Advancing the realistic simulations of Nitrous Oxide (N_2O) emissions in cold climate watersheds using Soil and Water Assessment Tool

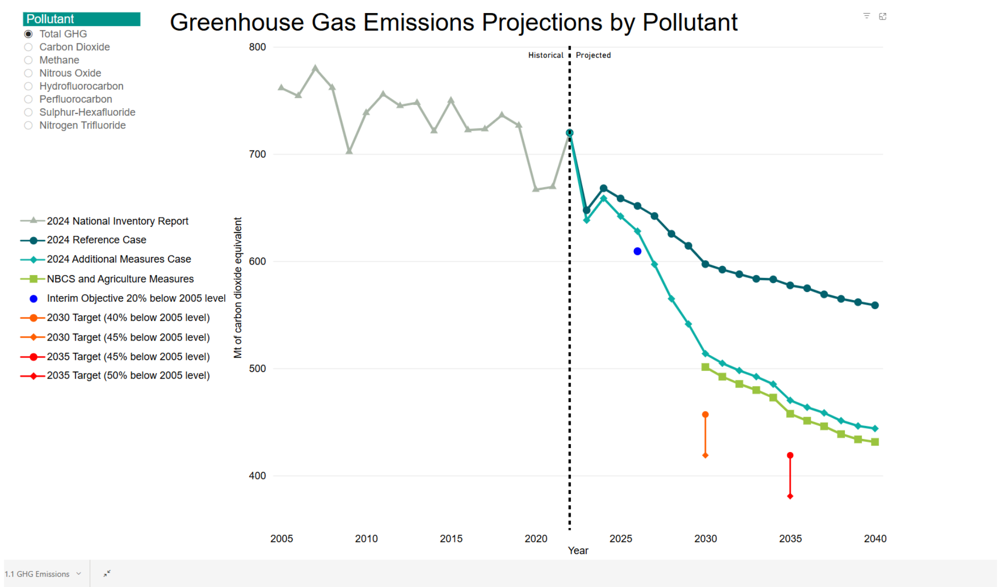
Uttam Ghimire, ughimire@uoguelph.ca

PhD candidate

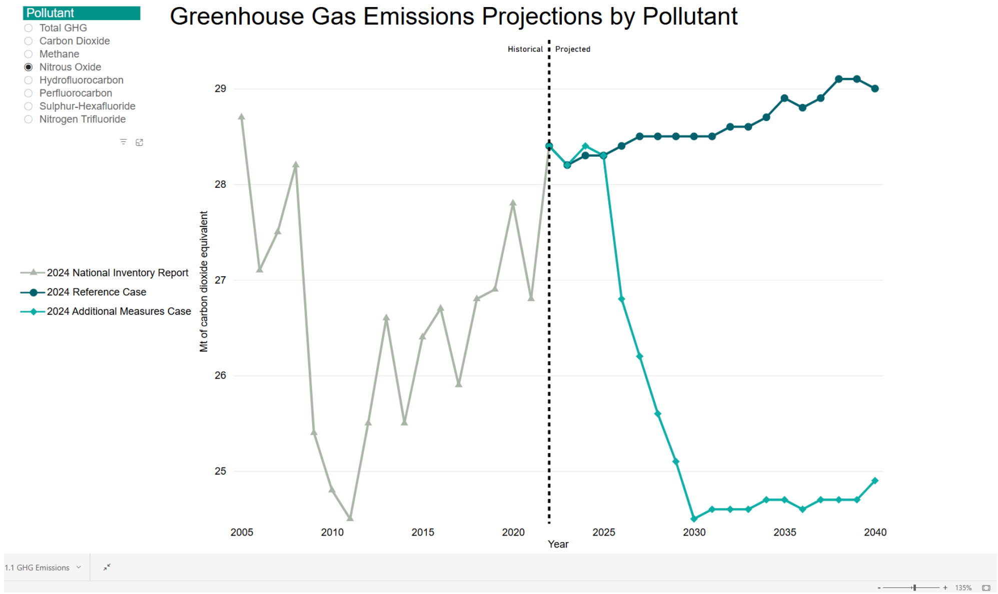
School of Engineering, University of Guelph

Green House Gases in Canada

- During 2005 to 2023, the total GHG emissions in Canada reduced from 764 to 694 Mt CO_2 eq.
- However, nitrous oxide (N_2O) emissions rose from 66 to 69 Mt CO_2 eq during the same period and is expected to keep increasing under business-as-usual scenario.
- Agriculture is the most dominant contributor of N_2O emissions (nearly 50%)



