with minimal or no calibration (Fang and Pomeroy, 2008; Fang et al., 2010; Mahmood et al., 2017; Cordeiro et al., 2017; Costa et al., 2017; Kokulan et al., 2019). Its merit as a flexible and fundamentally physically based cold regions hydrological model renders it an ideal model for incorporating nutrient processes, and hence to offer a more suitable modelling framework to support nutrient management in agricultural cold regions.

2. Materials and Methods

2.1. The Cold Regions Hydrological Model

The Cold Regions Hydrological Model (CRHM) has been developed from more than 55 years of research on Canadian hydrology (Pomeroy et al., 2007). It is a modular platform that discretizes the basin into hydrologically distinct landscape elements called Hydrological Response Units (HRUs). It provides a range of predictive methods embedded in various modules that can be selected depending on dominant climatic and regional settings, i.e., mountains and prairie environments and are applied to calculate energy and mass budgets and fluxes on the HRUs, which are then aggregated through surface and subsurface routing to provide basin-scale streamflow predictions.

CRHMs focus on cold regions, its ability to deal with prairie hydrology and the depressional storage relationship with contributing area (i.e., only a fraction of the basin contributes to streamflow due to lack of hydrological connectivity) that is common in post-glacial river basins, give it important capabilities that are neglected in most hydrological models (Pomeroy et al., 2007; Shook et al., 2015; Costa et al., 2020b), makes it attractive for hydro-biogeochemical applications in these regions. The model includes processes such as snow redistribution by wind and vegetation (e.g., Pomeroy and Schmidt, 1993; Pomeroy et al., 1998), snowmelt (e.g., Male and Gray, 1981), infiltration to unsaturated frozen soils, including cracked soils (e.g., Granger et al., 1984), evaporation from unsaturated surfaces (e.g., Granger and Gray, 1989), and hillslope water redistribution over frozen ground (e.g., Quinton and Marsh, 1999). CRHM is typically run at hourly or sub-hourly time steps, which is another relevant aspect for capturing nutrient export during the short but critical spring snowmelt period (Baulch et al., 2019; Costa et al., 2017; Kokulan et al., 2019).

2.2. Existing Modules: extending for nutrient transport

Fig. 2.2 shows a simplified conceptual model of CRHM to illustrate how existing hydrological modules were expanded to nutrient transport. In other words, all existing water mass balance and flux computations were extended to the transport of N and P (considering different mineral and organic species; see Section 2.3 ahead) within and across different hydrological compartments.

This includes a snow layer, depressional storage (e.g., that can be used for the representation of wetlands), a subsurface flow layer, two main soil layers, and groundwater. An additional surficial soil layer (shown in red) was introduced to describe the effect of soil mixing (e.g., tillage practices) and nutrient leaching.

[Figure 1 about here.]

The new mass-balance/transport equations for all N and P pools [M] (new model state-variables) take the general mathematical form of Eq. 1, with the different nutrient mass fluxes [M/T] being computed following Eq. 2. Subscript "n" refers to the different N and P species, and subscript "c" refers to the hydrological compartment.

$$\frac{d\big(V_{c,n} \cdot C_{c,n}\big)}{dt} = \sum_{i=1}^{L} L_{i,n} \tag{1}$$

$$L_{i,n} = F_i \cdot C_{i,n} \tag{2}$$

where $V_{c,n}$ and $C_{c,n}$ are the volume of water [L^3] and concentration [ML^{-3}] of each nutrient n in each model compartment l. $L_{n,i}$ is the nutrient mass transported (i.e., nutrient load) with the different water exchange fluxes F_i between compartments. L is the number of model compartments or layers in CRHM.

Predecessor WINTRA module

The development of nutrient modelling capabilities for CRHM is based upon developments in the process-based WINTRA module (Costa et al., 2019b, 2017; Roste, 2015). This module constituted an important step in incorporating cold region processes in the computation of nutrient transport. WINTRA targeted edge-of-the-field (EOF) simulations and explicitly focused on the development and incorporation of algorithms for the description of (1) the effect of snowcover depletion on the release of soil nutrients to runoff and (2) snow ion exclusion, which is a process that causes snow ions to be eluted preferentially throughout the snowmelt process (Davies et al., 1987; Pomeroy et al., 2005; Costa et al., 2019c, 2018). These WINTRA algorithms were incorporated into the new modules shown here. The reader is referred to Costa et al. (2019b, 2017) for more details about WINTRA.

Snowpack module

The snow module extended to water quality was pbsm and pbsmSnobal (Prairie Blowing Snow Module). These modules calculate blowing snow transport and sublimation fluxes between HRUs (see Fig. 2.2a) based on precipitation, snow availability, wind speed, air temperature, and relative humidity (Pomeroy and Li, 2000). Calculations of point transport and sublimation fluxes are performed using standard meteorological and landcover data or simple interfaces with atmospheric models by describing vertical humidity, temperature and wind speed profiles in columns blowing snow. Thresholds for different wind speeds, the effect of exposed vegetation on saltation and upwind fetch impacts on blowing snow flow development are considered. The reader is referred to Pomeroy and Li (2000) and MacDonald et al. (2009) for more details about these modules.

Soil module

The soil module extended to water quality was soil (Pomeroy et al., 2007, 2016a). This module divides the soil into 4 main compartments (see Fig. 2.2a): (1) a shallow subsurface detention flow layer, (2) an upper soil compartment (called the recharge layer), (3) a lower soil compartment representing the remaining soil column to the bedrock or impermeable layer, and (4) a groundwater compartment. Evaporation can occur from both soil compartments, and surface infiltration recharges the upper soil compartment until field capacity before it percolates down to the lower compartment. This is performed based on infiltration-excess and storage-excess infiltration concepts (Pomeroy et al., 2007; Dornes et al., 2008). The excess water from both soil layers can be distributed to groundwater, depressional storage and sub-surface flow (Pomeroy et al., 2016b). Water retained in the landscape via depressional storage can contribute to both surface flow and groundwater (Fang et al., 2010).

Routing module

The routing module extended to water quality is that calculates surface runoff, subsurface runoff, groundwater fluxes between HRUs using the lag and route method developed by Clark (1945). As described by Fang et al. (2010), the output flow of a given HRU is redistributed into another (or multiple) HRU(s), and it can recharge the groundwater, depression storage, the different soil layers or contribute directly to streamflow (see Fig. 2.2b). Likewise, groundwater flow from an HRU can take similar or different hydrological pathways and flow directions. The reader is referred to Pomeroy et al. (2007) for more information about this module.

2.3. New Modules: biogeochemistry, sources and sinks

Conceptual model

Fig. 2 shows the conceptual model used for the representation of biogeochemical cycling of N (Panel a1) and P (Panel a2) species, with Panel b providing more details about the different sources, sinks and transformation pathways. It is adapted from the general approach used in the HYPE model (Lindström et al., 2010; Arheimer et al., 2012) with modifications to emphasize important processes for Canada and other cold regions (highlighted below) and for integration within CRHMs model architecture. The mobile (i.e., moving with water) chemical species simulated are nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), dissolved organic nitrogen (DON), soluble reactive phosphorus (SRP), dissolved organic phosphorus (DOP), and particulate phosphorus (partP). Four additional soil (immobile) organic pools are considered, namely labile N and P, and refractory N and P. These pools represent the collective behaviour of the soil organic nutrient species that are either more reactive (labile N and P with rapid turnover of NH_4 and SRP, respectively) or more stable (refractory N and P with a slow turnover of NH_4 and SRP, respectively).

The model time step is flexible but was primarily developed for (and tested at) hourly or sub-hourly temporal resolutions. This is an important capability to capture rapid snowmelt and convective storm-driven rainfall-runoff events. A brief explanation of the logic used for the representation of the different biogeochemical processes, sources and sinks is provided below, but the reader is referred to Supplementary Material for a complete description of the theoretical and mathematical basis of these modules.

[Figure 2 about here.]

Biogeochemical cycling

The conceptual model of Fig. 2 was implemented using a process-based approach that implies that the mass of a chemical species is produced for every other nutrient species consumed. This mass balance is performed in terms of the N and P mass content of each chemical species. The conversion rates (F) between species are described based on first-order (reaction) kinetics that depends on the maximum reaction rate at the reference temperature of 20°C ($K_{reaction}$), and is affected by temperature (f_{temp}), soil moisture (f_{θ_w}), and half-saturation concentration (f_{conS}). This calculation takes the general form of Eq. 3 that is similar for all biogeochemical transformations described in Fig. 2b.

$$F_\beta = \left[f_{temp} \cdot f_{\theta_w} \cdot f_{conS} \right] \cdot K_{reaction} \cdot C_\beta, \tag{3}$$

where β is the chemical species consumed and C_β is its concentration.

Nitrification and denitrification are a source and sink of NO_3, respectively. The organic labile-N and labile-P pools are subject to mineralization, producing NH_4 and SRP, respectively. In turn, refractory-N and refractory-P can degrade into labile-N and labile-P, respectively. Dissolution of all soil organic pools (labile-N, labile-P, refractory-N and refractory-P) can produce dissolved organic nutrients (DON and DOP). The maximum mineralization, degradation and dissolution rates at 20 are used as model inputs, but the concentration of the respective source organic pool, as well as temperature and soil moisture, modulate the actual reaction rates throughout the simulation. The adsorption of P onto soil particles is computed from a dynamic equilibrium calculation between SRP and PartP that is based on Freundlich adsorption isotherm (Freundlich, 1926) solved based on the interactive Newton-Raphson method (an approach also used in other models, such as HYPE and HSPF).

