Subwatershed-based lake and river routing products for hydrologic and land surface models applied over Canada

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Introduction

Lakes and reservoirs have critical impact on hydrological, biogeochemical, and ecological process, and they should be one of the essential components in our hydrological and eco-hydrological models. This is particular important in Canada where there are tens of thousands of lakes. However, it is common for hydrological models to explicitly represent only large lakes (e.g., >80km²).

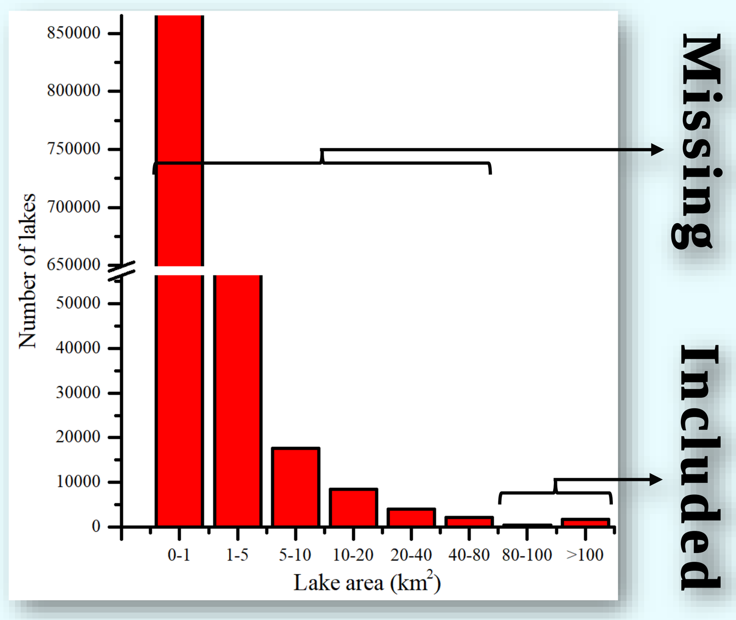

Figure 1. Histogram of Canadian lake areas in HydroLAKES database (Messenger et. al, 2018), all lakes > 10 ha in area.

Building hydrologically correct lake-river routing networks

- ❖ Lakes are always located at the outlet of any catchment with a lake, so that the outflow of such a lake catchment is controlled by the lake
- ❖ Lake drainage areas are derived based on DEM and lake pour points
- ❖ Each lake inflow pour point, multiple possible, are explicitly identified
- ❖ Lake-river routing structure B and C shown in Figure 2 are both correct, but approach in Figure B is preferred as dozens of small catchments are avoided