Total Green House Gases



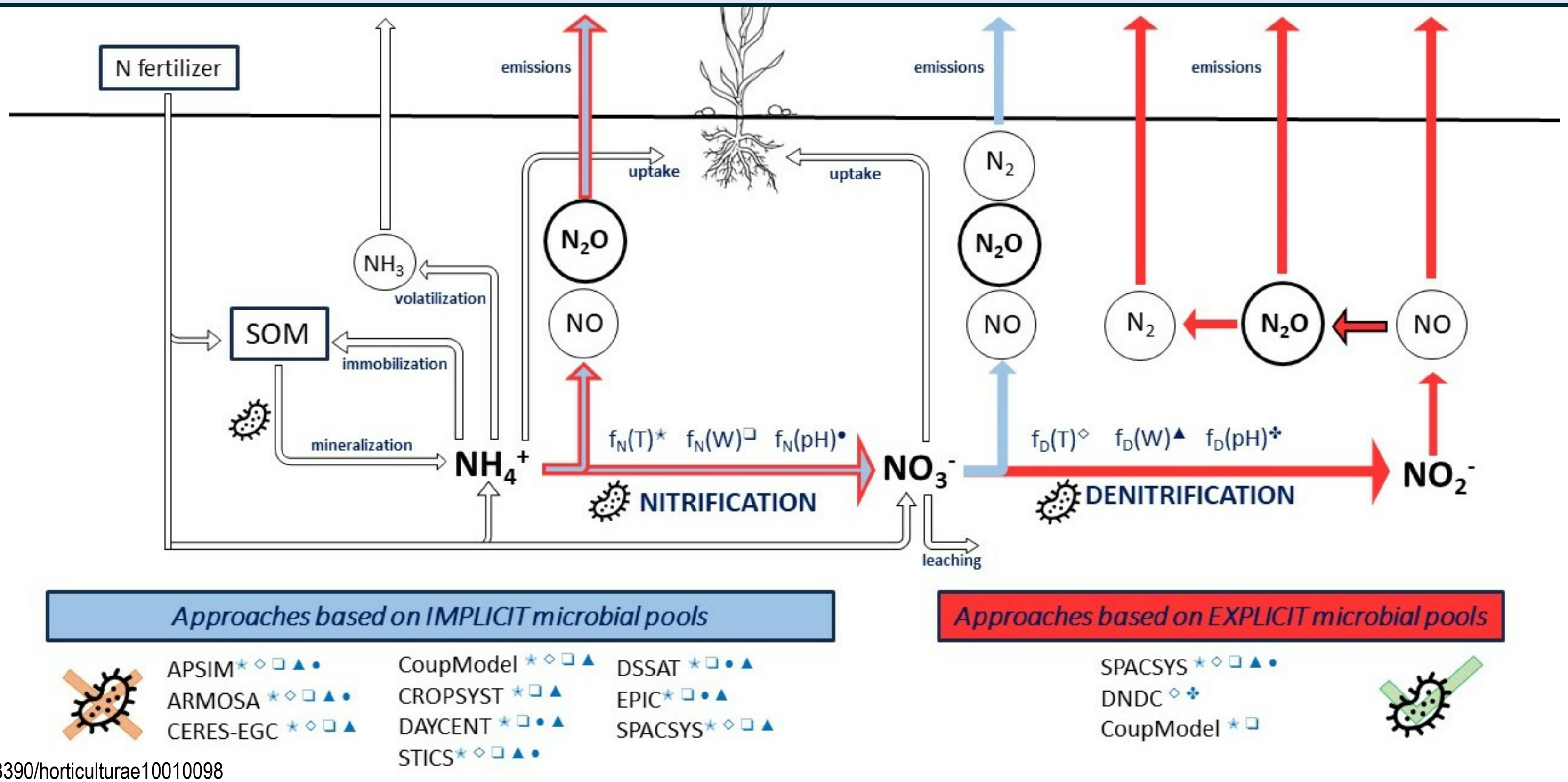
Nitrous Oxide emissions

Source: National Inventory Report 2025

Nitrous Oxide (N_2O) modeling

- N_2O is emitted as a bi-product of nitrogen cycle which is facilitated by microbes under favorable conditions. Several studies have reviewed process-based models capable of simulating the key processes involved in N_2O emissions estimation, i.e., nitrification and denitrification.

- Theoretically, any model capable of simulating nitrification and denitrification pathways in a nitrogen-cycle is capable of N_2O emissions modeling.

