An Assessment of Opportunities, Barriers, and Needs to Enabling Ensemble Watershed Modelling in the Canadian Great Lakes

Hosted by Toronto Metropolitan University (TMU), online via zoom: https://ryerson.zoom.us/j/92200527242?pwd=SFAyYjI1R2QxK25PVUxLd2RxRE5TZz09

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Overview

Background: There are commitments in place by national and state/provincial governments in the US and Canada to reduce the export of phosphorus to the Great Lakes, especially Lake Erie (Technical Team, 2015), by 40% of 2008 levels. Doing so requires reductions in nonpoint source nutrient export from all types of landscapes, including agricultural areas, which are estimated to be the main sources of nutrients into Lake Erie (Robertson and Saad, 2011). A number of sources argue that devising a strategy to do so, and likely evaluating whether these goals have been met, will require the use of process-based watershed models (Mohamed et al., 2019; Wellen et al., 2020). Further, Neumann et al. (2021) argue that it is imperative that we use an ensemble modelling approach, as to base important decisions on a single model poses the risk of being misled by idiosyncrasies. Indeed, as Martin et al. (2021) point out in a recent ensemble modelling paper focused on the Maumee basin, even different applications of a single modelling system (e.g., SWAT) can have very different predictions of the effects of the same 'stack' of management interventions.

Obligations under Transfer Payment Agreement (TPA) COA-GLS ID 1710 between TMU and the MECP: As per Section C.3.3: The Recipient (TMU) will organize and conduct a modelling workshop to bring together academic and government researchers in the Province of Ontario that are developing and running regional-scale water quality models for the purpose of assembling an ensemble of water quality models. The workshop will either be held virtually or at a central location with COVID-19 protective protocols in place, and will include discussions on standardized inputs, standardized scales and stations for calibration, and standardized outputs (e.g., what to report on). Recipient will summarize the findings and outcomes of the workshop and produce a publicly available report, through the Recipients website, which will include a set of recommendations for ensemble water quality modelling in Southern Ontario.

Objectives: Identify opportunities, barriers, and needs for supporting the development of an ensemble approach to watershed modelling in the Canadian drainage to the Laurentian Great Lakes. This workshop specifically examined the application of ensembles of watershed modelling to nutrient export from Canadian agricultural areas to the Great Lakes, though urban areas were also considered.

Format: A pre-workshop survey was sent out to assess past working experience with ensemble models, learn of barriers and opportunities perceived to be associated with an ensemble approach, and opinions on what is required to support this approach.

At the workshop, three keynote talks and nine lightning talks were presented by those whom have led watershed modelling projects in Southern Ontario in the morning. Breakout sessions in the afternoon focused on identifying opportunities, barriers, and required support for developing ensembles of watershed models in Southern Ontario. The workshop occurred virtually *via* Zoom. Breakout session topics included:

1. *Opportunities*: (e.g., should we use ensembles to test models in a semi-standard way, or come up with the best estimates of loads or future scenario results? Both? Other opportunities?);
2. *Barriers*: technical (e.g. difficulty in building many models to compare); institutional (e.g., hard to find enough seasoned modellers), cultural (difficult to share data); and;
3. *Needs*: What are the needed scales, both spatial and temporal (spatial [field - catchment - large basin] and temporal [event, season, year, decade, century]).

This report summarizes the findings of the workshop, and will be published on Wellen's research website and submitted to the MECP. This report has been commented upon by the attendees.

Survey questions and results

Workshop participants were well versed in watershed water quality modelling, with most having led the development of watershed model applications in the Canadian Great Lakes and/or the US side of the Great Lakes. Model application tended to focus on nutrients, while chloride was also addressed by some applications. Geographically, model applications included many small watersheds, while the Grand River, Thames/Sydenham Rivers, the Lake Erie basin (Canadian or Canadian plus US), and Credit River watershed were all listed as larger watersheds with existing model applications. The small and regional watersheds from the survey and from the lightning talks are listed in Table 3. The raw questions and responses are presented in Appendix 1.

The group pointed out many key examples of ensemble modelling that could serve as inspiration. Two of them (the GRIP-E/GRIP-GL and the Maumee ensemble work) had keynote talks focused on them so they will not be further mentioned here. Other examples from hydrology included work from the US forest sector (Vache et al., 2021) and hydrology in Australia (Viney et al., 2005). There were numerous examples of watershed model ensembles to draw important lessons from.

Subsequent questions addressed how feasible an ensemble modelling approach would be in Canada. Workshop participants were quite optimistic that it is feasible, with most participants agreeing with the statement *"Scientists are as well prepared to engage in ensemble modelling exercises about the Canadian drainage to the Great Lakes as the United States' drainage"* (7/11), and only 2/11 slightly disagreeing with the statement and the remainder voting neutral. The next questions asked about possible barriers to ensemble modelling in Canada. Some barriers did come up repeatedly (lack of funding for ensemble work, relatively weak winter hydrology representation, and the state of data availability for model development.) It was acknowledged that there were fewer 'model overlaps' in the Canadian side of the Great Lakes than the US side, where there is a significant focus on the Maumee basin.

Modellers were asked about their thoughts on important lessons after participating in a model ensemble project. They included the importance of time and communication between project participants (e.g., GRIP-GL took 4 years to ensure agreement between participants on various aspects of the modelling), the need for model expertise at multiple institutes, the need for more funding than for developing a single model, and the complicated nature of messaging the results (as synthesis between multiple models and communication of consensus despite some model disagreement is needed). There are also many decisions needed with respect to where/how to compare and evaluate models (e.g. do you calibrate and evaluate only on a mainstream, or on smaller subbasins as well)?

Finally, workshop participants were asked about the best first steps to developing an ensemble modelling practice in the Canadian side of the Great Lakes basin. Nearly all participants cited the need for a review and taking stock of some kind, including a review of ensemble modelling elsewhere, a review of watershed modelling that has been done in the Great Lakes specifically, and a review of which teams would ideally be part of an ensemble. The importance of forming a team or community of practice including modellers, stakeholders, and those who would use the results of an ensemble modelling practice were mentioned too. Finally, a pilot project was cited as a possible idea to work towards an ensemble modelling practice.

