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A hydrological prediction system based on the SVS land-surface scheme: efficient calibration of GEM-Hydro for streamflow simulation over the Lake Ontario basin

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Supplementary material: List of acronyms

AHPS	Advanced Hydrologic Prediction System
CLASS	Canadian LAnd Surface Scheme
CaPA	Canadian Precipitation Analysis
DEM	Digital Elevation Model
DDS	Dynamically Dimensioned Search
ECCC	Environment and Climate Change Canada
GLM-HMD	GLERL Monthly Hydrometeorological Database
GEM	Global Environmental Multi-scale
GHCND	Global Historical Climatology Network - Daily
GSDE	Global Soil Dataset for Earth system modeling
GLERL	Great Lakes Environmental Research Laboratory
GRIP-O	Great Lakes Runoff Inter-comparison Project for Lake Ontario
GRUs	grouped response units
ISBA	Interaction Sol-Biosphère-Atmosphère
IJC	International Joint Commission
LSS	Land-Surface Scheme
LBRM	Large Basin Runoff Model
LLTM	Large Lake Thermodynamics lumped Model
LZS	Lower Zone Storage
GR4J	modèle du Génie Rural à 4 paramètres Journalier
MESH	Modélisation Environnementale – Surface and Hydrology
NSE	Nash-Sutcliffe Efficiency criteria
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NBS	Net Basin Supplies
NWP	Numerical Weather Prediction
OF	Objective Function
PBIAS	Percent Bias
RDPS	Regional Deterministic Prediction System
SNODAS	SNow Data Assimilation System
SWE	Snow Water Equivalent
SVS	Soil, Vegetation and Snow
UH	Unit Hydrograph
USACE	US Army Corps of Engineers

WCPS-GLS water cycle prediction system for the Great Lakes and St. Lawrence River

Supplementary material: intercomparison of MESH, WATFLOOD, and GEM-Hydro-UH

1 Models

Three different platforms are compared in this study: MESH, WATFLOOD, and GEM-Hydro. They have in common a distributed representation of most hydrological processes occurring in a basin and a structure organized around two main components: a LSS for the representation of surface processes (evapotranspiration, infiltration, snow processes, water circulation in the soils), and a river routing scheme for simulating water transport in the streams, which consists of WATROUTE for all models. WATROUTE is a 1-D hydraulic model relying mainly on flow directions and elevation data (Kouwen 2010). It routes to the basin outlet the surface runoff and recharge produced by the surface schemes. In WATROUTE, runoff directly feeds the streams while recharge can be provided to an optional Lower Zone Storage (LZS) compartment, representing superficial aquifers, which releases water to the streams. WATFLOOD and GEM-Hydro make use of the LZS, whereas recharge from MESH feeds directly into the stream.

The version of MESH used in this study relies on version 3.6 of the Canadian LAnd Surface Scheme (CLASS). Each grid cell is subdivided in a number of tiles, and each tile is classified as belonging to one of the five grouped response units (GRUs), based on its land-use/soil type combination. In this paper, we follow the local calibration strategy advocated by Haghnegahdar et al. (2014) for MESH (see section on calibration strategy).

GEM-Hydro is very similar to MESH, but is tied to the LSSs available in GEM: ISBA and SVS. A previous study on the same basin demonstrated the clear superiority of SVS over ISBA, especially in regard to the baseflow component of the streamflow (see Gaborit et al., 2016 b). We thus only use SVS with GEM-Hydro in this paper.

WATFLOOD (Kouwen, 2010) is a distributed model of intermediate complexity that only needs precipitation and temperature as forcing, as opposed to MESH and GEM-Hydro which need additional atmospheric variables (Table 1). It relies on the GRUs concept and on many empirical equations. WATFLOOD has been employed by Pietroniro et al. (2007) over the Great Lakes basin.