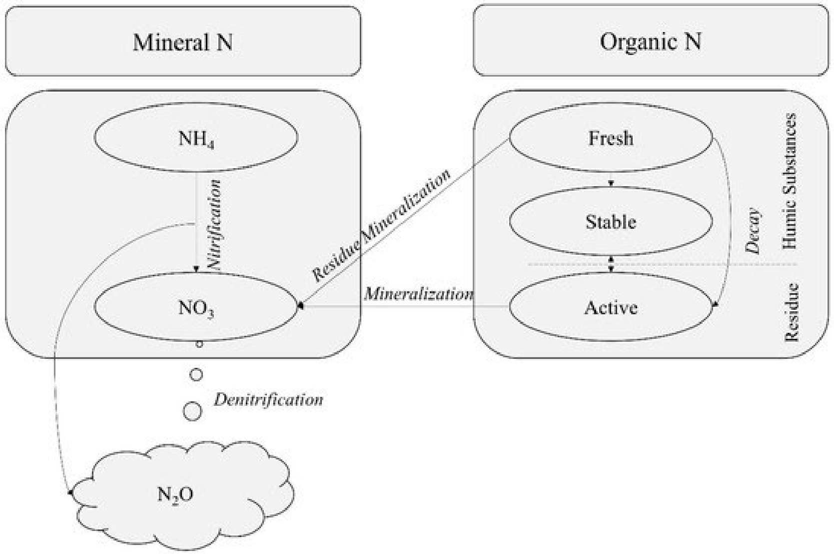


Source: https://doi.org/10.3390/horticulturae10010098

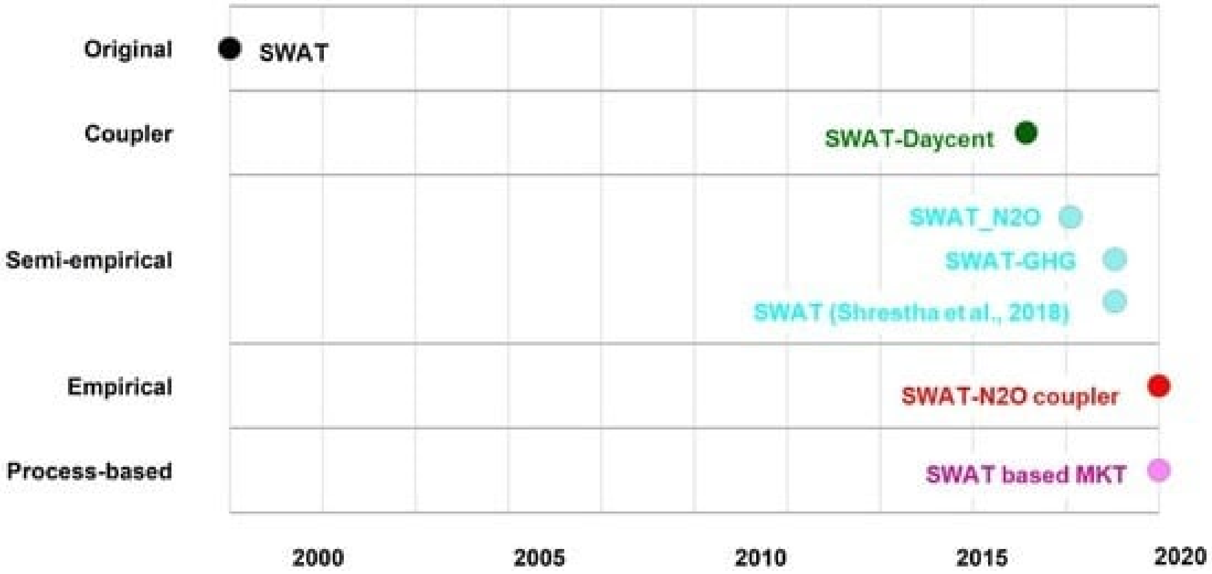
N_2O modeling with Soil and Water Assessment Tool (SWAT)

- SWAT is a good candidate for N_2O emissions modeling as it already accounts hydrology, soil pedoclimatic conditions and nitrogen cycle modules in it. Unlike other models, SWAT also considers the lateral transfer or nutrients and water at a watershed scale.

- The previous iterations of N_2O emissions modeling with SWAT included coupling techniques, integrating semi-empirical equations into the existing modules, developing empirical equations using field measured data and a microbial process facilitated technique.



Nitrogen cycle in SWAT



https://doi.org/10.3390/atmos11050450

Limitations in the context of Canada

- It is well understood that the nitrifications and denitrification pathways are significantly influenced by the soil moisture and temperature in addition to the amount of mineral nitrogen, acidity and carbon amount in soil.
- In cold climatic conditions, the soil moisture and temperature are not accurately represented in base SWAT. For e.g., even when the air temperature is subzero, the soil temperature may not be subzero because of insulative properties of snow. This allows the microbial activity to persist in conditions which was not accurately represented in SWAT.
- The freeze-thaw cycles significantly influence the N_2O emissions, which may not be accurately represented by a base SWAT model.
- The snowmelt equations can be better represented
- Thus, an integrated model with N2O emissions module + physical soil temperature module + physical snow melt module is desired.

https://doi.org/10.3390/atmos11050450

A semi-empirical N_2O emission module

- Shrestha et al 2018 developed a N_2O emission module in SWAT using the semi-empirical equations of nitrification and denitrification.
- N_2O = N_2O from Nitrification +N_2O from Denitrification
- Nitrification N_2O= function (Net nitrogen mineralization, ammonium content, Soil temperature, Soil moisture)
- Denitrification N_2O= function (nitrate level, Carbon content, Soil temperature, Soil moisture)
- Tested in fescue grasslands with long term grazing in Alberta, Canada and reported satisfactory simulations of daily N_2O emissions.
- However, in base SWAT model, if Soil temperature < $0^{o}C$, the mineralization and decompositions do not occur. Additionally, mineralization and decomposition are dependent on nutrient cycling water factor in soil. The nitrification and volatilizations occur only when soil temperature> $5^{o}C$.