Workshop Schedule Overview

Table 1: Workshop schedule

Time	Event
9:20	Welcome
9:30 - 10:00	Jay Martin - "Ensemble Modeling of the Maumee Watershed: Methods, Results, Benefits, Challenges."
10:00 - 10:30	George Arhonditsis - "Towards the Development of Ensemble Modelling Frameworks to Support Adaptive Management: What did we Learn from Lake Erie?"
10:30 - 11:00	Julie Mai - "Great Lakes Runoff Intercomparison Project - Great Lakes"
11:00 - 12:00 pm	Lightning Round
12:00 - 1:00	LUNCH
1:00 - 2:00	Discussion 1 - Opportunities to Ensemble modelling in the Great Lakes plus report back
2:00 - 3:00	Discussion 2 - Barriers and Caveats to Ensemble Modelling in the Great Lakes, plus report back
3:00 - 4:00	Discussion 3 - Needed Supports and Best First Steps for Ensemble Modelling in the Great Lakes, plus report back
4:00 - 4:10	Wrap and thanks

Morning session List of Attendees: Jay Martin (Ohio State University), George Arhonditsis (University of Toronto), Nandita Basu (University of Waterloo), Ramesh Rudra (University of Guelph), Wanhong Yang (University of Guelph), Prasad Daguppadi (University of Guelph), Amanjot Singh (Credit Valley Conservation), Becca Meunich (Arizona State University), Tiequan Zhang (Agriculture and Agri-Food Canada), Yongbo Liu (Environment and Climate Change Canada), Christopher Wellen (Toronto Metropolitan University), Kevin McKague (Ontario Ministry of Agriculture, Food, and Rural Affairs), Isobel Heathcote (Wyndham Research), Pradeep Goel (Ontario Ministry of Environment, Conservation, and Parks), Janis Thomas (Ontario Ministry of Environment, Conservation, and Parks), Chris Parsons (Environment and Climate Change Canada), Anna Phillips (Toronto Metropolitan University), Laya Ahmadi (Toronto Metropolitan University).

Regrets: Julie Mai (University of Waterloo)

Keynote presentations

Keynote presentations are summarized here.

Jay Martin (Professor, Department of Food, Agricultural and Biological Engineering, Ohio State University)

Martin's talk focused on the ensemble modelling work that was led first by Don Scavia at the University of Michigan (Scavia et al., 2016) and then by Jay Martin at Ohio State University (Martin et al., 2019). Two reports are available, as are journal articles on the work (Scavia et al., 2017; Martin et al., 2021). The work was focused on how the Maumee can reach its targets of 40% reduction of March - July total phosphorus (TP) and dissolved reactive phosphorus (DRP) load without reducing agricultural productivity. The main organizations involved included the Ohio State University, the University of Michigan, Heidelberg University, LimnoTech, the University of Toledo, and the USDA ARS Blackland Research Center. The USGS also contributed, though their model (SPARROW) was able to only contribute a few scenarios.

The experiment consisted of an effort by those with established models of the Maumee basin to contribute to an ensemble. The ensemble selected certain external forcings to be identical (meteorology, physiography). But considerable effort was spent in deciding on exactly what would be the same and what would be different across model implementations. Calibration was done to the annual March - July TP and DRP load. This was selected as the Western Basin appears to respond to the load from that time period (Martin et al., 2021). There was less exploration of the load from the non-growing season, though scenario rankings of effectiveness were the same.

Martin stressed the importance of the advisory group. They met twice yearly during projects and still meet yearly. The advisory group was an important set of project advocates to various agencies that were interested in the outcomes of the projects. Scenarios were guided by stakeholder input and surveys, and the advisory group often served as a liaison between the research team and other stakeholder groups. The advisory group also helped to ensure the scenarios investigated took into account what was feasible.

Scenario analysis focused first on single practice scenarios and then proceeded to bundled scenarios. Single practice scenarios showed that reducing P fertilizer by 25% was one of the least effective scenarios, while more effective ones included subsurface applications. Work then proceeded to bundled scenarios, and their work identified scenario bundles that achieved the goals of 40% reduction of P inputs to the Western Basin. However, they noted that no scenarios achieved a 40% reduction of DRP, indicating more fundamental research was needed on the reduction of DRP losses. The papers were published in journals, and Martin highlighted that keeping in contact with the advisory group was needed in the future to ensure adaptability.

Take home messages were then for the management of Maumee water quality, many of which are likely of general use, included a finding that multiple pathways can bring the system to reduction targets. These pathways could be targeted to farmer preferences. However, widespread adoption of multiple BMPs would be needed on 50 % - 70% of fields. Targeting BMPs was far better than random placement. The role of the advisory group was critical. Finally, total phosphorus goals were more attainable than dissolved reactive phosphorus goals.

Martin then led into a series of benefits and challenges of an ensemble approach. Benefits included a better quantification of uncertainty, an opportunity to question model assumptions and methods, a way to identify modelling needs and improvements, and a better agreement of which scenarios and recommendations were most salient.

Key challenges included needing modelling expertise at multiple institutions. Coordination among modelling teams also proved to be a challenge, and required one central leadership team. This team does not make all the decisions, but leads the team to collectively make the decisions on things like, e.g., which kinds of data to use for certain things, what to standardize across the ensemble, and which kinds of options are to be allowed for different processes. Sometimes the central team actually runs all the models from the others, sometimes it just coordinates the analysis. Coordination also required significant resources. Funding requirements are often higher overall than for single model projects, as multiple models and multiple teams are needed. For the first Maumee project, USD$250,000 for six groups was needed and this did not involve development of new models, only integration of an existing ensemble. Communicating results is significantly more complex with an ensemble of models than with a single.