In this project, WATFLOOD and MESH are implemented with a 10 arcmin (≈ 20 km) spatial resolution (both for their LSS and routing schemes), while GEM-Hydro is implemented with a 10 arcmin resolution for the LSS and 0.5 arcmin (≈ 1 km) for the routing. Sensitivity tests (Gaborit et al., 2016 b) revealed that 2 and 10 arcmin resolutions for SVS lead to quite similar performance in terms of streamflow at the outlet, while a substantial amount of computation time is saved when running the coarser resolution (almost proportionally if using the same number of nodes). The same was shown for WATROUTE which produces outputs of similar quality be it implemented at a low (10 arcmin for MESH and WATFLOOD) or high (0.5 arcmin with GEM-Hydro) resolution, as long as results are evaluated for large enough catchments (i.e., catchments which spread over at least a few grid cells). However, the high-resolution WATROUTE version is preferred in GEM-Hydro for consistency with the WCPS-GLS (Durnford et al., in Press) recently developed at ECCC. Hence, the higher resolution GEM-Hydro's routing scheme is not expected to give GEM-Hydro any advantage in comparison to MESH and WATFLOOD.

The internal time-step used for GEM-Hydro is 10 minutes, which slightly improves streamflow simulations in comparison to a 30 min. time-step (see Gaborit et al., 2016 b). Further reducing it does not improve the results. The internal time-steps used for MESH and WATFLOOD are respectively equal to 30 and 60 minutes. The internal time-step of a model is generally maximized up to the desired output interval, provided that it satisfies numerical stability. In the GEM-Hydro version used in this study, a 10-min. time-step was required to achieve numerical stability, but a newer version now allows to increase it. Table 1 summarizes the main specificities of the models and the required forcing data. Table 2 shows the datasets used for physiographic information.

The physiographic data required by the distributed models under study consist of soil texture, land use / land cover, Digital Elevation Model (DEM), and flow direction grids. Table 2 lists the datasets used to provide the physiographic and atmospheric inputs required by the models. 26 land cover classes are defined in GEM-Hydro, while WATFLOOD and MESH rely only on 7 of them, which are aggregations of GEM-Hydro classes. Soil textures are from the Global Soil Dataset for Earth system modeling (GSDE; Shangguan et al., 2014), which contains information down to 2.8 m. However, soil texture is calibrated for MESH (Table 5). Soil texture was not calibrated for GEM-Hydro-UH, but some hydraulic parameters, which are derived from soil texture, were calibrated (Table 3). WATFLOOD does not need soil texture information. By default, the maximum soil depth was set to 1.4 m in GEM-Hydro (for the area under study), 4.1 m in MESH, and is not defined in WATFLOOD. The maximum soil depth is calibrated in GEM-Hydro and MESH (Table 3 to Table 5). The parameter ranges of Tables 3-5 were generally chosen as wide as possible while remaining physically realistic, in order to let more freedom to the optimization algorithm, which may a priori increase the chances of finding optimal parameter sets during calibration.

2 Calibration strategy

Different paradigms were used to calibrate the models. GEM-Hydro-UH was calibrated using multiplicative coefficients that adjust the spatially-varying values of a given parameter, leading to a reasonable number of free parameters (16) while preserving spatial variability (Table 3). MESH was implemented calibrating the 12 free parameters of its 5 different GRUs in an independent manner, thus resulting in 60 free parameters (Table 5). WATFLOOD had the lowest number of free parameters during calibration, and involved calibrating parameter values which are valid for the entire subbasin (no spatial variability) or for one of the three main land cover types considered inside the model, i.e. bare ground, snow covered ground, or other grounds (Table 4).

It is important to emphasize that the approach used to calibrate GEM-Hydro may result in unrealistic values for some parameters, as the multiplicative coefficients could bring the associated parameter values beyond the range of physical coherence. More precisely, soil water content thresholds and albedo (Table 3) cannot be higher than 1. Therefore, these values were constrained to realistic ranges after they were adjusted by the calibration algorithm by imposing them a minimum value of 0 and a maximum of 1.