Nutrient Sources and Sinks

Atmospheric deposition: Wet and dry atmospheric deposition can be added for all mobile species contemplated in the model (NO_3-N, NH_4-N, DON, SRP, DOP, parP). For wet deposition, the inputs are associated with precipitation, and the users need to associate the corresponding nutrient concentrations to the precipitation flux. For dry deposition, deposition rates are defined via constants [M/T] or dynamically as time-series via input files. The atmospheric deposition of nutrients is added to the snow or soil depending on the presence of snow and can include dust deposition on snow from windblown soils (Pomeroy and Male, 1987).

Blowing snow transport and sublimation: The wind transport of mineral (NO_3-N, NH_4-N, SRP) and organic (labile-N and labile-P) nutrients is computed between HRUs, but also in and out of the basin depending on the blowing snow calculations performed by the WQ_pbsmSnobal module. This allows to adequately account for snowdrifts and their effect on the spatial redistribution of snow nutrients. The transformation of concentrations during blowing snow transport and sublimation is not currently not considered but will be addressed in future research.

Fertilizer/manure application, plant residue and tillage practices: Nutrients from fertilizer ("fert") and manure ("man") applications can be added as mineral (NO_3-N, NH_4-N, SRP) and organic (labile-N and labile-P) inputs. Future research will consider enabling a fraction of manure to be treated as refratory P and N. The timing, duration and magnitude of fertilizer and manure applications for each HRU are added via time series that can be loaded as input files. It is possible to include the effect of tillage practices and the fertilizer application method (e.g., broadcasted, with seeding, incorporated) by splitting the fractions of fertilizer/manure inputs that go into the surficial (surfsoil) and upper (soil_rechr) soils layers. The user can also define the fraction of mineral and organic N and P in manure. Similar to atmospheric deposition, fertilizer and manure are added to the snowpack when present at the time of application. While adding manure to the snow before snowmelt is strongly discouraged, it is sometimes observed (Liu et al., 2018). The infiltration rates computed by CRHM are currently used to estimate nutrient leaching in the soils based on a scaling parameter.

Snowpack-soil-runoff interactions for nutrient release: The release of nutrients from snow and soil to runoff is based on the approach developed for the WINTRA module (see Section 2.2 and Costa et al. (2017)). The effect of heterogeneous snowcovered area depletion and infiltration to partially frozen soils on the interaction between runoff and the soil is computed using snowcover depletion curves (Essery and Pomeroy, 2004). These curves are computed using coefficients of variation of maximum SWE for each HRU obtained through local measurements or literature values (Pomeroy et al., 1998). Areal infiltration to frozen soils is then calculated as per Gray et al. (2001).

Plant nutrient uptake: The uptake of NO_3, NH_4 and SRP by plants is simulated based on a maximum potential uptake rate defined by the user that depends on the plant species. The actual uptake rate is then internally modulated by the concentration of these nutrient species, soil moisture and the wilting point.

Erosion of sediments and partP: The calculation of the sediment and partP eroded fractions are based on the methodology used in HYPE (Lindström et al., 2010; Arheimer et al., 2012), which relies on a parametric function for estimation of the potential (energy) of mobilization of falling hydrometeors and surface runoff. The energy of falling hydrometeors is calculated using an empirical logarithmic curve that depends on precipitation rates and the time of the year. The ability of falling hydrometeors to set soil particles into motion depends on the erodibility of the soil and crop cover - erodibility is currently characterized by a parameter [g/J]. Thus, the fraction of soil particles mobilized by runoff is calculated empirically as a function of a soil cohesion coefficient [kPa] and the average HRU slope. Once the maximum potential mobilizable partP is calculated, additional parametric expressions are used to account for the average soil grain size (i.e., finer particles are more likely to be eroded and contain more P), the transport capacity of the field, and the filtering capacity of river and buffer vegetation strips. There are already ongoing efforts to further enhance this erosion model.

3. Model application

The model was applied to the small Steppler Basin within the South Tobacco Creek Basin, Manitoba, which has a drainage area of 205 ha and contributes to Lake Winnipeg via the Red River (Fig. 3a). The Steppler Basin is of particular interest to the study of nutrient export to major Canadian lakes because it is intensively farmed and contributes to Lake Winnipeg, which is becoming increasingly eutrophic (Schindler et al., 2012).

The setup of the model benefited widely from the intense monitoring program established in this basin since 2005, as well as previous modelling work in the region, e.g., Roste (2015); Mahmood et al. (2017); Costa et al. (2017, 2019b). The basin has been divided into 42 fields for research and monitoring purposes. This division was used to define the HRUs of the model (Fig. 3b) to maximize the direct use of the field data collected, such as that related to agricultural practices. HRU numbering results from field numbering used throughout the STC research basin. The results from previous research on hydrological connectivity and runoff pathways of this basin were used to characterize HRU routing in CRHM (Costa et al., 2020b).

Basin soils are dominantly the Dezwood series (moderately well to well drained Orthic Dark Gray Chernozem soils developed on calcareous deposits) with a solum depth between 25 and 80 cm divided into 4 horizons (Ap at 0-12 cm, Bt at 12-40 cm, BC at 40-50 cm, and Ck at 50-80cm). Soil type was defined as 7 on a scale of 1-11 (scale used in the soil modules of CRHM), with 1 corresponding to sand and 12 to clay, based on geomorphological and soil quality assessments performed for the small experimental Twin Basin adjacent to the Steppler Basin (Michalyna, 1994). The thickness of the till over the bedrock varies between 1 and 10 m (Michalyna, 1994), and an average of 5 m was considered in combination with an estimated saturation water content of 0.42 to allowed to calculate a maximum soil moisture of 840 mm for use in the model. Crop rotations in the simulation period (2005 and 2011), the simulation period, included mainly canola and wheat, but also sporadically barley, oat, fall rye, and pasture. Based on these crops, a 1-m thick upper soil layer subject to evapotranspiration withdrawals was established. There were no significant changes in drainage and forested area during this period, and there is no tile drainage. The surface water storage potential in wetlands, holding ponds and weirs was represented by a maximum depressional storage defined for each HRU.

The data available for model forcing and validation are summarized in Table 1. The hydrological component was forced with meteorological data, including precipitation, air temperature, relative humidity, wind speed and incident short-wave radiation. These data were collected from a weather station near the northern border of Steppler Basin. The weather station collects air temperature and rainfall data (5-minute tipping bucket data) but is not operational between late fall and early winter. Extrapolation of observations from four nearby weather stations was needed to complete data gaps during the winter months. Hourly air temperature, relative humidity and wind speed data from the Deerwood station (5.5 km distance from the basin) were used for this purpose, with occasional missing data being filled with data from the Carman station located 45 km away from the basin. The hydrological model results were validated using snow water equivalent (SWE) and streamflow observations. Streamflow was estimated at five gauges distributed throughout the basin (see Fig. 3). The recordings were performed at 15- to 30-minute intervals. They were upscaled to hourly averages to match the temporal resolution of the model. The water quality component was forced with recorded fertilizer and manure application loads and validated for EOF stream NO_3-N, NH_4-N, SRP, and partP concentrations.

Information about the amount, location, type, timing and application method of fertilizer and manure in each field was collected by Agriculture and Agri-Food Canada (AAFC) and Environment and Climate Change Canada (ECCC) and was used to force the model with N and P loading explicitly. It was assumed that fertilizer application (1) with seeding was evenly split between the surfsoil and soil_rechr layers to account for varying seeding depths, (2) with broadcasting it mostly sits at the surfsoil layer but some degree of incorporation can be realized by high disturbance seeding implements (90% goes to surfsoil and the remaining to soil_rechr), and (3) with banding the placement of fertilizer is often below the surfsoil layer (80% goes to the soil_rechr layer and the remaining to surfsoil) - see the hydrological compartments of the model in Fig. 1. Future work should focus on refining and evaluating this splitting approach, as well as improving the characterization of soil stratification - soils are often measured at 0-5cm, 5-15 cm, and 15+ cm depths and frequently show considerable differences in nutrient concentrations.

[Figure 3 about here.]

[Table 1 about here.]

4. Results

4.1. Hydrology

Fig. 4 compares observed and simulated SWE in fields F3 and F4 (locations are shown in Fig. 3). The observations correspond to the average snow accumulation peaks measured at the onset of spring snowmelt. The results show that the model can capture both the interannual and spatial variabilities in SWE distribution. Substantial heterogeneity in annual snow accumulation can be noticed within each field - note the standard deviation (error bars) for each year as a measure of the spatial variation in the SWE values, but the model was able to predict these average patterns successfully.