The spread of the predicted scenarios across the ensemble is something they talked about the most. They wanted to know why certain scenarios had such a spread, and related this to aspects of the models, but never quite got there.

A number of questions followed. It was asked which inputs were standardized and which were not, and Martin emphasized that all the forcings (meteorology and hydrology) and all the landscape data (topography, land use) were identical. Martin was also asked why he thought the 25% fertilizer reduction did not result in a commensurate reduction of stream phosphorus, and Martin indicated that he believed that legacy phosphorus played a role. Another question was asked about why there was so much variability in the results, if the inputs were standardized and the models were the same. Martin indicated that the team actually debated this at considerable length, probably more than any other issue. The team had wanted to explain which decisions in the modelling process led to which differences in the final scenario results, but were not able to.

George Arhonditsis (Professor, Ecological Modelling Lab, University of Toronto at Scarborough)

Arhonditsis presented an overview and synthesis of a number of recent publications from his group that advanced a framework for adaptive management of Lake Erie from the Canadian side. The framework was comprehensive, and included an examination of the role of lake water quality models; ecosystem service valuation, including crop yield productivity; and watershed modelling (Neumann et al., 2021). The lake, watershed, and ecosystem services frameworks were all envisioned to be making use of ensembles for reasons similar to those described by Martin (Scavia et al., 2017; Martin et al., 2021).

Arhonditsis then focused on the watershed model ensemble for the remainder of the talk. He mentioned that there were two main strategies that are possible for the coupling of watershed ensembles to other ensembles. A first approach is to take the outputs of each ensemble member and integrate them into a single ensemble prediction, which is then input into another model. Alternatively, each ensemble member's output can be used as input into another model. Both are viable strategies, though there are pros and cons with either strategy.

A framework was proposed involving various levels of watershed model detail. At the top level was a regional assessment that was largely accomplished by data driven models. The next level was the watershed scale planning stage. Finally, the most detailed assessment was a field level assessment. Data based approaches included concentration-discharge relationships, empirical models such as the widely used SPARROW model, and mass balances. Process based watershed models most prominently highlight the Soil-Water Assessment Tool, but a number of other watershed modelling packages were reviewed as well. Results indicated that of ten additional models, SWAT, HYPE, HSPF, and Ann-AGNPS would be the most appropriate for the watershed planning stage. These models were selected for recommendation due to their comprehensiveness of processes (including nutrient cycles and water cycles), representation of land use for scenario analysis, and diversity of process representations.

Important points for model calibration were made. Models are often unable to represent extreme events, though recent frameworks have been advanced to improve our ability to do so (e.g. Wellen et al., 2014; Dong et al., 2021). Model calibration should focus on both the loading and the concentration, as loading is driven significantly by flow.

The motivation for field scale modelling is that the effectiveness of beneficial management practices (BMPs) is characterized by significant site to site variability. A review of information from the Great Lakes area, supplemented by information from the Chesapeake Bay area in the United States (Arnillas et al., 2021), highlighted that the effectiveness of BMP variability was quite wide ranging, often included negative performances (instances where BMP implementation increased nutrient loads or concentrations), and the causes of this variability were not well documented. Arnillas et al. (2021) performed a causal path analysis, comparing a path analysis of BMPs of the real world, with a similar analysis of the causal pathways of the same BMPs in the model systems. Such analysis highlights areas the models ignore causal pathways or simplify them using empirical relationships.

Questions after the talk focused on the applicability of some of the data sources to the Canadian context. Arhonditsis recognized that there are some compelling research questions about the performance of BMPs in the non-growing season. This is because of the importance of the non-growing season to nutrient loading in the Great Lakes, and also because the extreme Canadian winters may result in different performances of BMPs in milder US conditions. However, Arhonditsis also emphasized that the data quality in Canada is sufficient to support an ensemble of watershed models.

Juliane Mai (Research Assistant Professor, Civil and Environmental Engineering, University of Waterloo)

Dr. Mai presented an overview of the Great Lakes model Intercomparison Project (GRIP-GL), the details of which are recently published (Mai et al., 2022). This overview describes the GRIP-GL project, an ensemble project for hydrological models set in the Great Lakes involving 13 models. Models included process based and data driven, as well as lumped and semi-distributed versions. Care was taken to standardize as much as possible to isolate the effect of the hydrological process representation.

The meteorology and geophysical data; streamflow; and the set of variables for model evaluation were identical for all models. All of the models (except one) also used the same routing component. While model calibration strategy (globally fixed or locally varying parameters) was allowed to vary, only one common parameter transfer approach was allowed where one was used. Temporal resolution also varied, and could be daily (8), 6h (1), hourly (1), or sub-hourly (3). Spatial resolution of the models varied between lumped, semi-distributed and gridded setups. Each model was however trained wwith the exact same set of calibration basins (141) and validated with the same set of validation basins (71). Model validation was conducted spatially (same time as calibration but different locations), temporally (same locations as calibration but different time period) and spatio-temporally (different time period and locations).

Results showed that the locally calibrated models (parameters varied across watersheds) had better fits than regionally calibrated models during the calibration phase. Model fit varied across calibration strategy (i.e., local, regional, or global) much more than it varied between models (i.e., lumped, semi-distributed, gridded). During temporal validation the locally calibrated models maintained their superiority. During the spatial validation experiment, the locally calibrated models tended to lose much (but not all) of their edge over the regionally calibrated models. During spatiotemporal validation, the performance of all the models degraded, though the locally calibrated models still had a small edge in performance over the regionally calibrated models. Dr. Mai highlighted that the data driven model (LSTM, a neural network) vastly outperformed all the other models during calibration and all validation experiments.