DOI: 10.1007/s11356-018-2719-2

Physical snow melt & Physical Soil temperature module

- In base SWAT model, snowmelt is estimated using a temperature index model. Snowmelt = linear function of difference between avg snowpack max air temperature and threshold temperature for snowmelt.

- A physical energy balanced snow melt module of Qi et al 2017 has reported better simulation of streamflow during snowmelt periods and realistic simulation of snow depths for cold climates. Snowmelt = Snowmelt due to Shortwave radiation + Longwave radiation + sensible energy (convection)+ latent energy (vapor condensation) + heat conduction from ground + energy in rainfall

- In base SWAT model, soil temperature is estimated as a function of previous day's soil temperature, average annual air temperature, current day's soil surface temperature and depth in the soil profile.

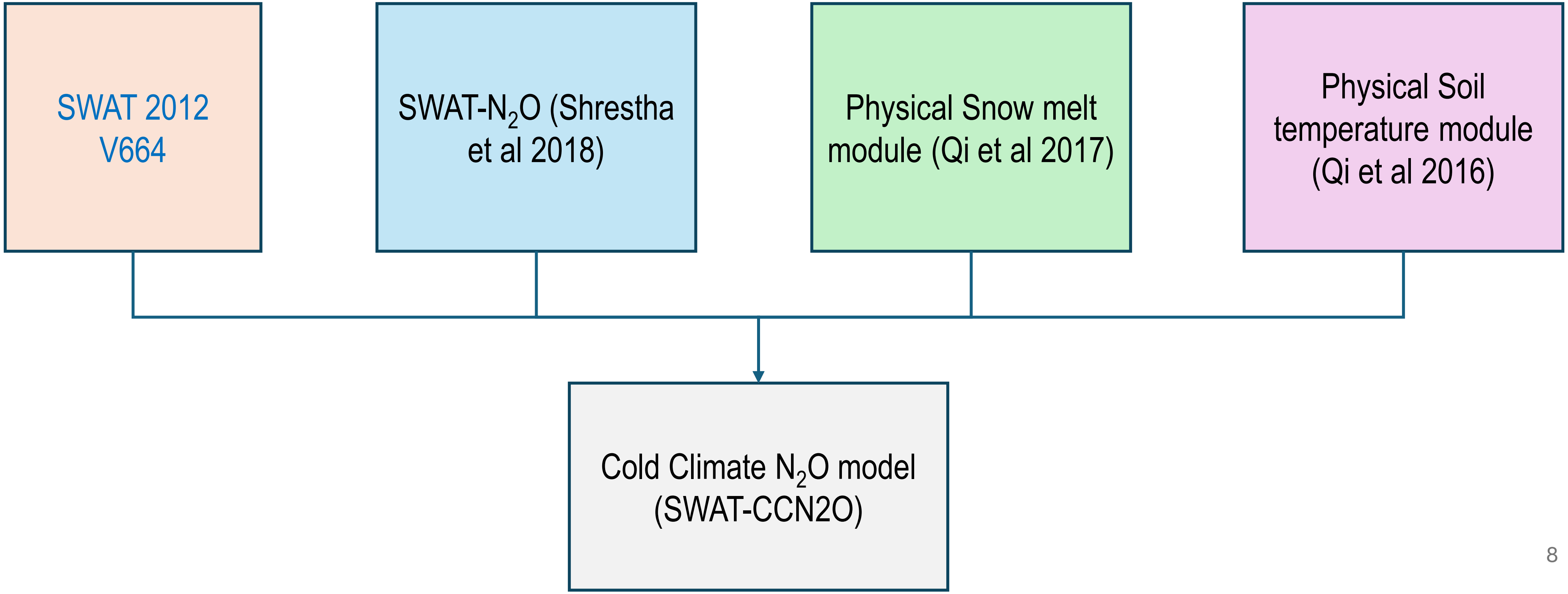
- A physical soil temperature module of Qi et al 2016 has reported realistic simulation of soil temperatures at different depths for cold climate. Soil temperature = Energy status of soil depending on energy exchange between air, snow, soil surface and individual soil layers. Heat transfer due to conduction and latent heat exchange associated with phase changes of water in soil

https://doi.org/10.1016/j.jhydrol.2019.02.020 , https://doi.org/10.1016/j.jhydrol.2016.05.003

Cold Climate N_2O model (SWAT-CCN2O)