The initial parameter values were either set to default ones that generally provide satisfactory results for the model (GEM-Hydro-UH, Table 3) or to random values (WATFLOOD, MESH). The number of maximum model runs allowed depends on the model being used. For example, 400 runs revealed sufficient for GEM-Hydro-UH (Sect. 2.2) in the sense that no significant performance improvement was achieved beyond. This is because the number of GEM-Hydro-UH free parameters is relatively low (16, Table 3). The DDS algorithm is very efficient in the sense that it adjusts the search behavior to the maximum number of objective function evaluations (model runs) in order to converge to good quality solutions (Tolson and Shoemaker, 2007). The similarity of the performances obtained with GR4J and GEM-Hydro-UH (Fig. 3 in main document) supports the choice of the methodology used here, as GR4J was implemented with a maximum of 2000 model runs, three distinct calibration trials, and had an even lower number of free parameters (6, see Gaborit et al., 2016 a).

A maximum of 1000 model runs was used to calibrate MESH and of 1500 for WATFLOOD. Finally, the calibration strategy used for MESH consists of an improved and reliable strategy based on the work of Haghnegahdar et al. (2014). Despite the random initial values used for MESH and WATFLOOD, only one calibration trial was performed for each of the models on a given subbasin. Even though the three models studied here were not calibrated using the same number of free parameters and the same maximum allowed model runs, it is assumed that the calibration strategies employed allow each model to come very close to its optimal performance for a given subbasin and the time period considered. Indeed, the strategy used for each of the three models is the result of expert knowledge and always involves parameters affecting the whole range of the main hydrological processes, i.e. evaporation, snowmelt, infiltration, soil transfer, and time to peak (channel friction). It is thus logical to use different strategies for each of the models as these do not involve the same parameters, land use classification, or even physical processes. The most important methodological consistencies for achieving a fair comparison between models include, in our view, a common calibration algorithm and objective function, along with common physiographic and forcing data.

3 Results

This section aims at comparing MESH, WATFLOOD, and GEM-Hydro-UH performance values. The calibration strategy used for each of them is described in Sect. 1.3 of the main document. Note that MESH was only calibrated on the Moira and Black Rivers, and WATFLOOD on the Moira, Black, and Salmon Rivers. Calibration and validation performances are presented in Fig. 1 and calibrated hydrographs, in Fig. 2.

It was deemed uninformative to present the calibrated parameter values since they are highly location dependant and subject to the equifinality issue (see section 2.1 of the main manuscript). Table 4 of the main document however highlights the final parameter ranges for GEM-Hydro-UH. Overall, GEM-Hydro-UH outperforms MESH and WATFLOOD, both in calibration and validation (Fig. 1). The robustness of the models is generally quite good, but less so for MESH on the Black River (subbasin 7 in Fig. 1).

When looking closely at the Moira River hydrographs (Fig. 2), important differences arise between the models. For instance, WATFLOOD has a more flashy behavior and tends to overestimate peak flow events, MESH generally underestimates flows, and GEM-Hydro-UH lays somewhere in between. Peak flow events (even for other subbasins) associated to the spring freshet are generally better represented by MESH, which may be due to a better representation by

CLASS of various cold regions hydrological processes, such as snow accumulation and melt, snow interception by vegetation, as well as soil freezing and thawing.

It is possible that the differences in model performance may be explained by the different calibration strategies used for each model, and that better performances could be obtained with MESH and WATFLOOD for these watersheds, although the calibration details were in each case determined by an expert user of each model. The optimal calibration strategy, as well as the number of free parameters, could be revisited for each model in order to see if this explains the above differences, but this is quite beyond the scope of the paper.

Even if the intercomparison is obviously limited in the number of available test cases, it allows highlighting the mandatory need of calibrating hydrologic models, that models have unique behaviors that translate in substantial differences in hydrographs, and that each of the models could benefit from some strengths of its competitors. For example, SVS would likely benefit from the implementation of the soil freezing and melting processes that are present in CLASS.