Model outputs were also compared with additional datasets not used for calibration auch as soil moisture, actual evapotranspiration, and snow water equivalent derived from remote sensing. Variables were aggregated to modelled watersheds, but model predictions were also disaggregated to data grid cells. When evaluation datasets were compared at the grid cell level, the fully distributed models performed the best. An overall validation examined how often a model was on the pareto front formed by all the members of the intercomparison project, across all of the simulated variables for which observations were available (streamflow, actual evapotranspiration, soil moisture, and snow water equivalent). Unsurprisingly, complex gridded models such as GEM-Hydro-Watroute performed the best. Surprisingly, the simple HYMOD2-lumped model performed the second best, followed by more complex models. This suggests that the value of complex models may become more apparent when a larger variety of outputs are analysed, but they still may not outperform more simple models by a wide margin.

Lightning Round Presentations

The lightning round consisted of 9 talks from 11 am to 12 pm designed to assess and review the modelling work that has already taken place around the Great Lakes' Canadian drainage. This serves as a 'lessons learned' document regarding the feasibility of an ensemble, as well as an inventory of possible model applications and expert collaborators to draw upon. While this document makes an attempt to summarize the talks of each member, the table below distills the specific lessons learned for ensemble modelling.

Table 2: Lightning round speakers

Speaker Number	**Speaker Name**	**Speaker Affiliation**
1	Nandita Basu	University of Waterloo
2	Ramesh Rudra	Guelph University
3	Wanhong Yang	Guelph University
4	Prasad Daguppadi	Guelph University
5	Amanjot Singh	Credit Valley Conservation
6	Becca Meunich	Arizona State University

7	Tiequan Zhang	Agriculture and Agri-Food Canada
8	Yongbo Liu	Environment and Climate Change Canada
9	Christopher Wellen	Toronto Metropolitan University

Table 3: Keynote and lightning round speakers and their geographical extents of existing model applications

Model application Basin	**Scale**	**PI(s)**	**Notes**
Lake Erie Basin	Whole	Basu, Daggupati,, Wellen, Mai	For Wellen, part of their application lies outside of this area. Also, only the Canadian drainage is included with Wellen's application. For Mai, there is no water quality component.
Thames River Basin	Headwater - Wigle, Jeanette, McGregor, Kettle Creek. Nissouri Creek, Big Creek	Daggupaddi - Wigle, Jeanette, McGregor, Kettle Creek. Wellen - Nissouri, Big	Many other headwater creeks with model applications already.
Thames River Basin	Whole	Basu, Daggupadi, Wellen, Meunich, Mai	For all, part of their application lies outside this area. For Mai, there is no

			water quality.
Credit River Basin	Whole	Singh	MIKE platform (SHE and Urban).
Grand River Basin	Whole	Basu, Daggupati, Wellen	Wellen's application is part of a larger model application. The resolution on the Grand is somewhat coarse.
Hamilton Harbour	Whole	Arhonditsis	Does not include the combined sewer area of Hamilton Harbour.

Table 4: Summary points of lightning round speakers

Speaker	**Lessons learned (specifically regarding ensembles)**
Basu	Some models (e.g. SWAT) do not do a good job with very long term (decades to centuries) applications. The legacy effect of past land uses can make changes in land management take a long time to show up in the stream. Basu's group has developed the model ELEMeNT to specifically examine long term dynamics (legacies and trajectories). Basu is applying ELEMeNT to the entire Lake Erie basin. Basu highlighted the importance of internal validation of a model's predictions by comparing model predictions to estimates of accumulated phosphorus sediment in reservoirs of the Grand River. Basu's group is developing a map of all the barns in Southern Ontario for use in manure management studies, has developed a mass balance of Lake Erie's basin.

Rudra	Rudra listed all of the models he has developed or worked with in the past. They include SWAT, GAMES, and others. Rudra highlighted that 75% of P loss happens during the winter. It is important for models to be able to deal with winter P loss effectively. Soil erodibility varies with season. Current work is focused on critical source area delineation as a way to target beneficial management practices (BMPs).
Yang	Yang shifted from modifying and using SWAT to developing IMWEBs, a grid based model that makes results available to users through the web. IMWEBs can integrate different kinds of information including economic and biodiversity information. Stressed the importance of collection of long term data to assess models with. Specifically, streamflow and land management data.
Daggupati	Daggupati's talk included an overview of his work using SWAT and AgNPS to delineate critical source areas in a number of headwater basins. Daggupati has also examined the co-benefits of BMPs, including the greenhouse gas and carbon dioxide benefits of BMPs. Daggupati is also working on improved model process for SWAT, particularly regarding legacy dynamics.
Singh	Singh presented his work with the Credit River watershed with the MIKE model. The MIKE model was selected because of the One Water approach the CVC is following. MIKE was the only platform that could integrate the sourcewater (lake and groundwater), surface, agriculture, and urban components of the watershed, along with the lake and various infrastructure components such as drinking and waste water treatment plants. Singhs work examines the impacts of nutrients as well as road salts and heat.

Meunich	Meunich presented work on watershed modelling in a variety of locations, including SWAT applications to the Maumee, Thames, and Sydenham. Meunich presented field scale applications from the US Great Lakes. Applications included pay for performance in River Raisin. Meunich presented some thoughts on using multiple models from her previous experience. Multiple models allow a better assessment of uncertainty. If using multiple models, do not attempt to pick a best model - the ensemble as a whole is better than the best model. Communication is the key to achieve results. However, communication is hard with a multi model framework. Differences between models must be communicated clearly. There is a tradeoff to consider between model applications that already exist, and those that are developed specifically for a multi-model framework. Budget is always limiting her first ensemble project was USD$100,000 in a year, just integrated existing models. Limiting work to those with existing models saved significant time and was a good first step. Meunich had thoughts on Southern Ontario specifically from her work developing SWAT models on both sides of the US-Canadian border. There are some data limitations she encountered. The winter data specifically were sparser than in the US. The Hydrology close to Lake Erie is unique - there is a very low slope and a lot of greenhouses by the lake. There are also large urban portions. Lake St. Clair plays an important role as an interface. Finally, there are significant loads coming from Lake Huron into Lake Erie, as well as significant uncertainty associated with those loads.