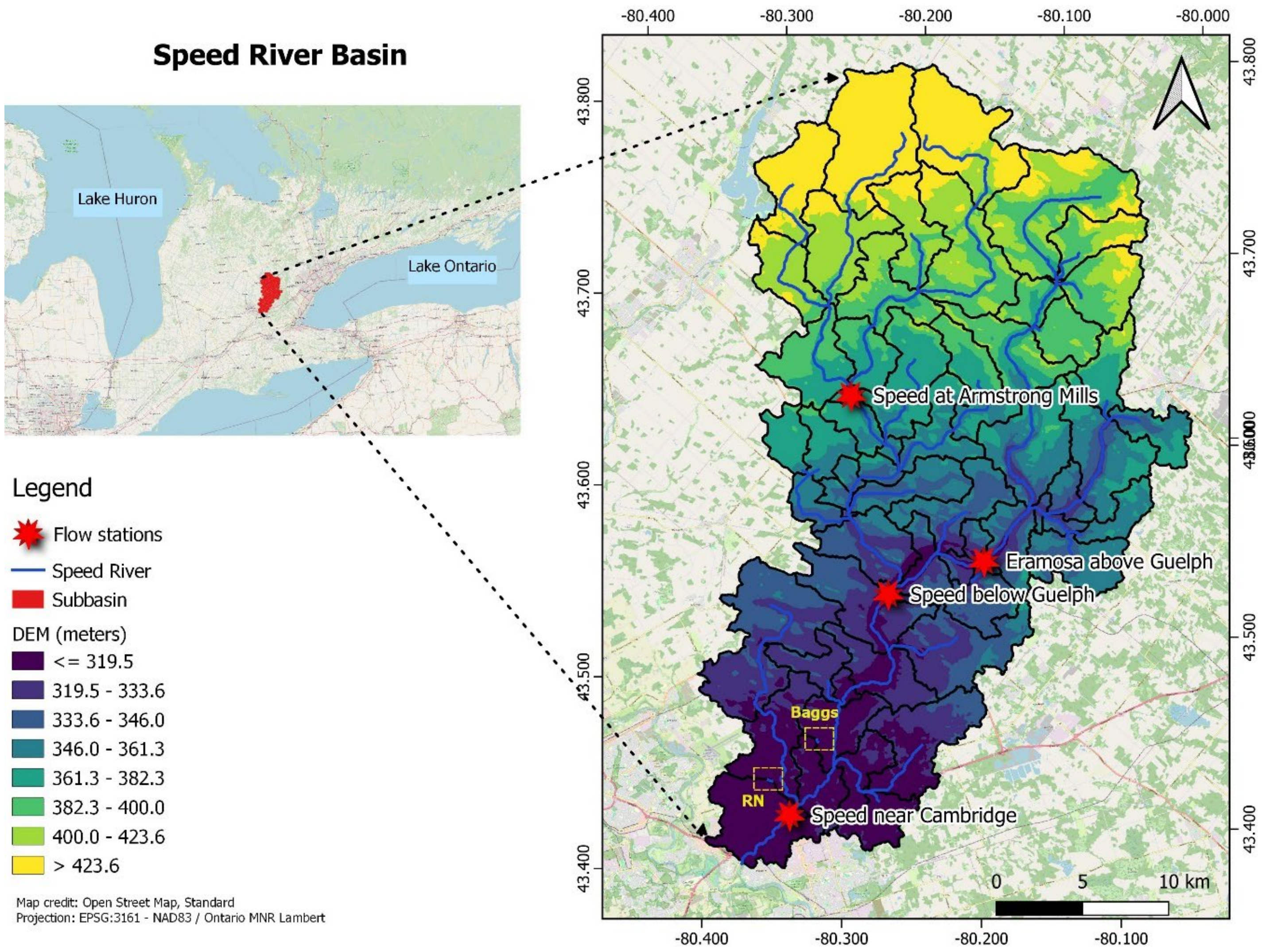
- Incorporating Physical Snowmelt module + Physical Soil temperature module + Semi- Empirical N_2O emission module in SWAT 664

- Testing the improved SWAT model vs base SWAT model in simulating hydrological processes in Speed river basin, Ontario