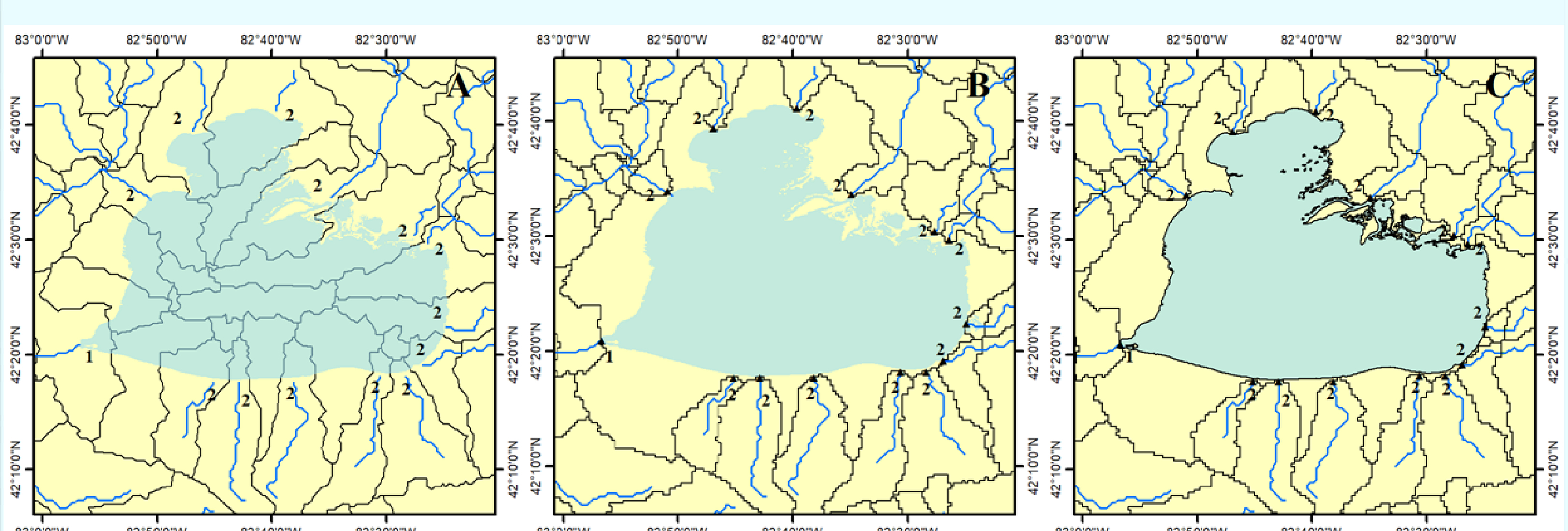

Figure 2. (A) An example of overlaying lake and catchments polygons. (B) An example of lake-river routing structure with a large lake catchment combining lake surface area and local drainage areas along the shoreline. (C) An example of lake-river routing structure that defines the lake polygon as a lake catchment. The yellow polygons (black boundaries) are catchments. The light blue polygon is a sample modelled lake. The solid blue lines are channels in the modelled river networks. The points labeled as 1 is the lake outlet point while the points labeled with 2 are all the lake inflow points from upstream river channels.

Process to generate lake-river routing products

A workflow to generate of lake-river routing network was developed to derive all catchment, channel and lake properties required to drive a hydrologic routing model at various resolutions across Canada. Figure 3 shows example routing networks for two products. ***The workflow is being developed into a flexible and generalized ArcGIS python toolbox.***

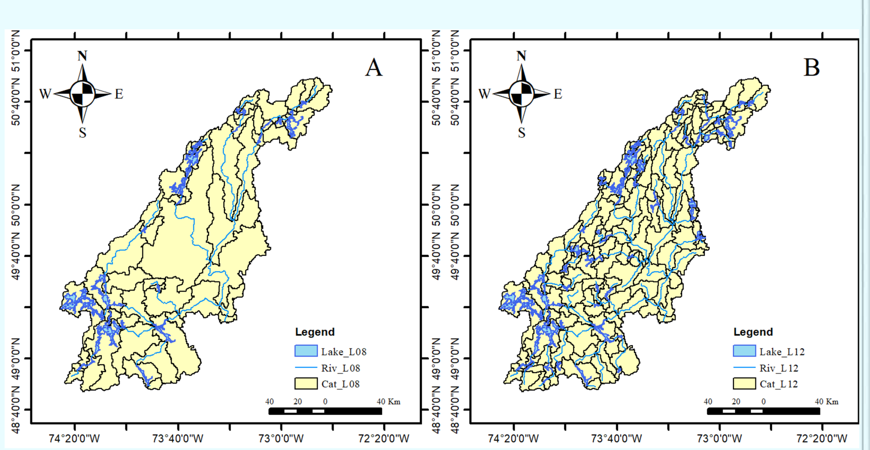

Figure 3. An example of two generated lake-river routing network with HydroSHEDS Level 8 and 12 catchment delineation.

Data and derived lake-river routing products over Canada

- ❖ Products derived from HydroSHEDS 15 arc-second datasets (Lehner, 2014) and HydroLAKES datasets (Messager et al., 2016)
- ❖ 6372 observation gauges from HYDAT database (HYDAT, 2018) define additional catchment outlets (assumed points of interest for modellers) by snapping them to the closest river reach of HydroSHED river system
- ❖ A global database for bankfull width, depth provides bankfull width and depth for each generated catchment river channel (Andreadis et al., 2013)