Zhang	Zhang has done a significant amount of work on hydrology and nutrient losses at the field scale. In addition to monitoring these empirically from the Harrow site, Zhang has worked to develop models for understanding nutrient dynamics at the Harrow field site. These models include EPIC, EPIC+SurPHOS, EPIC + RCM, IceCream, APEX, SWAT, RZWQM-P. Need new P subroutines for direct P loss from soil surfaces, especially of recently applied fertilizer and manure. Also important are preferential flow, connectivity of fields to water bodies, assess model uncertainty. These are important research needs an ensemble approach could help address, especially impact of the P cycle. Zhang also highlighted that an ensemble is a good opportunity to build interactions between different stakeholders, experimentalists, and modellers.
Liu	Liu talked about ECCC's new National Water Quality Modelling Framework. They plan to combine water quality models into ensembles. There are six priority watersheds, including the Sydenham, the Thames, the Grand, the Humber, the Rouge, the Duffins, and the Carruthers. Models already exist for these locations, they just need to be updated. They plan to update SWAT or Can-SWAT for these watersheds, and assess different scenarios with them. Liu also talked about some of the lessons he had learned in previous work about watershed modelling. These included the driving role of data availability; the importance of good snowmelt submodels; the importance of land management's effects, and the importance of hydraulic structures such as dams.

Wellen	Wellen presented his group's work on regional modelling, which had shown that calibrating a watershed model (HYPE) to stations monitored by the Provincial Water Quality Monitoring Network (PWQMN) produced a model solution that was nearly identical to that calibrated at the very intensively sampled Multi-Watershed Nutrient Study (MWNS) sites. This result, somewhat in contrast to that typically found when using statistical models, suggests that the water quality data available are more than sufficient to support process model calibration in Southern Ontario. Other work highlighted was the significant amount of descriptive data collected from the MWNS headwater research basins to support the development of models, including farmer surveys and soil surveys.

Afternoon Discussions Summary

Afternoon discussion session attendees included: Janis Thomas (Ontario Ministry of Environment, Conservation, and Parks), Tiequan Zhang (Agriculture and Agri-Food Canada), Prasad Daguppadi (University of Guelph), Ramesh Rudra (University of Guelph), Pradeep Goel (Ontario Ministry of Environment, Conservation, and Parks), Kevin McKague (Ontario Ministry of Agriculture, Food, and Rural Affairs), Isobel Heathcote (Wyndham Research), George Arhonditsis (University of Toronto), Christopher Wellen (Toronto Metropolitan University), Anna Phillips (Toronto Metropolitan University), Laya Ahmadi (Toronto Metropolitan University).

Discussion session 1: Opportunities for ensemble modelling in the Great Lakes

This session was framed in terms of applied opportunities, theoretical opportunities, and the best places to start.

Some of the discussion in this session focussed on potential spatial scales of ensemble modeling efforts. For example, ensemble modeling could begin in smaller watersheds rather than the whole Great Lakes basin. Smaller watersheds are often used as research basins due to feasibility considerations, and also due to the ability to isolate a small number of factors. There seemed to be agreement that this was a promising strategy in principle but that finding such a site may be challenging. Lake Erie as a whole, on the other hand, already has multiple watershed-water quality models existing, and more water quantity models that could potentially be augmented to become water quality models.

One suggestion for where to begin ensemble modeling was a small watershed in Essex because this would facilitate comparison to the Maumee study, the region is well studied at the field and plot scale through the AAFC's Harrow center, and at the catchment scale through initiatives such as AAFC's Living Labs, and the Province's Great Lakes Agricultural Stewardship Initiative (GLASI) project. However, it was pointed out that Essex is somewhat unusual for a number of reasons. It has greenhouses, which might present a challenge to model and are also not representative of the majority of agricultural land elsewhere in the Province. It is also extremely flat, drained by powered pumps, and has cracking clays (vertisols), which have significant preferential flow. Vertisolic preferential flow is difficult to model at scale but also not representative of the rest of the Province’s agricultural areas. The group tended to agree that despite the major field scale resources available for modelling in the Essex region, the region’s idiosyncrasies (low slope, pumping ponds), lack of understanding of their hydrological functioning, and relative data paucity at the watershed scale make it a difficult place to undertake headwater catchment scale modelling. These idiosyncrasies may also make it difficult to generalize the results from Essex to other parts of the Canadian Great Lakes drainage basin.

Another small watershed that was mentioned was Gully Creek on the eastern shore of Lake Huron, as there is a large amount of data available there. Other possible sites of research headwater catchment status include the Multi-Watershed Nutrient Study sites (Rosamond et al., 2018; Biagi et al., 2022). While the idea of focusing on small research catchment areas for ensemble modelling work is promising, finding an appropriate place may prove challenging.

A contrasting approach to focusing on a small number of headwater catchments is to begin with a large catchment. A number of model applications already exist for large watersheds in the Canadian drainage to the Great Lakes, including the Thames River, the Grand River, and others. Several workshop participants (Wellen, Basu, and Daggupaddi) all have watershed models of the Lake Erie basin already, making a Lake Erie application an opportunity with existing models.

It may be possible to integrate a pilot study within the 2024 Lake Erie Cooperative Science and Monitoring Initiative (CSMI). While the CSMI tends to focus on lake issues, it could tie in with modelling efforts. Such efforts could be at the scale of the whole basin or a subwatershed. At the scale of the entire basin of Lake Erie, multiple water quality models already exist, and more hydrology only models that could be augmented with water quality capabilities also exist. A specific vehicle to enable work within the CSMI is an Alliance grant from the Natural Science and Engineering Research Council of Canada (NSERC), focused on Lake Erie. The Alliance grant could focus on the theoretical portion and the provincial governments could propose a more applied portion in tandem. It was noted that in-hand funds can be used for matching, but the money needs to be in hand when the project begins.