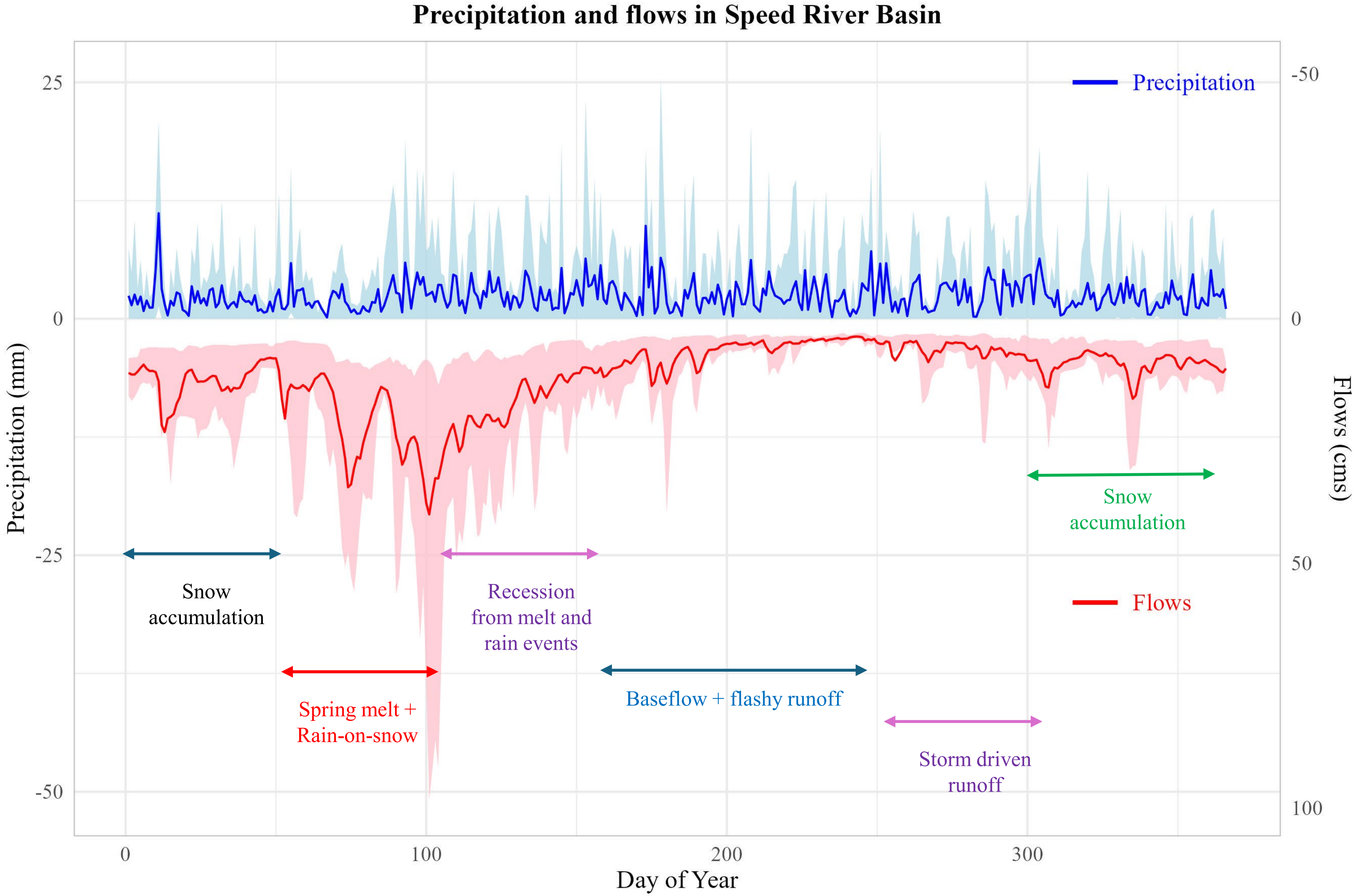


Testing SWAT-CCN2O

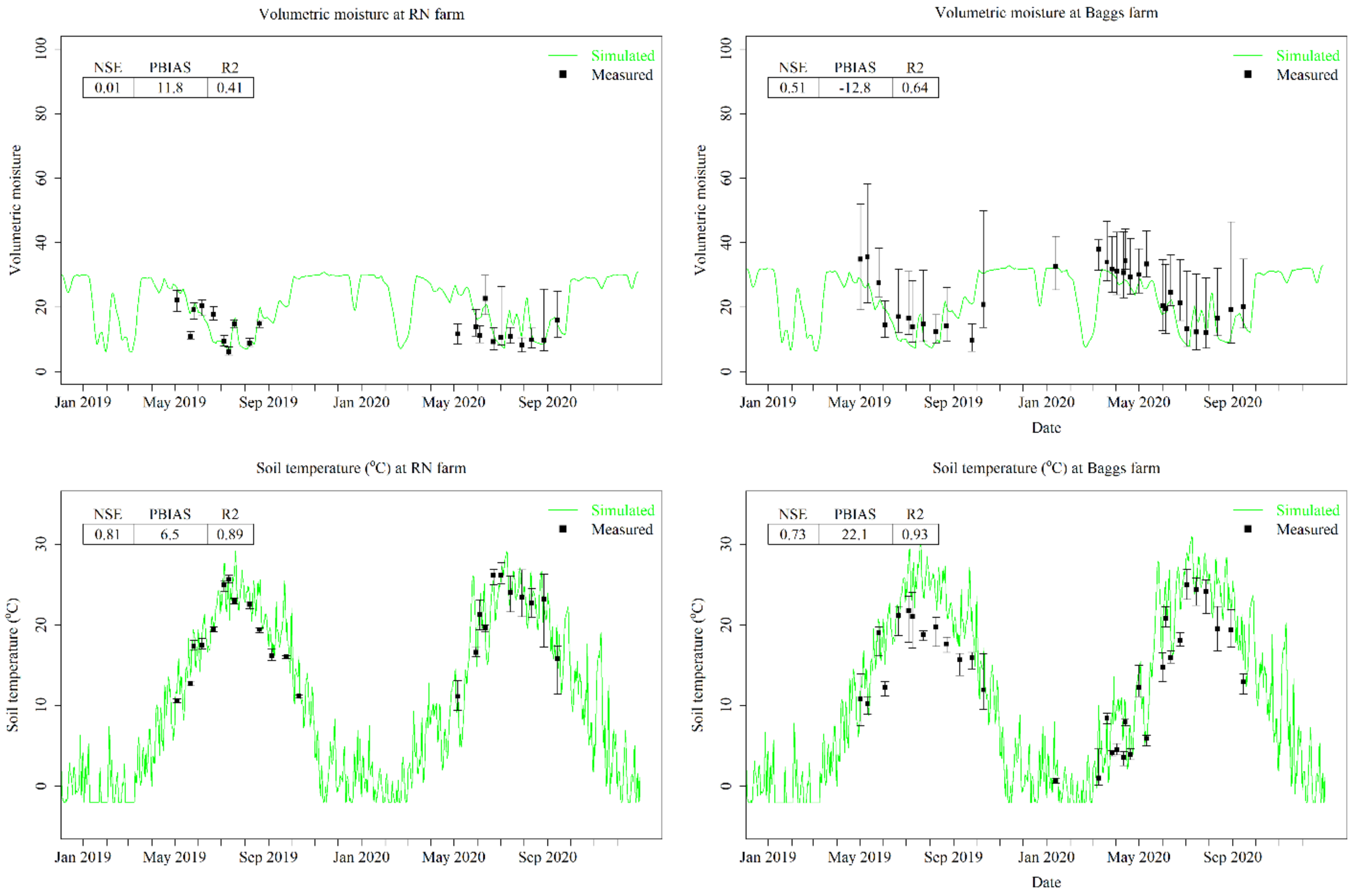
- Speed river basin, Ontario selected as a test watershed
- Distinct improvements in daily streamflow simulation and realistic soil temperatures at different depths compared to the original SWAT model
- Volumetric soil moisture, N_2O, Inorganic nitrogen and phosphorus calibrated at the outlet of watershed