Observed and simulated streamflow are compared for the different HRUs (stream gauge stations) (Fig. 5). Table 2 shows the model performance for both SWE and streamflow, as well as peak nutrient concentrations (see Section 4.2). The model can capture the strong spatiotemporal patterns of hydrological response within the basin. It can generally predict well both the timing and magnitude of flows at different locations within the basin. This is challenging as it can be noticed by the complex conceptual model needed for this basin (see Fig. 3b) and the wide range of flow values observed between HRUs, with HRU 28 showing the highest peak values above 40 L/s and HRU 39 showing the lowest below 0.04 L/s. This basin is characterized by ephemeral streams and extreme events that include snowmelt and convective rainfall-runoff storms. A key aspect of these simulations is that they were performed at hourly time intervals. This proved essential for capturing the highly non-linear streamflow production patterns (timing and magnitude) in this basin (more detailed analysis on the importance of hourly simulations is provided in Section 5.2).

[Figure 4 about here.]

[Figure 5 about here.]

[Table 2 about here.]

4.2. Water quality

Nitrogen

Figs. 6 and 7 compare observed and simulated streamflow NO_3 and NH_4 concentrations, respectively. The model processes affecting the NO_3 and NH_4 budgets are atmospheric deposition, fertilizer, manure, plant uptake, nitrification (NH_4 to NO_3), denitrification (NO_3 loss to N2), and mineralization (labileN to NH_4) - see Fig. 2 and Section 2.3. The model can adequately capture both the timing and magnitude of concentration peaks of NO_3 and NH_4. The concentrations are highly dynamic in part due to the transient nature of the streams within the Steppler basin that often only transport flow during higher runoff events. However, there are some events and locations where the model performed poorly for NO_3 that should be highlighted, such as in 2010 and particularly for HRUs 17, 29 and 38. A closer look into the results and model forcing in 2009 and 2010 shows no records of fertilizer application and//or tillage that could cause the exceptionally high peak concentrations observed. Since there was nothing else documented about the farmers practices in this particular year, we suspect that there was an issue with the reporting of (1) fertilizer-manure application or (2) additional local source(s) (e.g., feces from grazing livestock). Recall that the fields represented in HRUs 17 and 29 are small, about 17 and 6 hectares, respectively; therefore, they have lower dilution capacity to buffer major new nutrient inputs.

[Figure 6 about here.]

[Figure 7 about here.]

Phorphorus

Figs. 8 and 9 compare observed and simulated SRP and partP concentrations. Results suggest that the model can predict well the overall spatiotemporal concentration dynamics. However, similar to NO_3 (Fig. 6) and NH_4 (Fig. 6), the model fails to simulate the magnitude of some high concentration peaks, particularly in HRU 34. Although it is hard to identify the reasons for this mismatch, it may be related to the same local effects described above for N that were not included in the model due to lack of information. Future model enhancements on the simulation of erosion and sediment sorption-desorption mechanisms may also help to improve the prediction capacity of the model. See Section 5.3 for further discussion on possible sources of model uncertainty.

[Figure 8 about here.]

[Figure 9 about here.]

5. Discussion

5.1. Critical management of timing of fertilizer use relative to major runoff events

Spring snowmelt is frequently the major annual nutrient export event in the Canadian Prairies, but fertilizer and manure applications in the growing season can also be mobilized via summer and spring rainfall-runoff events Nicholaichuk (1967); Hansen et al. (2002); Glozier et al. (2006); Liu et al. (2013b). This model and model application show that the timing of nutrient applications plays a key role in the amount of nutrients exported via runoff in southern Manitoba. Fig. 10 highlights that by showing the temporal impact of fertilizer application on surficial soil NO_3-N mass and EOF streamflow concentrations. While NO_3, NH_4, SRP are removed through plant uptake and biogeochemical processes (e.g., nitrification, denitrification, dynamic-equilibrium with partP), excess fertilizer use can lead to nutrient accumulation in soils that can be mobilized with runoff. Fig. 11 shows that snowmelt accounted for 30%, 31%, 20%, and 16% of the total annual load of NO_3, NH_4, SRP and partP. This is a disproportionate amount that was rapidely delivered during average 9-day freshet events annually that accounted for 21% of the annual flow.

Field studies have also highlighted the importance of the amount, type, placement and timing of fertilizer application (e.g. Grant et al., 2019; Duncan et al., 2017; Plach et al., 2018). The location relative to runoff pathways, the depth relative to runoff water penetration (Brunet and Westbrook, 2012; King et al., 2015), and the timing relative to major runoff events are all critical control factors in fertilizer use that impact nutrient export Little et al.

(2007); Baulch et al. (2019). Other determinants such as tillage practices and perennial vegetation can similarly affect the rate of nutrient uptake and contact time with runoff that can affect downstream transport of nutrients (Elliott and Efetha, 1999; Tiessen and Elliott, 2010; Renton et al., 2015; Liu et al., 2014).

[Figure 10 about here.]

[Figure 11 about here.]

5.2. The importance of hourly model temporal resolution

Fig. 12 compares the predicted NO_3 (left panel) and NH_4 (right panel) concentrations when using hourly (black dotted line) and daily (gray line) model resolutions. Results show that daily model simulations can capture the timing of concentration peaks but tend to underestimate their magnitude. Thats because they represent an average daily concentration that is intrinsically related to the temporal resolution of the hydrological simulations that average streamflow values to daily averages. This can be problematic since such daily averages fail to capture the instantaneous severity (i.e., intensity and rate) of nutrient loads/concentrations that are often observed by conventional water quality monitoring based on instant grab (point) sampling (Piniewski et al., 2019), which has implications for overall load estimation (Williams et al., 2015).

[Figure 12 about here.]

5.3. Importance of local effects: lessons learned

The model failed to capture the magnitude of specific high concentration peaks. While it is hard to know with certainty the reason(s) for this mismatch, local effects may be the cause. Many of the fields within the Steppler Basin were used to grow forage that depending on amount and quality at freeze-up, could lead to additional loads (e.g., White, 1973; Elliott, 2013; Costa et al., 2019a). Similarly, deficiencies in the reporting of fertilizer and manure use by farmers may also lead to the underrepresentation of the nutrient inputs in the model. Depending on the pathways of runoff, surface/wetland or tile drainage arrangements, these additional local sources of nutrients can be mobilized with runoff (Brunet and Westbrook, 2012; King et al., 2015). Since CRHM-WQ is process-based (see the conceptual model in Figs. 1 and 2) and was run at hourly timesteps, it tracks the nutrients budgets in the soil, soil-pore water and surface water at fine temporal resolutions, and so such misrepresentations of boundary conditions may have a substantial effect on the results. For example, while surface flow quickly interacts with surficial soil layers and can transport nutrients located mainly in these regions, infiltration and subsurface flow mix with nutrients that may have leached through the soil profile through a more prolonged process. While the model considers these hydrological pathways, it requires the nutrient sources to be well understood and characterized in the model in order to predict hydrochemical fluxes well.

5.4. Contribution to the current modelling capacity

A major challenge for the transient simulation of nutrient dynamics in cold agricultural environments is the adequate prediction of flowpath evolution, despite evidence that this is a key factor in determining the origin of nutrients in runoff (Baulch et al., 2019; Costa et al., 2020a, 2017). However, considerable progress has been made in recent decades in the simulation of hydrological processes in open cold regions with models such as CRHM (Pomeroy et al., 2007), MESH (Pietroniro et al., 2007) and CHM (Marsh et al., 2020). These improvements allow for better predictions of blowing snow redistribution and sublimation (Pomeroy and Schmidt, 1993), snow densification and spatial variation in snow water equivalent (SWE) (Pomeroy and Gray, 1995; Pomeroy et al., 1998), snow-covered area depletion (Shook and Gray, 1996), snowmelt energetics (Gray and Landine, 1988), ground heat flux (Male, 1980), turbulent fluxes (Male, 1979) and runoff over frozen and partially frozen soils (Gray et al., 2001).

However, despite the importance of these advances for adequate hydrological simulations, they have not yet been fully integrated into nutrient models (Costa et al., 2020a). For instance, wind redistribution of snow and sublimation can dramatically change the spatial distribution of snow in prairie environments (Pomeroy and Schmidt, 1993) and can transform chemical concentrations in snow (Pomeroy et al., 1991; Pomeroy and Jones, 1996), but are neglected in all process-based nutrient models examined by Costa et al. (2020a) that include SWAT, INCA, HSPF, AnnAGNPS and HYPE. Some recent advances should be noted, such as developments in SWAT to (1) account for the regulation of a snow nitrate pool by snow-snowpack dynamics and snowmelt (Zhang et al., 2016), and (2) the introduction of seasonally varying erodibility parameters to enable variations in soil erosion between frozen, thawing and unfrozen soils (Mekonnen et al., 2017).

The new CRHM-WQ model proposed in this study contributes to improving the physical hydrological and chemical basis of cold region water quality modelling. This is important to support nutrient management in the cold agricultural regions of Canada that face nutrient pollution. In essence, this was accomplished by (1) using CHRM to provide the necessary hydrological simulations specialized in cold climates, and (2) developing process-based biogeochemical modules to represent N and P cycling.

6. Conclusions

A series of process-based transport and biogeochemical modules have been developed for the Cold Regions Hydrological Model (CRHM) to simulate nitrogen (N) and phosphorus (P) in cold agricultural basins. The new model aims to address critical issues with existing nutrient models for simulation of these environments.