Several scientific opportunities were discussed in this session including the following: (1) It was mentioned how multiple lines of evidence coming together is valuable from a government perspective, so an ensemble approach is likely to enhance the quality of government decisions; (2) An ensemble modeling project would serve as a guide for modelling work generally, improving and enhancing work using single models; (3) Ensemble work is an opportunity to investigate differences in models and establish why even similar models may give a different result, even when the model codes and forcing data may be the same; (4) The potential opportunity to examine specific uncertainties in the models such as sorption dynamics, phosphorus pools, and distinguishing between incidental and legacy losses from phosphorus pools; and (5) Testing different ways of incorporating field scale monitoring such as the ONFarm program, Lonesborough sites, farmer surveys, and soil test phosphorus estimates.

Interest was also expressed about how the results of model scenarios are to be used by management and policy. This was especially relevant considering the level of uncertainty of some of the scenarios.

Discussion session 2: Barriers and caveats to ensemble modelling in the Great Lakes

Several barriers and challenges to ensemble modelling in the Great Lakes' Canadian basin were discussed in this session. These included financial, logistic, and scientific considerations.

Financial considerations included that procuring funding might be challenging, as more funding would be required than for one modelling team. It was also pointed out that funds are easier to acquire for developing models rather than for integrating them. Opportunities for leveraging existing funds include NSERC Alliance grants. The Maumee ensemble work required USD $250,000 for the first project and presumably a similar amount of funds for the second project, and this was without new model development.

A major challenge discussed was the coordination of a project of this scope. Modelling expertise would be needed at multiple institutions and coordination between these teams would be extremely important, but would also be demanding and require significant resources. It was also pointed out that modeling takes time and all models are developed for different reasons, so time would need to be spent getting to know all participating models and their purpose. The Maumee work discussed by Martin took around 15 people at 6 institutions. It may be hard to find 15 qualified model developers.

Scientific challenges included the importance of determining what inputs and routines would be the same and what would be different between the models. Data availability was also discussed, in particular for winter and spring data. It was pointed out that soil temperature data is not widely available. However, Tiequan Zhang noted that he has a comprehensive dataset with soil temperature and other important factors in the field that could help with some of the lack of data. Challenges with spatial data were also discussed, particularly regarding how the spatial data can be standardized into model inputs in a variety of ways.

Other discussion points in this session included the fact that fundamental research is needed to improve representation of winter/spring conditions in models. And, it is important to consider the complexity of the landscape and hydrological conditions of the region as well as the intensive human activity such as urban, agriculture, livestock, and land management. It was also pointed out how more interactions between modelers and experimentalists are necessary to improve modeling efforts.

Finally, it must be pointed out that this session ended on a very positive note. While there are difficulties to overcome, they are ones fairly common to watershed modelling in general. The supporting data available in Canada are not drastically different than those in the US. Indeed, Julie Mai's keynote talk demonstrated that it is possible to build models with respectable performance criteria using the existing data sources in Canada and the US. Most of the difficulties pointed out in this session were also faced by the Maumee team, and they were overcome there. Participants tended to agree that there is more than enough to support a project.

Discussion session 3: Needed supports and best first steps for ensemble modelling in the Great Lakes

The needed support and best first steps for ensemble modeling were also touched upon by participants in the previous two sessions, so this session was left quite short. Discussion in this session focused on a few key first steps that ought to be taken, including a pilot ensemble project; detailed review of the existing model applications and data sources in the Ontario portion of the drainage to the Great Lakes; and the need to learn from existing ensemble projects such as the Maumee work and the GRIP projects.

The Maumee and GRIP projects did highlight the importance of establishing which aspects of the model would vary between ensemble members, and which should be identical. The biogeophysical data and meteorology should be identical, while it may also be desirable to standardize various aspects of the model structure.

Conclusions and Recommendations

The workshop was an important step in establishing a watershed modelling ensemble community of practice on the Canadian side of the Laurentian Great Lakes. This report describes the experiences of other ensemble modelling projects in the Maumee basin and the Great Lakes basin, while outlining some of their lessons learned. The report also outlines conceptual frameworks proposed by Arhonditsis's group for watershed ensemble integration. Finally, the report also highlighted the large number of existing water quality model applications in the Canadian drainage of the lower great lakes, particularly Lake Erie.

Overall, workshop participants were quite optimistic about the feasibility of ensemble modelling. Existing data sources are adequate to the task. Participants were confident that the overall level of preparation in Canada is roughly comparable to that of the United States regarding ensemble water quality modelling. An ensemble of hydrological models (but not water quality models) has already been developed by a team of collaborators led by Juliane Mai (Mai et al. 2021; Mai et al., 2022). It was noted that there already exist several regional scale water quality model applications on the Canadian side of Lake Erie's basin developed by Becca Meunich, Nandita Basu, Prasad Daggupadi, and Christopher Wellen, as well as a host of finer scale headwater models, though it was not clear whether an opportunity existed to integrate those.

It was also highlighted that establishing a community of practice regarding ensemble modelling is critical. Best practices include having significant discussion beforehand regarding what is to be standardized, and what is left up to the individual modellers, and having a specific team in a consortium be the 'lead team' that organizes the others. Communication between all modelling teams, and between modellers and a group of engaged stakeholders, is also critical. Finally, the importance of taking a long term view in the model scenario analysis was highlighted by different workshop attendees, as models may work differently when trying to address long term dynamics than short term dynamics.

A number of recommendations arose from the workshop. These included the need for an in-depth review of existing model applications and data sources. While significant review of existing data sources that are broadly available has been done already, this recommendation is particularly salient for smaller, intensively studied catchments where significantly augmented data sources on, e.g. land management or soil nutrient levels may already exist, and where detailed model applications may already exist. While specific examples were outlined in the workshop (e.g. Gully Creek, the Multi-Watershed Nutrient Study catchments), it is possible that others exist or that an in-depth review of those headwater research sites may yield some valuable data sources. As we discuss below, there was interest in an ensemble modelling pilot project for a small, intensively studied creek, but no agreement on where existing model applications, data sources, and generalizability aligned. Such a review may point to one such opportunity.