Results however strongly indicate that SVS can compete with more established Canadian models for simulating streamflow. In the coming years, after SVS becomes operationally implemented within ECCC's GEM-based NWP systems, it will be possible to obtain useful streamflow predictions by simply post-processing the runoff output from GEM using a unit hydrograph, or by routing these time series using a more sophisticated routing scheme.

Many distributed models do exist worldwide, each one possessing its own advantages and drawbacks, but also its own optimal implementation and calibration methodology, which makes a perfectly fair inter-comparison quite challenging, if not unrealistic.

4 References

Haghnegahdar, A., Tolson, B. A., Davison, B., Seglenieks, F. R., Klyszejko, E., Soulis, E. D., Fortin, V., and Matott, L. S.: Calibrating Environment Canada's MESH Modelling System over the Great Lakes Basin. Atmos.-Ocean, 52(4), 281–293, 2014.

See References of the main document for additional references.

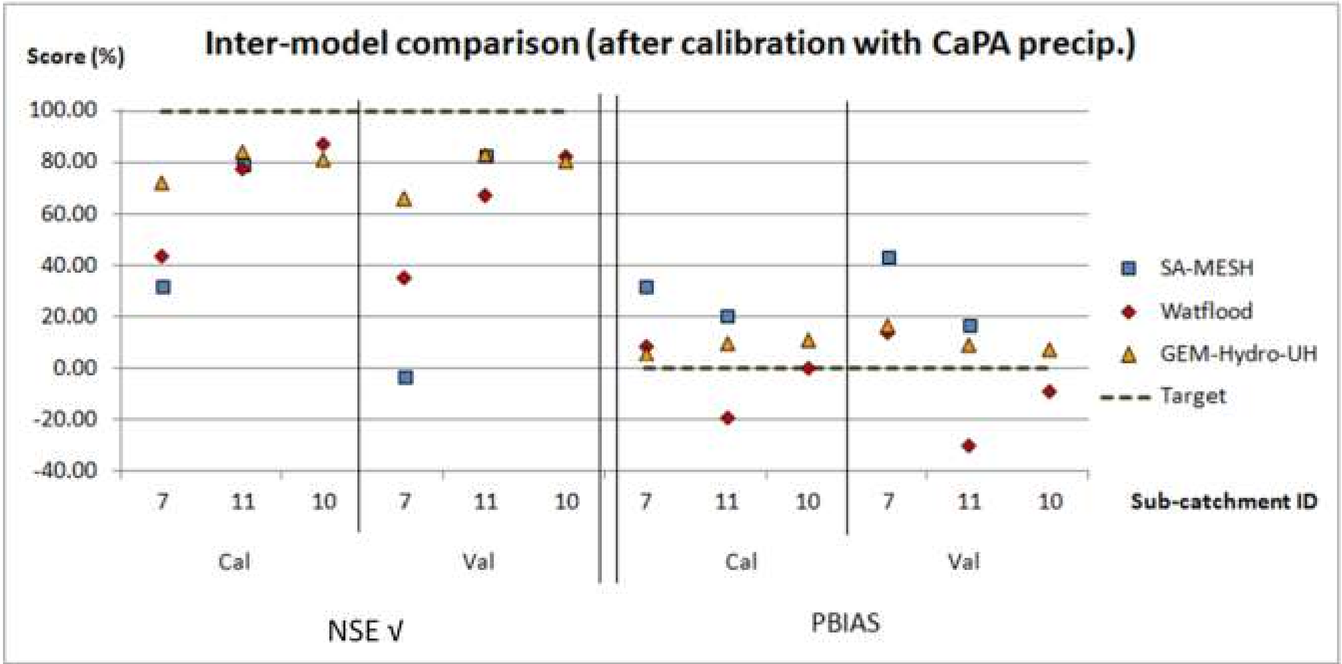

Figure 1: Intercomparison for three GRIP-O subbasins (Table 3 in main document). MESH was not implemented on subbasin 10. Cal, Val: calibration and validation periods, respectively. Scores that would be achieved if models provided a perfect fit to observations are indicated by the dashed line and labelled "Target".