The new modules calculate nutrient fluxes throughout the basins hydrological system that includes the snowpack, soil, streams and depressional storage (e.g., potholes and wetlands). This is possible through full coupling with the hydrology internally computed by CRHM. Conceptual models for representation of the N and P biogeochemical cycles were implemented and include the explicit computation of transformation processes within and between different mineral and organic species: NO_3, NH_4, DON, organic labileN, and organic refractoryN, in the case of N, and SRP, partP, DOP, organic labileP, and organic refractoryP, in the case of P.

The model was applied to the agricultural Steppler Basin in Manitoba and was generally able to capture the spatiotemporal patterns (both timing and magnitude) of SWE, streamflow, and NO_3, NH_4, SRP and parP concentrations in streamflow. The results highlight the importance of critical management in fertilizer application timing relative to major runoff events to avoid excessive nutrient export. The model failed to capture some specific high-magnitude nutrient concentration peaks likely due to local effects, such as animal grazing and feces, that were not included due to lack of information. It has been shown that hourly temporal model resolutions were critical to achieving the concentration peaks measured in the field.

Data Availability Statement

The data that support the findings of this study are available from Agriculture and Agri-Food Canada (AAFC) and Environment and Climate Change Canada (ECCC). Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with permission of AAFC and ECCC.

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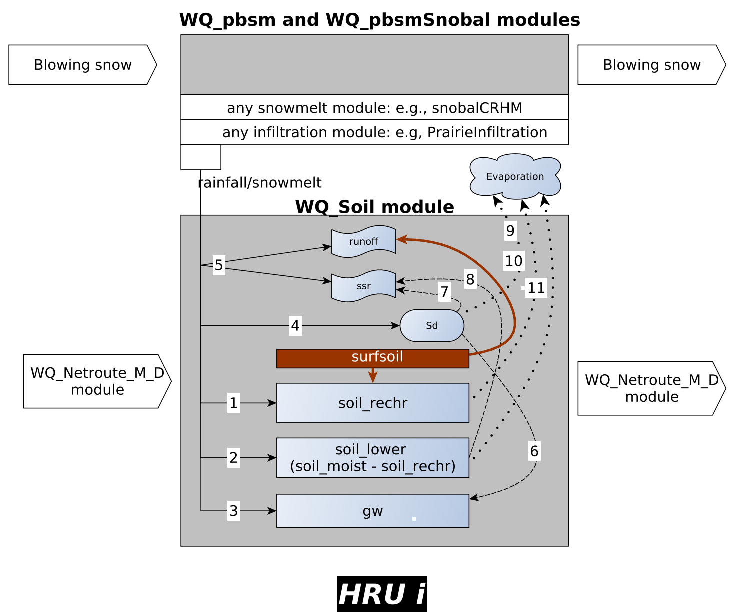
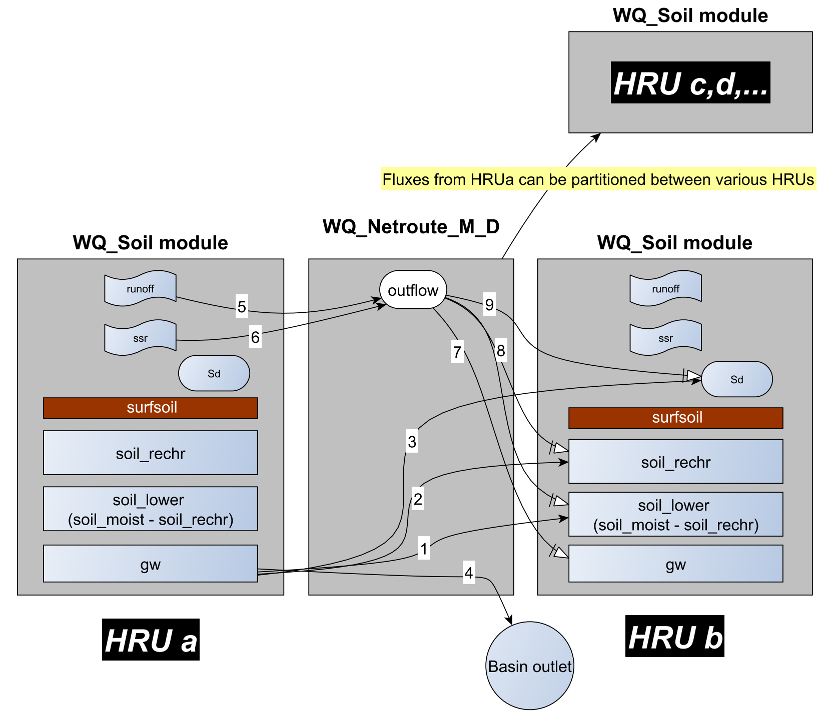


(a) Snow and soil modules

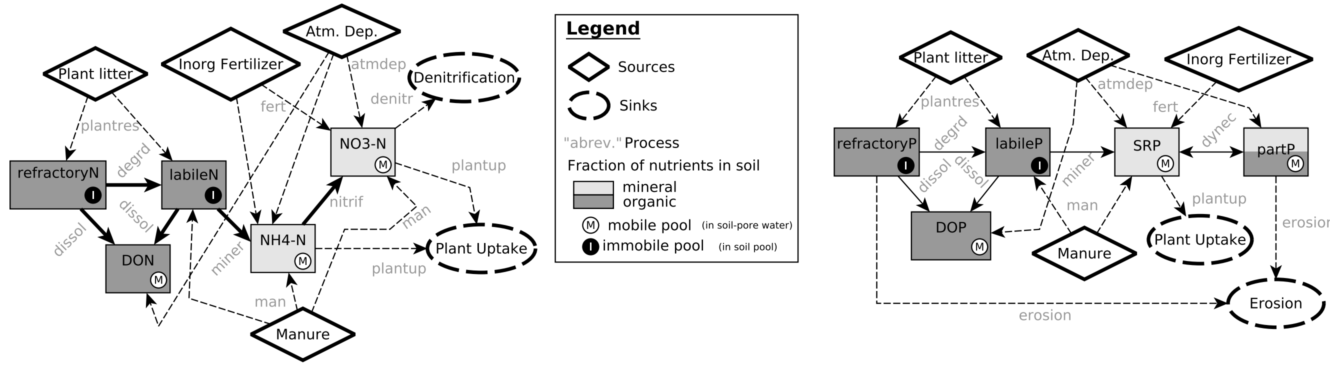


(b) Routing module

Figure 1: Conceptual model for the incorporation of nutrient transport and storage calculations in existing CRHM modules. This includes modules for (a) snowpack, runoff, subsurface runoff, depressional storage, upper soil, lower soil, and groundwater, (b) routing between HRUs. The numbers in the arrows represent the sequence in which the fluxes are computed. White-head arrows refer to optional fluxes, while dotted arrows refer to evaporation fluxes from different compartments

SOURCES/SINKS: atmospheric deposition (atmdep), fertilizer (fert), manure (man), plant residue (plantres), erosion (erosion), plant uptake (plantup)
BIOGEOCHEMICAL PROCESSES: mineralization (miner), denitrification (denitr), degradation (degrd), dissolution (dissol), dynamic equilibrium (denitr)

(a) Conceptual model
(a1) Nitrogen (N) (a2) Phosphorus (P)



(b) List of sources, sinks and biogeochemical transformations

Nutr.	Phase	Form	(+)Sources and (-)Sinks	Biogeochemical Processes: Removing	Adding	Dyn. Equil.
N	Dissolved	NO_3-N	(+)atmospheric deposition, (+)fertilizer, (+)manure, (-)plant uptake	denitrification (to N_2)	nitrification (from NH_4)	-
		NH_4-N	(+)atmospheric deposition, (+)fertilizer, (+)manure(-)plant uptake	nitrification (to NO_3)	mineralization (of labileN)	-
		DON	(+)atmospheric deposition	-	dissolution (of labileN), dissolution (of refractoryN)	-
	Immobile	labileN	(+)plant residue, (+) manure	dissolution (to DON), mineralization (to NH_4)	degradation (of refractoryN)	-
		refractoryN	(+)plant residue	dissolution (to DON), degradation (to labileN)	-	-
P	Dissolved	SRP	(+)atmospheric deposition, (+)fertilizer, (+)manure, (-)plant uptake		mineralization (of labileP)	dynamic equibrium (with partP)
		DOP	(+)atmospheric deposition	-	dissolution (of labileP), dissolution (of refractoryP)	-
	Immobile	labileP	(+)plant residue, (+) manure	dissolution (to DOP), mineralization (to SRP)	degradation (of refractoryP)	-
		refractoryP	(+)plant residue	dissolution (to DOP), degradation (to labileP), erosion	-	-
	Particulate	partP	(+)atmospheric deposition, (-)erosion			dynamic equibrium (with SRP)

Figure 2: Conceptual model for simulation of biogeochemical cycling of N and P

(a)

(b)