There was also a recommendation for a pilot project that integrated model applications already available at one of the larger sites. The candidates for such a site are listed in Table 3, but the main candidates to emerge are the entire Canadian Lake Erie basin or one of its largest tributaries (e.g. the Thames or the Grand). Either the Thames or the Grand are desirable because they are large but manageable from a research perspective, have a number of well studied headwater sites to augment end of basin information, and have a number of key infrastructure features that are hydrologically interesting but typical of the larger province (e.g. large managed reservoirs). Further, the Lake Erie Collaborative Science and Monitoring Initiative (CSMI) is coming up in 2024. Ensemble work on one of Erie's major tributaries, or the entire lake, could be boosted by the CSMI focus on the Lake. The Natural Sciences and Engineering Research Council of Canada (NSERC)'s Alliance grant funding program would be a viable vehicle to fund such an effort. Such a pilot initiative is designated as highly desirable by the workshop, as it would galvanize the community and build institutional capacity for ensemble modelling. The Maumee case showed that building institutional capacity for ensemble modelling takes time.

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Appendix: Data from Pre-Workshop Survey

1. **If you or your team have developed watershed models in the Great Lakes basin, which subwatersheds have you developed models for?**

Grand River watershed, Canagagigue Creek watershed, Fairchild Creek watershed, Upper Medway Creek watershed, McGregor Creek watershed, Big Creek watershed, Big Otter Creek watershed, Catfish Creek watershed, Kettle Creek watershed, Gully Creek watershed, Garvey Glenn watershed

1 response

Have never "developed models - just applied existing models to small "within field" watersheds located in the Maitland and Ausable basins. - although I had to get the model developers at the time to enhance their tile drainage routine for my application

1 response

Hamilton Harbour's basin Nissouri Creek Big Creek (essex) Southern Ontario Regional Etobicoke Creek

1 response

212 basins within the Great Lakes watershed (https://hydrohub.org/mips_introduction.html#grip-gl)

1 response

Detroit River Corridor, Maumee River, River Raisin, Huron river

1 response

Maumee watershed (US-Ohio, Indiana, Michigan)

1 response

Grand, Thames, Sydenham

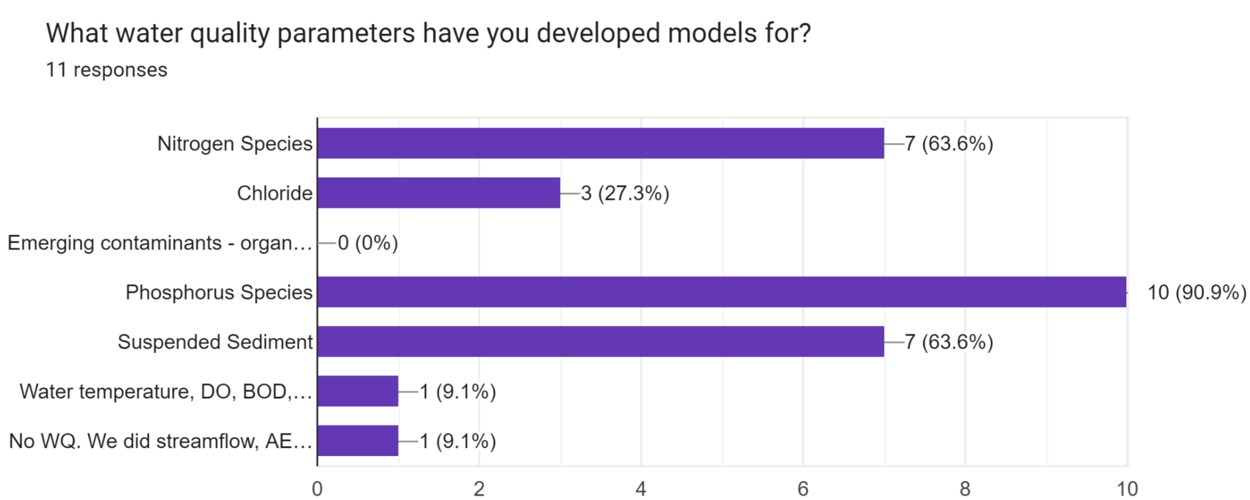
1 response

Credit River watershed

1 response

Lake Erie

2. What water quality parameters have you developed models for?



3. Can you think of a 'model example' of an ensemble modelling approach that could be looked to by the group? If so can you include a reference?

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1 response

Zhaozhi Wang, T. Q. Zhang,* C. S. Tan, X. Wang, R. A. J. Taylor, Z. M. Qi, and J. W. Yang, Modeling the Impacts of Manure on Phosphorus Loss in Surface Runoff and Subsurface Drainage J. Environ. Qual. 48:39–46 (2019)

1 response

Martin et al., 2021. Evaluating management options to reduce Lake Erie algal blooms using an ensemble of watershed models. Journal of Environmental Management.

1 response

Thames River watershed. ECCC conducted SWAT modelling for the Thames River watershed previously.

1 response

Maumee River ensemble model; many publications on this, but started with DOI: 10.1002/fee.1472

1 response

GRIP-GL (https://hess.copernicus.org/articles/26/3537/2022/)

1 response

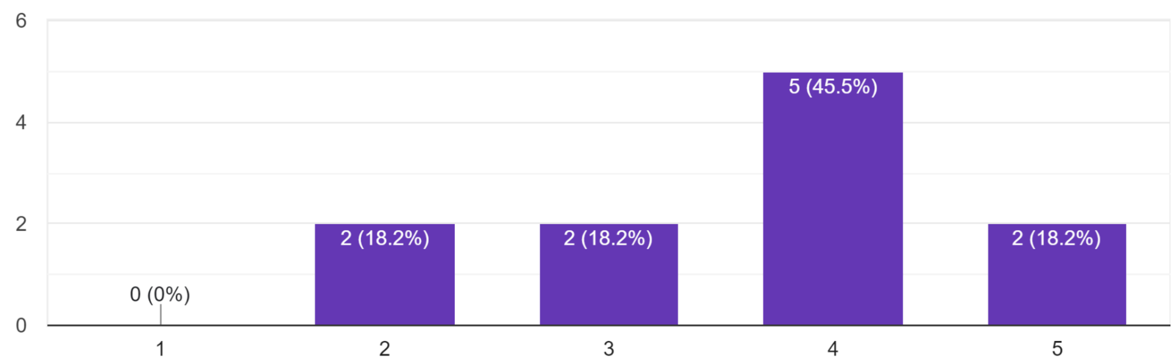
Martin et al. 2021 Maumee paper.