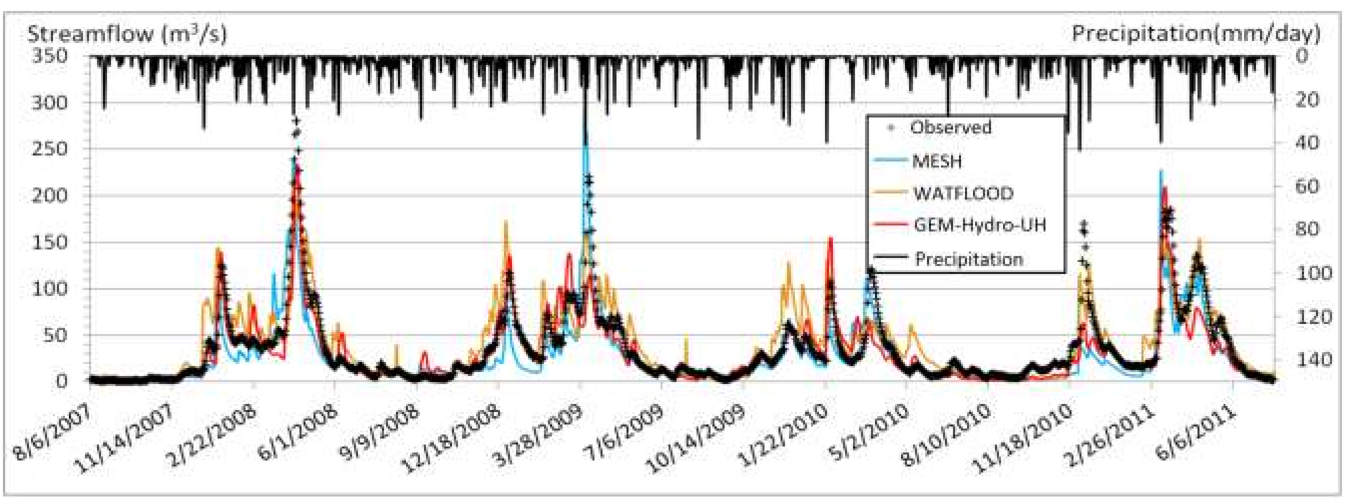

Figure 2: Intercomparison for the Moira River (calibration period, CaPA pecipitation).

Table 1: Data requirements and model specificities. P: precipitation, T: temperature, H: humidity, R:, radiative forcings (short- and long-wave incoming radiations), W: wind, Ps: pressure; LULC: Land Use / Land Cover, Topo: elevation data, Flow Dir: flow directions. Brackets indicate time-step used in this study.

Model name	Underlying theory	Spatial distribution	Time-step [min]	Forcing data	Physiographic data
WATFLOOD	Physical/Conceptual	Semi-distributed	Flexible [60]	P, T	LULC, Topo, Flow Dir
GEM-Hydro	Physical	Semi-distributed	Flexible [10]	P, T, H, R, W, Ps	LULC , Soil, Topo, Flow Dir
MESH	Physical	Semi-distributed	Flexible [30]	P, T, H, R, W, Ps	LULC, Soil, Topo, Flow Dir

Table 2: Data sources; NA: North America

Dataset/origin	Type of data	Coverage	Resolution/scale	Source
GSDE	soil texture	Global	~ 1km (30")	Shangguan *et al.* 2014
GLOBCOVER 2009	land cover	Global	300m (10")	ESA 2009
HydroSheds	Flow directions	Global	~ 1km (30")	USGS and WWF 2006
SRTM	DEM	Global	90m (3")	NGA and NASA 2000
HyDAT	Gauge stations	CAN	N/A	ECCC
NWIS	Gauge stations	US	N/A	USGS
CaPA v2.4b8	Precipitation	NA	~ 15 km	ECCC
RDPS	Atmospheric forcings	NA	15/10 km	ECCC

Table 3: Information on GEM-Hydro-UH 16 free parameters; LZS: Lower Zone Storage; coeff. : coefficient; mult. : multiplicative; precip. : precipitation; param.: parameter; min.: minimum; max.: maximum.