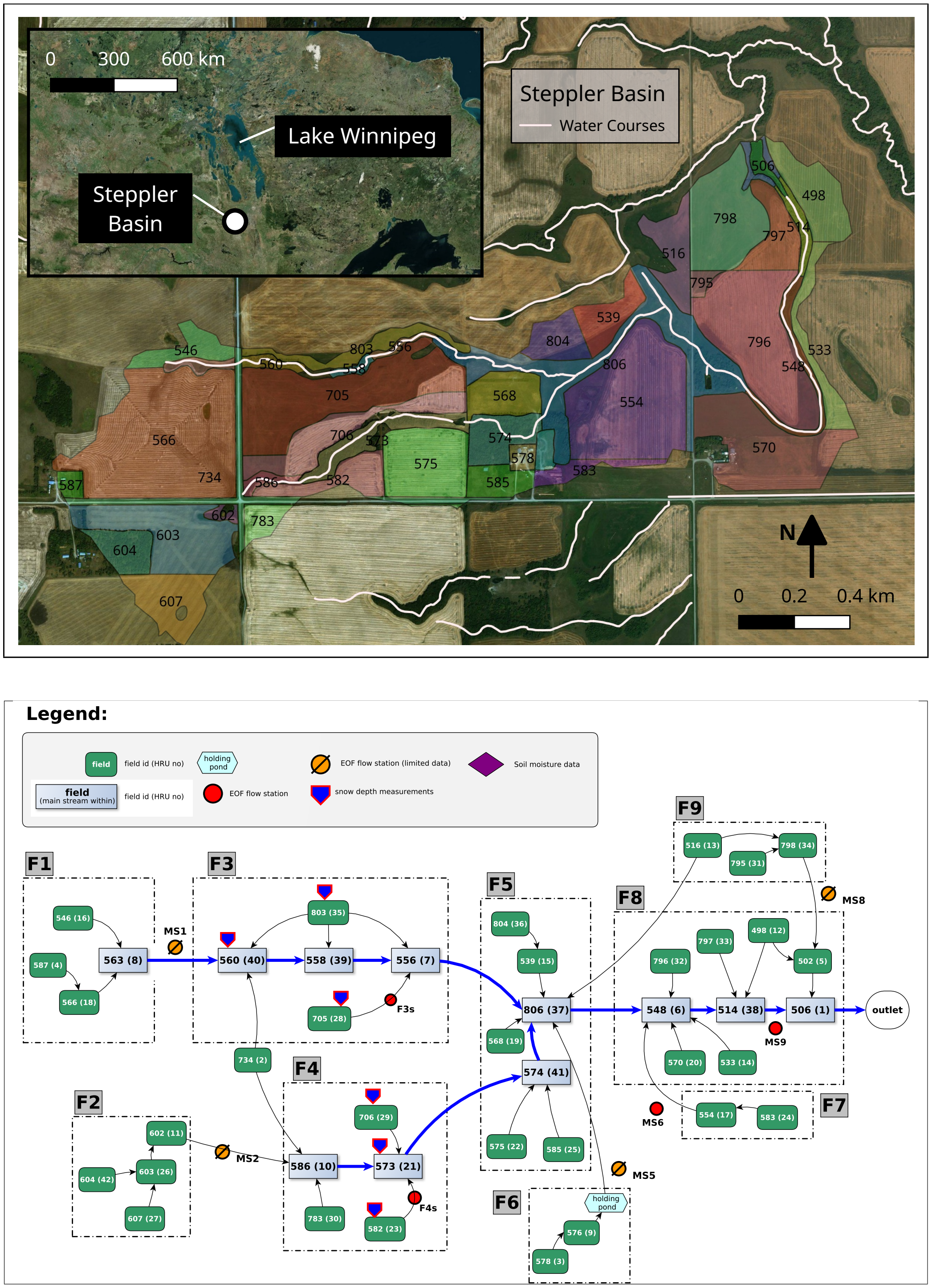
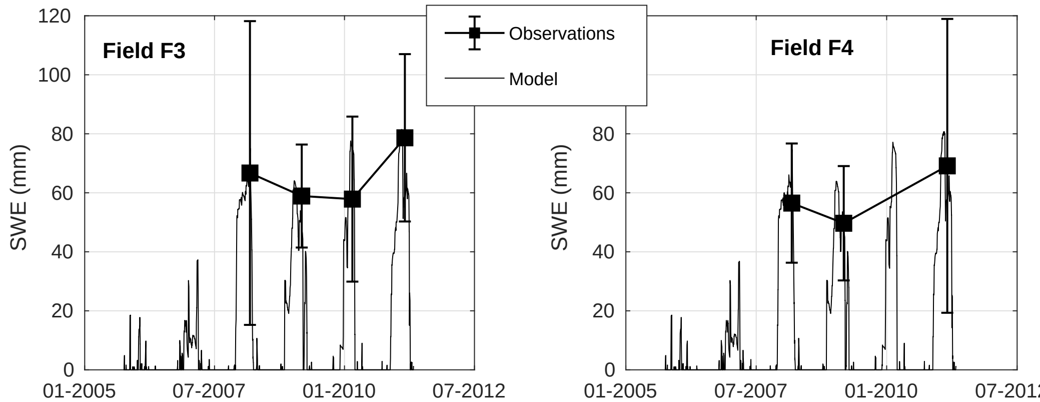


Figure 3: Case study region and conceptual model: (a) map of the Steppler Basin with the different fields represented as individual HRUs highlighted in different colours, and (b) conceptual model based on HRUs used to simulate the basin, and location of hydrometric stations, snow measurements and reservoirs



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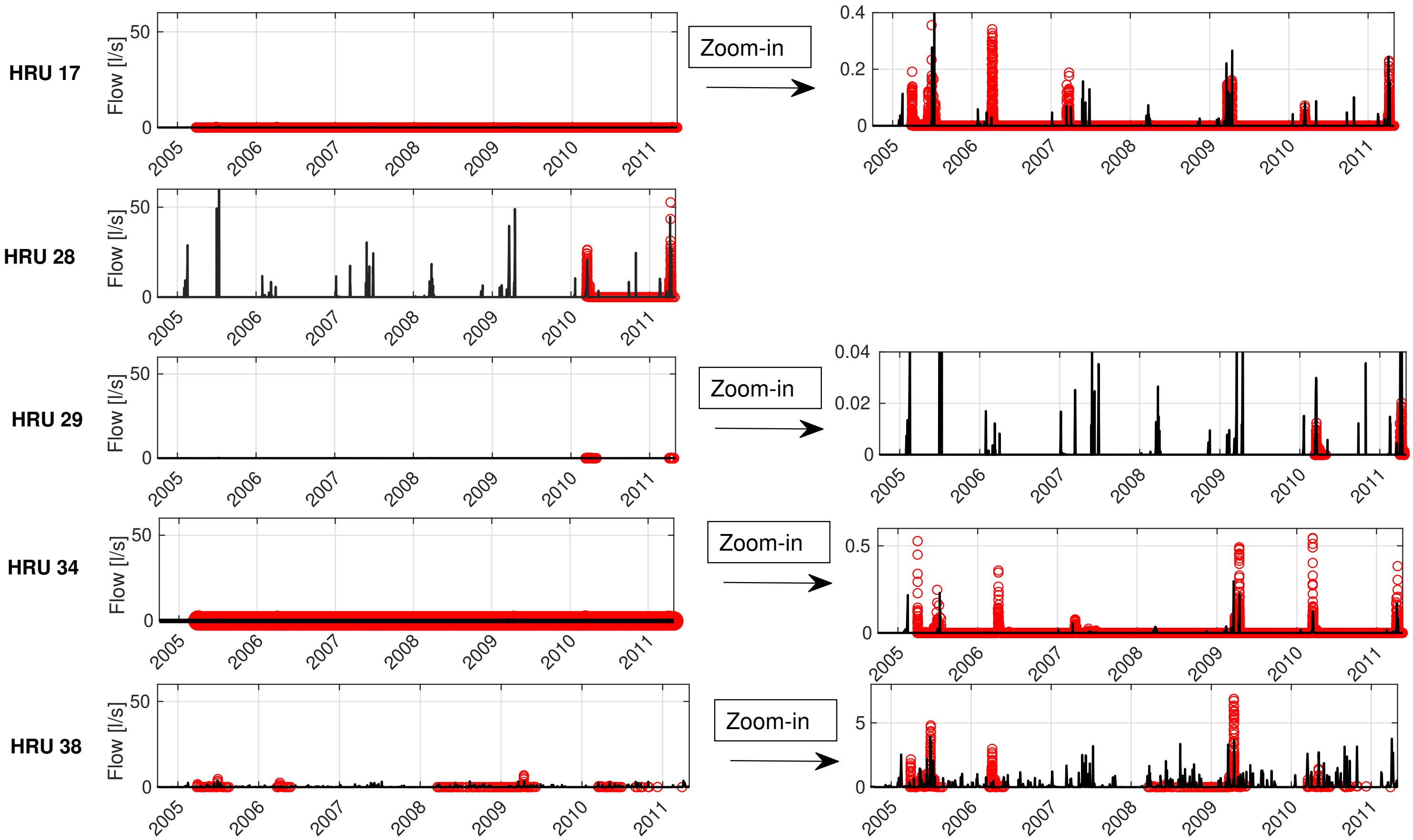