Hydrology of Speed river basin (2007-2020)

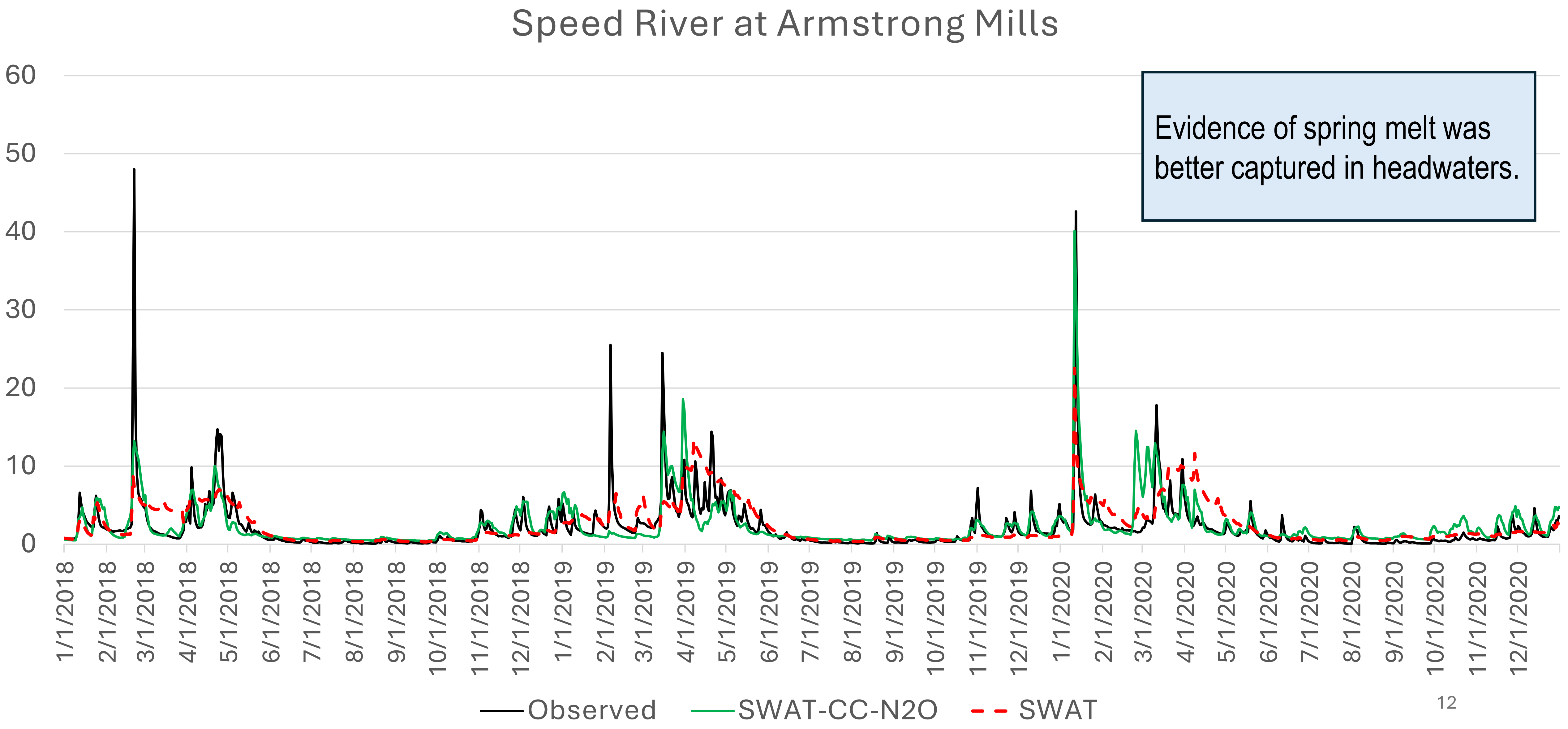


Soil moisture and temperature



In the two farms (red boxes in the location map) where discrete observed data was available for years 2019 and 2020, the soil moisture and temperature show encouraging results.