Param. \ range	description	initial	Min.	Max.	Param. \ range	description	initial	Min.	Max.
HU_decay	response time (h)	60.0	20.0	400.0	LAI	Leaf-Area Index mult. coeff.	1.0	0.2	5.0
FLZCOEFF	LZS mult. coeff.	1.0E-05	1.0E-07	1.0E-04	Z0M	roughness length mult. coeff.	1.0	0.2	5.0
PWR	LZS exponent coeff.	2.8	1.0	5.0	TBOU	boundary between liquid and solid precip. (˚C.)	0.0	-1.0	1.5
MLT	coeff. To divide snowmelt amount	1.0	0.5	2.0	EVMO	evaporation resistance mult. coeff.	1.0	0.1	10.0
GRKM	Horizontal conductivity mult. coeff.	1.0	0.1	30.0	KVMO	vertical conductivity mult. coeff.	1.0	0.1	30.0
SOLD	soil depth (m)	1.4	0.9	6.0	PSMO	soil water suction mult. coeff.	1.0	0.1	10.0
ALB	albedo mult. coeff.	1.0	0.2	5.0	BMOD	slope of retention curve mult. coeff.	1.0	0.1	10.0
RTD	root depth mult. Coeff.	1.0	0.2	5.0	WMOD	threshold soil moisture contents mult. coeff.	1.0	0.1	10.0

Table 4: Information on WATFLOOD 14 free parameters; LZS: Lower Zone Storage; coeff. : coefficient; mult. : multiplicative.

parameter	minimum	maximum	parameter	minimum	maximum
channel Manning's N	0.01	1.0	upper zone retention (mm)	1.0	300.0
LZS mult. coeff.	1.0E-09	1.0E-05	infiltration coefficient bare ground	0.8	0.99
LZS exponent coeff.	2.0	3.0	infiltration coefficient snow covered ground	0.8	0.99
melt factor (mm/dC/hour)	0.1	3.0	overland flow roughness coefficient bare ground	1.0	75.0
interflow coefficient	1.0	100.0	overland flow roughness coefficient snow covered ground	1.0	75.0
interflow coefficient bare ground	1.0	200.0	Interception evaporation factor	0.1	75.0
interflow coefficient snow covered ground	1.0	200.0	base temperature (dC)	-3.0	3.0

Table 5: Information on MESH 60 free parameters: independent values are sought for each of the 5 model Grouped Response Units (GRUs; source: Haghnegahdar, 2015).

parameter	description	vegetation or river class (5)	minimum	maximum
ROOT	Annual maximum rooting depth of vegetation category [m]	crop and grass	0.2	1.0
		Forest	1.0	3.5
		Crop	60.0	110.0
RSMN	Minimum stomatal resistance of vegetation category [$s.m^{-1}$]	Grass	75.0	125.0
		Forest	100.0	150.0
VPDA	Vapour pressure deficit coefficient	All	0.5	1.0
SDEP	Soil permeable (Bedrock) depth [m]	All	0.35	4.1
DDEN	Drainage density [km/km^2]	All	2.0	100.0
SAND	Percent sand content [%]	All	0.0	100.0
CLAY	Percent clay content [%]	All	0.0	100.0
RATIO	The ratio of horizontal to vertical saturated hydraulic conductivity	All	2.0	100.0
ZSNL	Limiting snow depth below which coverage is less than 100% [m]	All	0.05	1.0
ZPLS	maximum water ponding depth for snow-covered areas [m]	All	0.02	0.15
ZPLG	maximum water ponding depth for snow-free areas [m]	All	0.02	0.15
WFR2	Channel roughness factor	All	0.02	2.0