1 response

4. **Please rate your agreement with the following statement: Scientists are as well prepared to engage in ensemble modelling exercises about the Canadian drainage to the Great Lakes as the United States' drainage.**

Please rate your agreement with the following statement: Scientists are as well prepared to engage in ensemble modelling exercises about the Canadia...o the Great Lakes as the United States' drainage.

11 responses



5. If we are not as well prepared for ensemble modelling in Canada as we are for the United States, what do you think are the main reasons?

Biggest problem - few models out there that adequately handle winter hydrology , little data out

htere to validate sinter (year round0 hydrologic conditions and models (both US and Canada0 are

weak in representing tile drainage (pore flow modelling)

1 response

1. Lack of models that are suitable for water quality simulation under cold climate conditions in the region. 2. Lack of long-term field monitoring data for specific BMPs. 3. Lack of experienced model developers.

1 response

Spatial data are a mess - no standardization. We have nothing like the HUC system, so it is hard to compare model subwatersheds or land cover classes. Funding - no money to integrate models, just to develop them.

1 response

I'm just not as aware of what models already exist in Canada, but I believe there is already a lot of work.

1 response

Need strong coordination and sufficient funding

1 response

Not well aware of Canadian status.

1 response

Data availability

1 response

Resources

6. If you have participated in an ensemble modelling effort, what are some important lessons for how to do so successfully? If you have not participated in an ensemble modelling effort, please leave this blank.

Modeling expertise needed at multiple institutions Coordination among modeling teams essential and demanding Determine same/different inputs and routines for models Funding greater than needed for one modeling team More complicated messaging of results

1 response

1. Understanding of field physical processes. 2. Focus more on reasonability of spatial patterns but not only calibration at mainstream stations. 3. Input data consistency and reliability.

1 response

strong consideration on what should be the same and what should be allowed to be different. Need good communication with users on why there is this need.

1 response

Communication and community building as well as enough time to make decisions everyone agrees on (took more than 4 years for GRIP-GL)

1 response

Reach out to the experimental scientists and use the data available as much as possible.

1 response

NA

7. What are some of the main barriers to developing an ensemble of watershed models in the Canadian Great Lakes?

Spatial data are a mess - no standardization. We have nothing like the HUC system, so it is hard to compare model subwatersheds or land cover classes. Funding - no money to integrate models, just to develop them. Hard to get groups working together. Coordination takes time and money. Not lots of models already developed - need to work from scratch.

1 response

1. Complexity of landscape and hydrological systems. 2. Intensive human activities - urban, agriculture, livestock. 3. Extensive land management practices. 4. An effective system design to meet project objectives while accounting for major influencing factors.

1 response

Modeling expertise needed at multiple institutions Coordination among modeling teams essential and demanding Determine same/different inputs and routines for models Funding greater than needed for one modeling team

1 response

Modeling takes time and all models are developed for different reasons so need to spend time getting to know all the models and their purpose

1 response

Interactions between modelers and experimentalists; shortage of incorporation of new data that are currently available into modelling.

1 response

Limited communications between various modelling initiatives, limited coordination and funding for modelling initiatives

1 response

Data, time, funding

1 response

Resources

8. In your mind, are there any limitations or caveats with an ensemble approach?

Potnetially many of these models have the same origins or base algorithms, so likely still not independent of each other intheir methodology. For example, many rely on the USLE to estimate erosion and sediment loss. Such models will always say that p losses from upland (more erosive landscapes) are higher, yet our field observations would suggest the delivery of P from lowlands is greater even though flat slopes give low USLE soil loss values.

1 response

1. Cannot be too complicated. 2. Be able to assess future land management and climate change scenarios. 3. Keep an efficient workflow and data flow within the system. 4. Data availability.

1 response

If not same approaches and data are used to setup models, it may limit the conclusions that can be drawn (see problems of drawing conclusions in Nelson MiP and GRIP-E)

1 response

Limits number of individual scenarios that can be analyze, in favor of multiple runs of same scenarios. More complicated messaging of results

1 response

You can integrate some of the extremes away - no peaks. This is unrealistic and may change how downstream systems respond.

1 response

Set reasonable expectations for an ensemble approach and potential applications for policy and management

1 response

They are as limited as the models themselves

1 response

to do it incorrectly

1 response

No

9. If you have an idea about what the best first step is to develop an ensemble modelling practice in Canada's Great Lakes basins, what is it?

Determine existing modeling expertise, and see if there is interest in expanding, and interest in working together to pursue ensemble effort. In my experience, there must be one team that will serve as leader of effort. Funding for such an effort is also critical, as is support of advisory group.

1 response

Identify all potential models that have been developed or are in development. Should include metadata like who created them, for what purpose, when, using what model tool and version, what and when was it calibrated for

1 response

Pilot study in a small, well studied system. Review of existing models to see if existing model integrations can be attempted.

1 response

Compare the origins of the algorithms in each model you want to include in the ensemble. Do they have the same roots?

1 response

Identify a representative watershed with strong partnership interests (with funding investigation)

1 response

1. Review of existing ensemble modeling systems, and 2. Feasibility study and framework design.

1 response

Form a team consisting of modelers, experimental scientists, and stakeholders

1 response

Engage contributors and be up front how much time and effort this will take

1 response

get the inputs consistent