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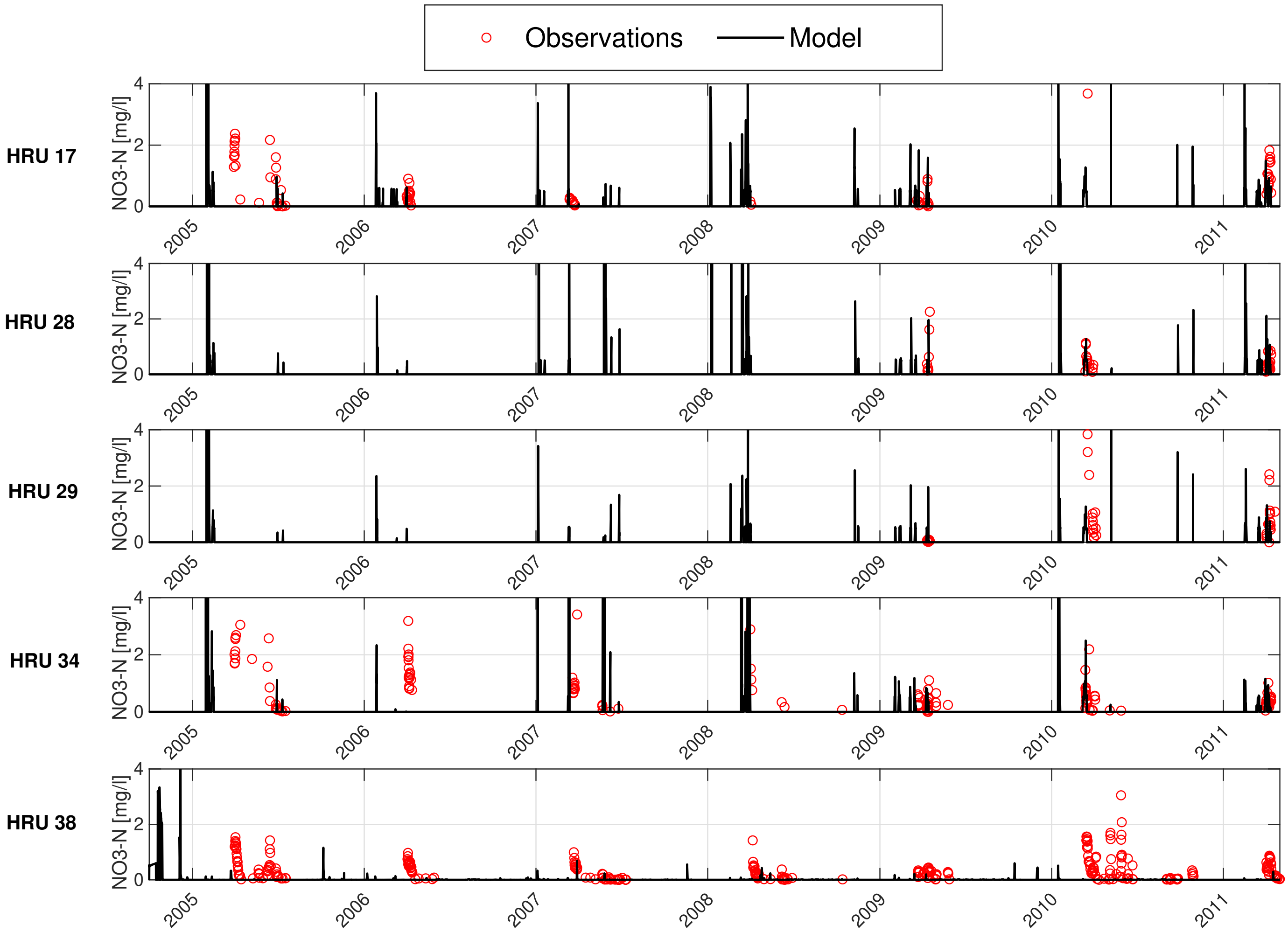

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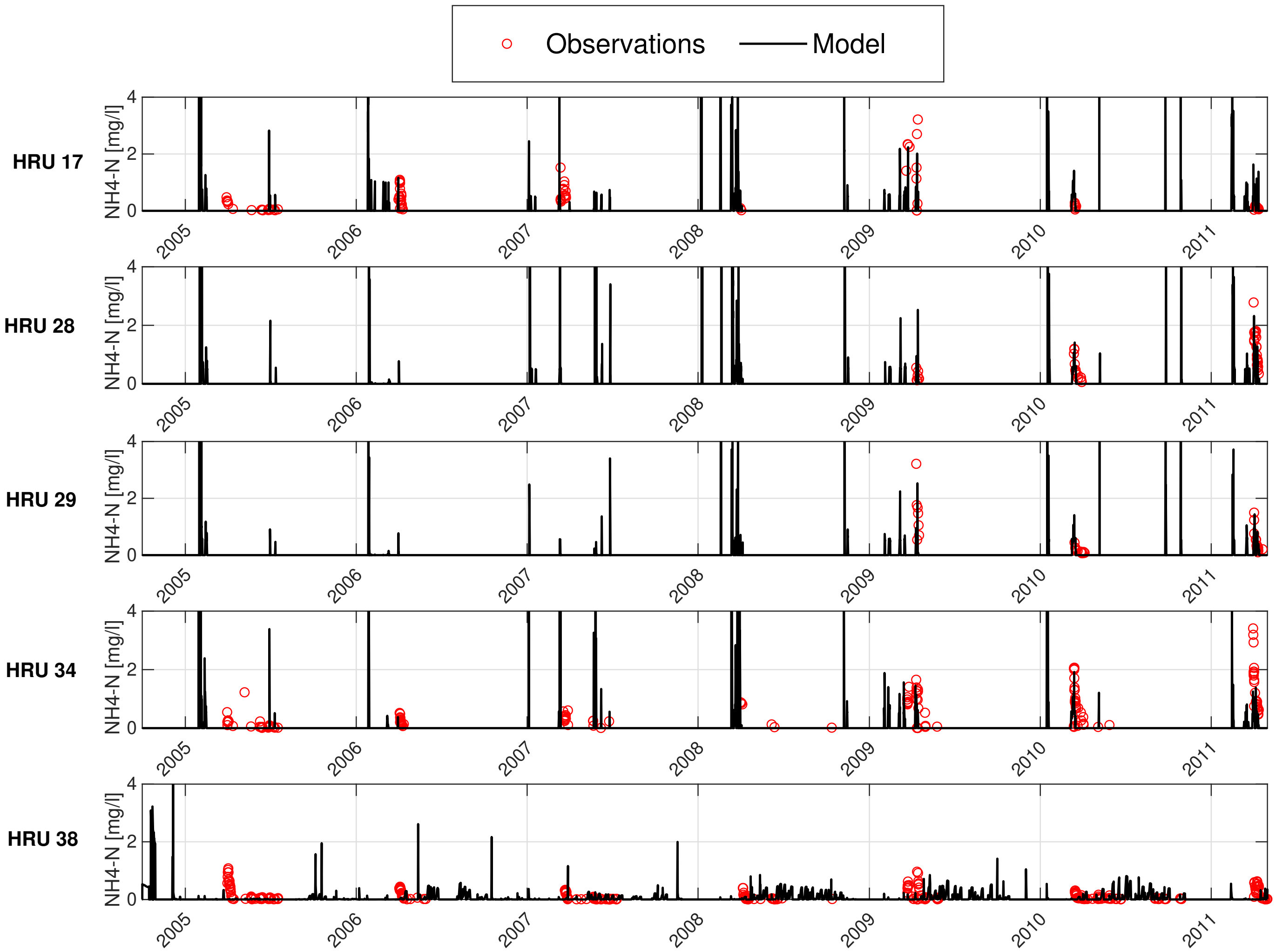

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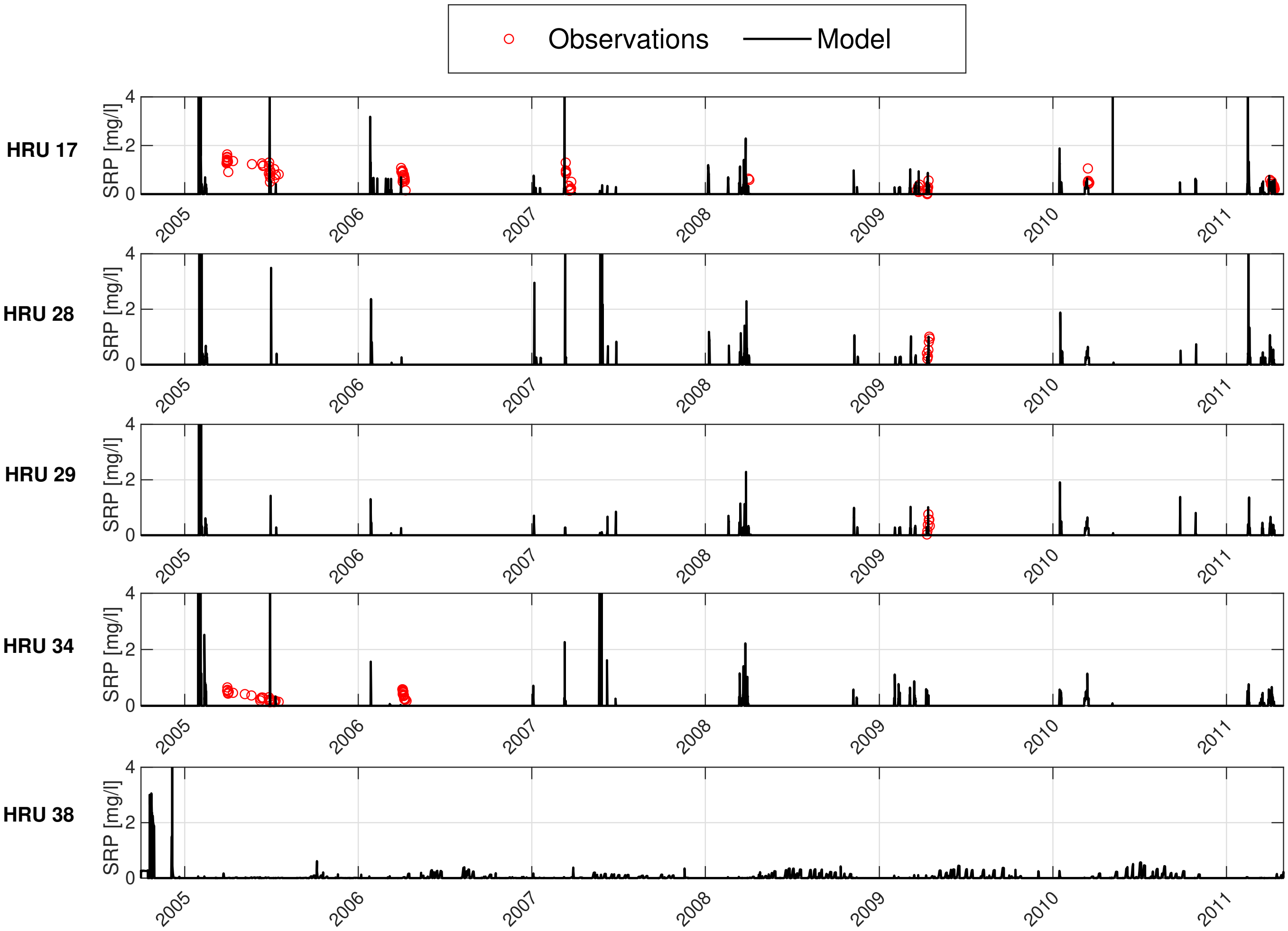