Flows

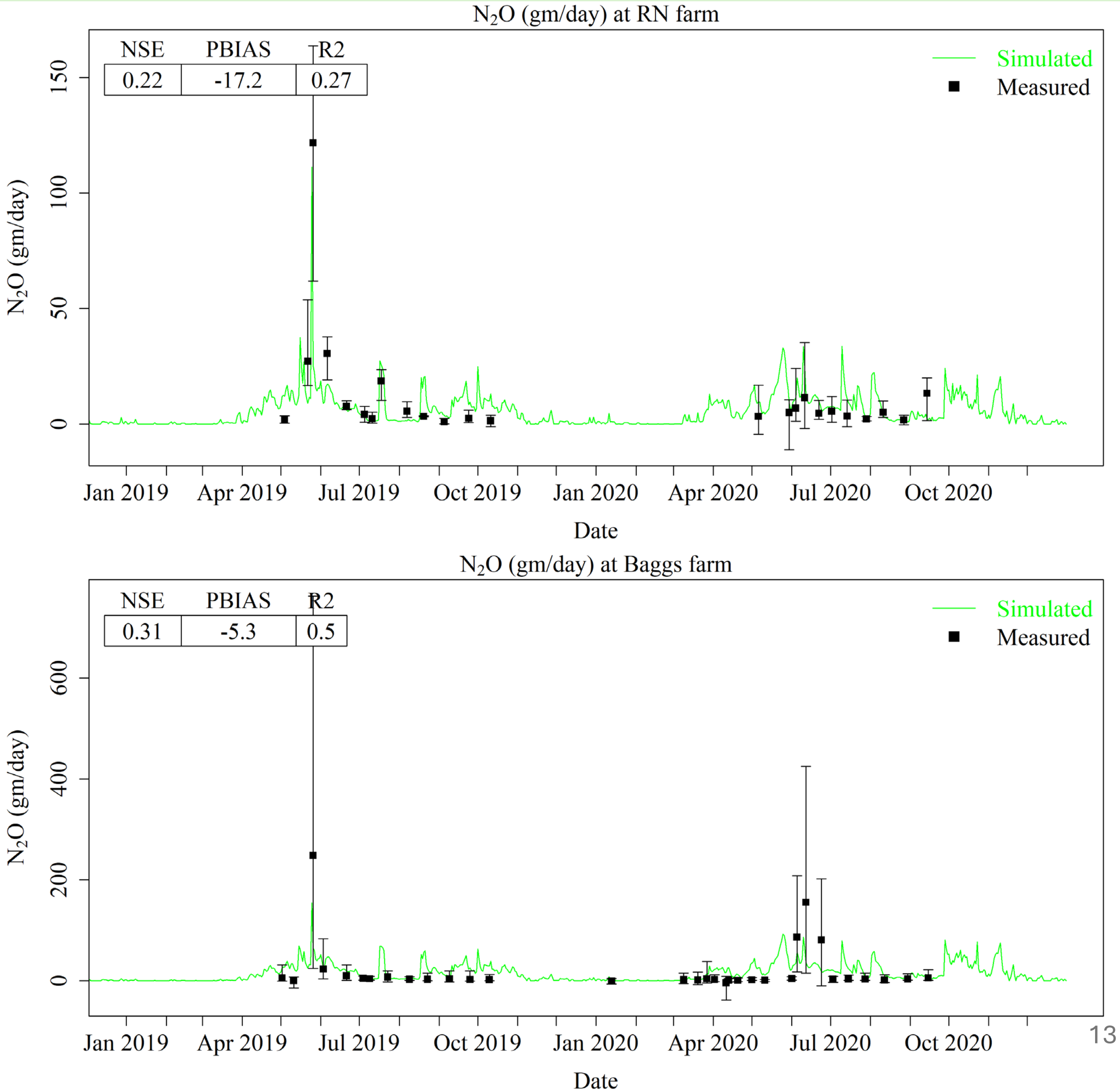


Evidence of spring melt was better captured in headwaters.

N_2O emissions

- Since we had only limited discrete data over the 2 years, we could not split it into calibration and validation periods

- The results are encouraging; however, they need more validation.



Further steps

- More rigorous testing with long term continuous N_2O measurements
- More case studies
- More variables pertaining to cold climate needs testing (for e.g. snow depths)

Thank you for your kind attention.

Special thanks to my advisory committee

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Prof. Claudia Wagner Riddle