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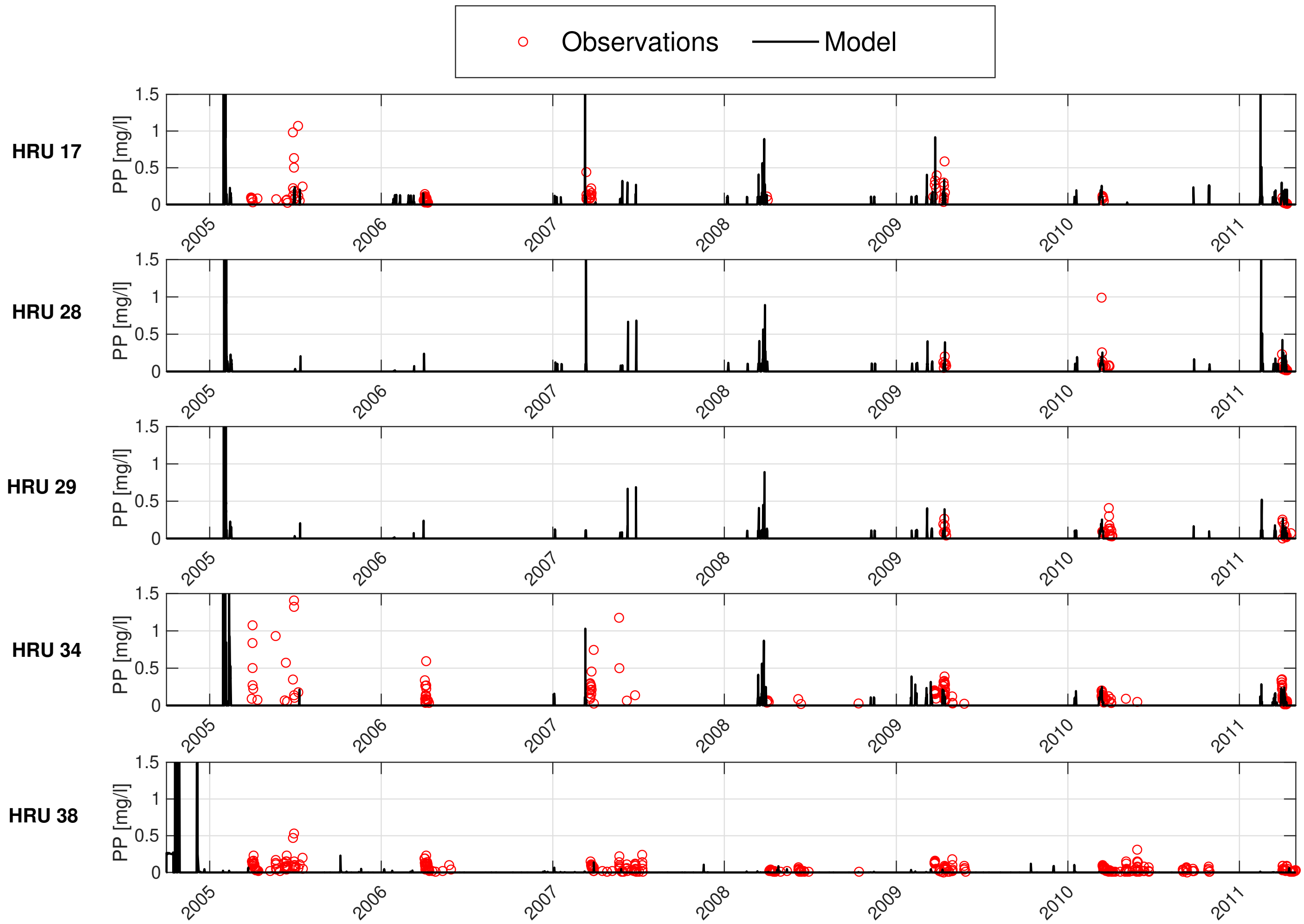
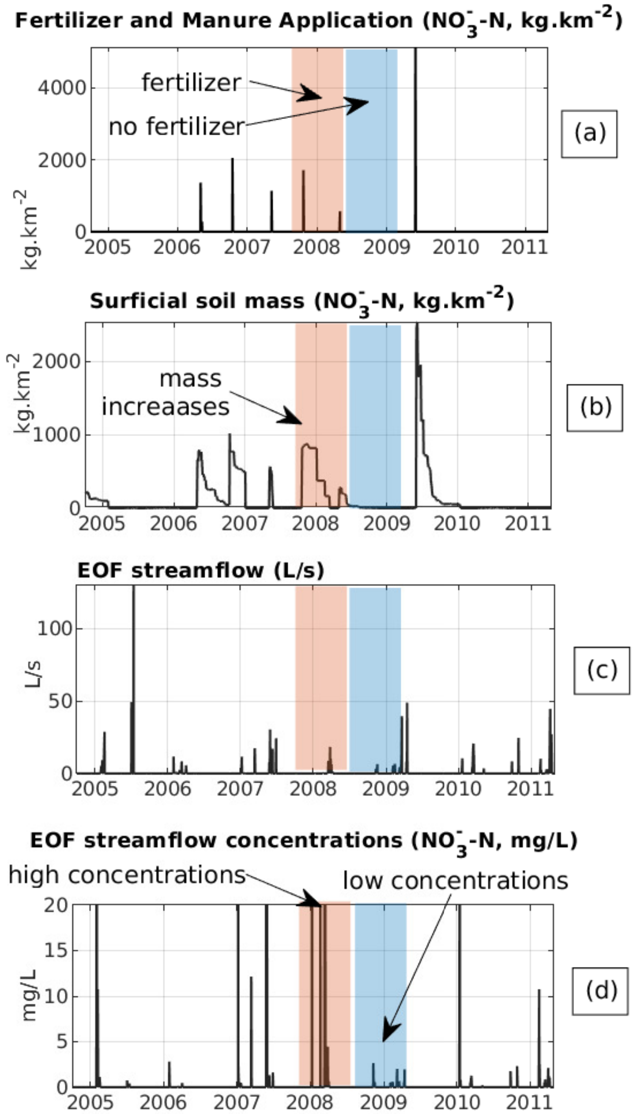


Figure 9: Observed and simulated streamflow partP concentrations



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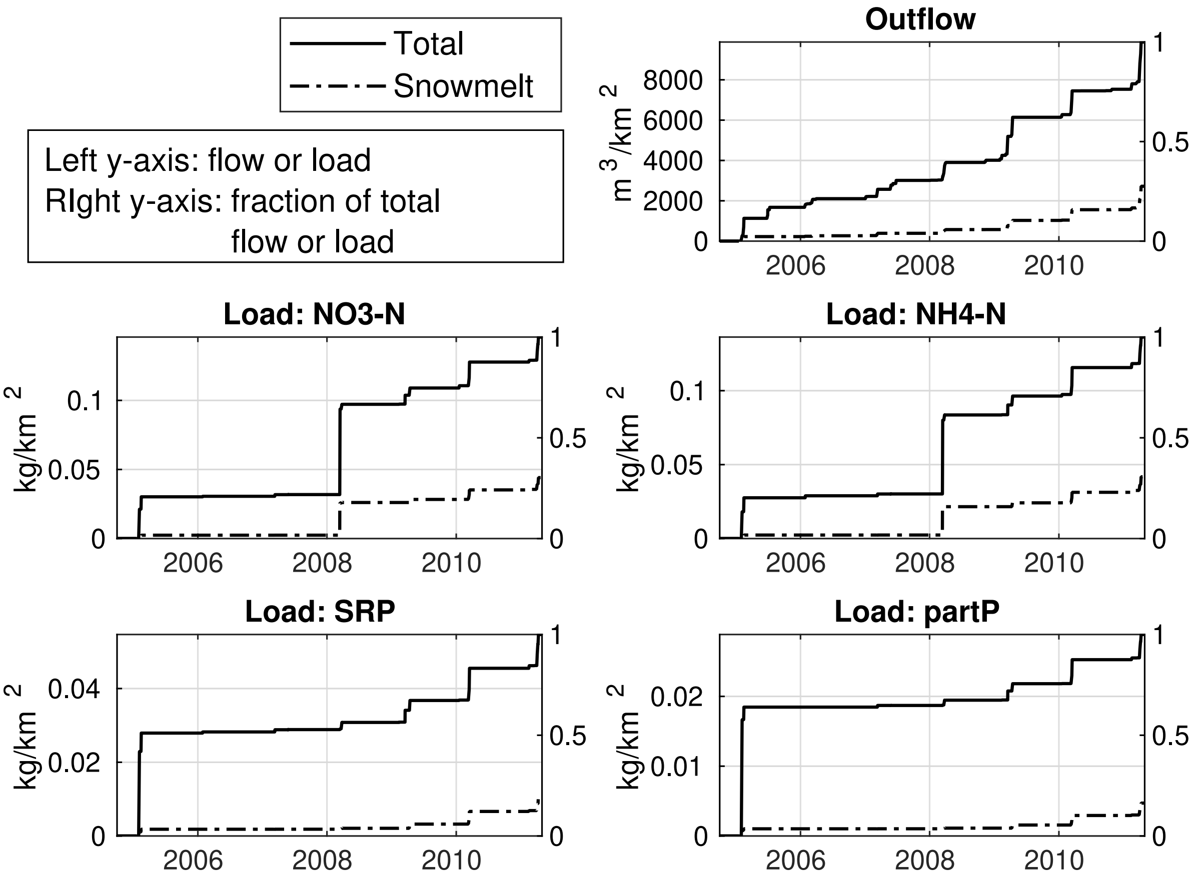

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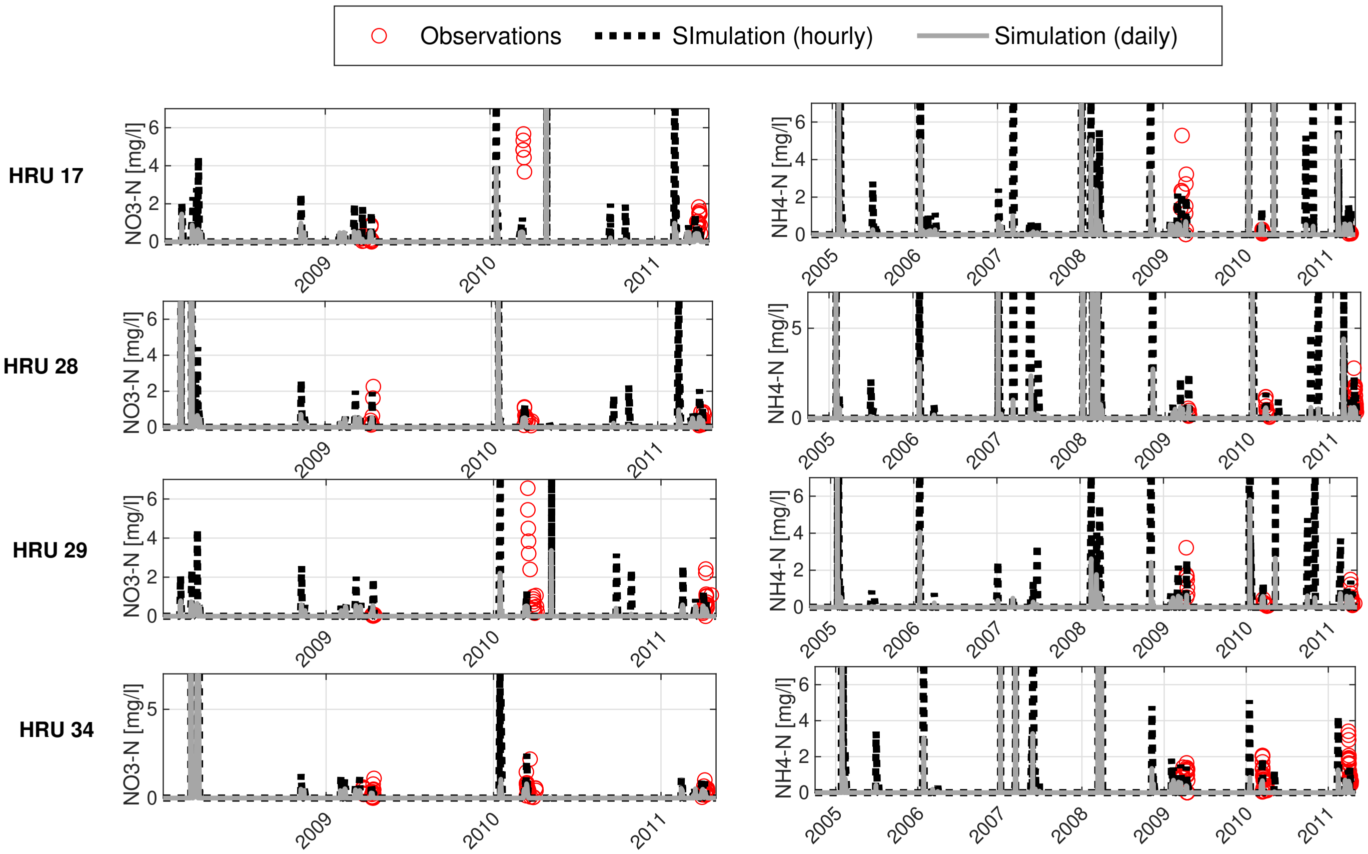

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Table 1: Data used as model inputs and for validation of the model performance

Purpose	Data type	Variable	Monitoring stations (Flow and WQ)				
			MS6	F3	F4	MS8	M9
		Corresponding model HRU #	17	28	29	34	38
Model forcing	Weather	Precipitation	applicable to the entire basin				
		Air Temperature	applicable to the entire basin				
		Relative Humidity	applicable to the entire basin				
		Incident short-wave radiation	applicable to the entire basin				
	Agricultural practices	Fertilizer application: N*	available at all fields/HRUs				
		Fertilizer application: P*	available at all fields/HRUs				
		Manure application: N*	available at all fields/HRUs				
		Manure application: P*	available at all fields/HRUs				
Model validation	Hydrology	EOF streamflow	•	•	•	•	•
		SWE#	available at F3 and F4 (see Fig. 3b)				
	Water Quality	EOF flow NO_3	•	•	•	•	•
		Soil NO_3	•	•	•	•	•

*information available about the timing (day), location (field/model HRU), duration of application (days) and amount applied (kg/ha)
#snow water equivalent

Table 2: Model performance for peak SWE, streamflow and streamflow nutrient concentrations based on NSE, RMSE and mean bias.

SWE	HRUs	NSE [-]	RMSE [mm]	Bias [-]
	HRUs in field F3[&]	0.63	4.93	-0.03
	HRUs in field F4[&]	0.77	3.55	-0.03
	HRU (field #, Gauge Station id)*	NSE [-]	RMSE [m^3/s]	Bias [-]
Flow	17 (554, MS6)	0.93	0.05	-0.30
	28 (705, F3)	0.66	4.52	-0.28
	29 (582, F4)	0.99	0.01	-0.53
	34 (798, MS8)	0.90	0.05	1.19
	38 (514, MS9)	-0.51	1.04	-0.62
NO_3	17 (554, MS6)	-0.26	2.00	1.12
	28 (705, F3)	-0.27	0.72	-0.25
	29 (582, F4)	-0.03	2.48	1.90
	34 (798, MS8)	-2.42	2.89	0.50
	38 (514, MS9)	0.16	0.65	10.7
NH_4	17 (554, MS6)	0.23	1.15	0.03
	28 (705, F3)	0.42	0.76	-0.122
	29 (582, F4)	0.31	0.88	0.08
	34 (798, MS8)	-5.76	2.02	-0.28
	38 (514, MS9)	-0.76	0.46	-0.38
SRP	17 (554, MS6)	-3.49	1.06	0.57
	28 (705, F3)	0.94	0.09	0.10
	29 (582, F4)	0.57	0.26	-0.40
	34 (798, MS8)	-35.45	1.51	-0.23
	38 (514, MS9)	NA	NA	NA
partP	17 (554, MS6)	-0.23	0.33	0.64
	28 (705, F3)	0.06	0.29	0.16
	29 (582, F4)	0.43	0.16	0.27
	34 (798, MS8)	-0.10	2.78	25.91
	38 (514, MS9)	0.30	0.31	17.37

*See Fig. 3 for location of the HRUs, fields and gauge stations
[&]Performance values correspond to the average calculated for all HRUs within the corresponding fields, see Fig. 3 for identification of the HRUs within each field