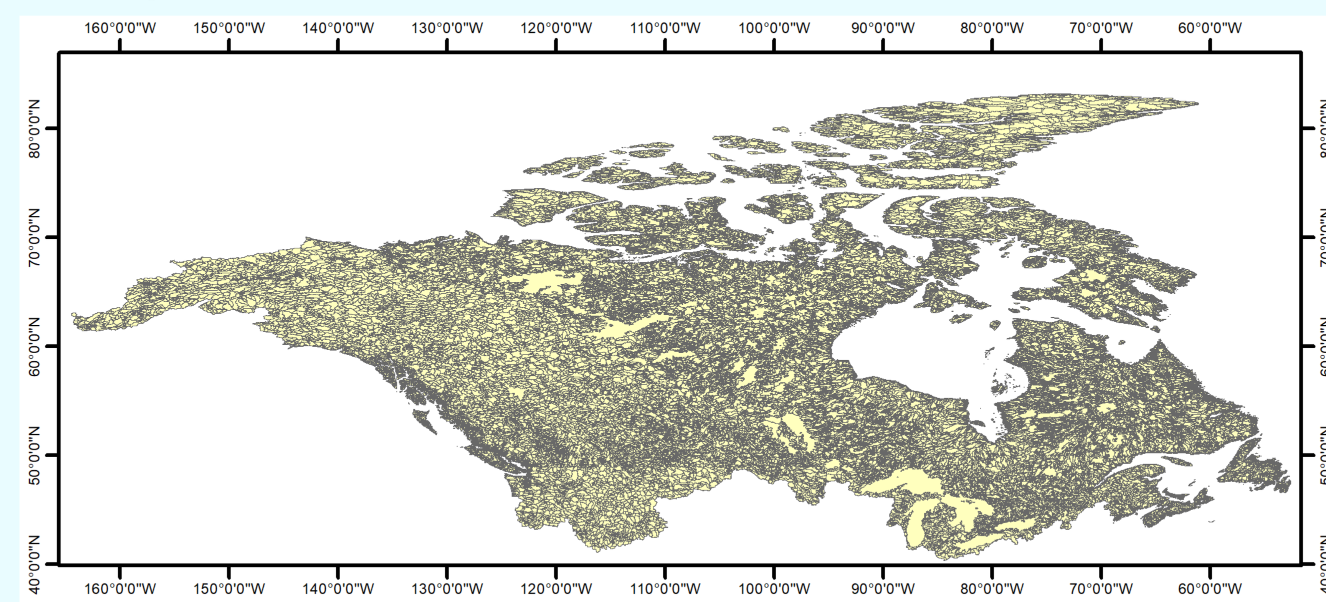

Figure 4. Developed routing product L08-Lake0, which combining HydroSHEDS level 8 product and all lakes with lake area larger than 0 km² in HydroLAKES that are connected by river network

Table 1. The developed routing products and their general attributes. The L7-Lake0 means lake-river routing structure developed by using HydroSHEDS Level 07 products and all lakes in HydroLAKES with surface area larger than 0 km² included explicitly.

Product Name	Number of catchments	Average catchment area (km²)	Number of lakes	Median lake area (km²)
L7-Lake0	53219	230	20708	0.79
L8-Lake0	90455	135	40674	0.74
L9-Lake0	149419	82	68490	0.69
L10-Lake0	198481	62	85362	0.67
L11-Lake0	205309	60	86982	0.66
L12-Lake0	205376	60	86991	0.66
L7-Lake1	40387	303	11416	3
L8-Lake1	62626	195	19956	3.1
L9-Lake1	100684	121	31277	2.9
L10-Lake1	137415	89	37493	2.8
L11-Lake1	142608	86	37856	2.8
L12-Lake1	143372	85	38088	2.8

❖ Properties included in each of the 12 routing products:

- **Catchment properties:** downstream ID, catchment area, averaged slope, observation ID
- **Channel properties:** channel slope, bankfull width & depth, mean annual discharge, channel length, flood plain Manning's n (from Modis landuse type), channel Manning's n (back-calculated)
- **Lake properties:** lake ID, lake surface area, lake volume, lake depth, and lake type (natural or regulated), vertical side-slopes assumed, lake outlet assumed to behave like a broad-crested weir and assigned a weir width equal to the bankfull width for a channel assuming no lake was present

Demonstrate routing products for hydrologic routing in Hudson Bay basin (~ 40% of Canada)

Data and routing model setup

- ❖ Forcings: hourly surface runoff and groundwater recharge from SVS land surface scheme (Asante et al., 2008; Gaborit et al., 2017)
- ❖ Hydrologic routing: Raven (Raven Development Team, 2018) in diffusive wave routing mode (no in-catchment routing simulated) and simulating lake water levels & baseflow
- ❖ Spatial overlay of gridded forcings and routing network generates weights for Raven, enabling direct read of original resolution gridded forcings (in NetCDF or ASCII format) and then internal conversion to catchment-level forcings
- ❖ 3 year simulation period: 2007-01-01 to 2010-10-01; hourly time step
- ❖ Results checked at 15 flow gauges (with no upstream reservoirs)

Runtime of routing model in forecasting mode

Table 2 shows the Raven routing configuration computation times and demonstrates some of the flexibility of Raven as a hydrologic routing tool supporting lake/reservoir routing. Simulation times are reasonable and faster than equivalent-detail gridded routing model benchmark (WatRoute).

Table 2. Raven runtime (serial) with different products in example forecasting type of simulation.

Product	# of catchments	# of lake catchments	Runtime for a 10-day, hourly time step simulation (min.)
L8-lake0	26419	14975	13.4
L7-lake0	15565	8191	6.0
L7-No-lakes	4288	0	0.7

Impact of lakes on Raven routing results

- ❖ Base scenario: routing with all lakes explicitly simulated
- ❖ Average NSE for base scenario at all 15 gauges was 0.52. Since the routing model was not calibrated, this good result suggests lake-river routing structure and derived data are reasonable
- ❖ The impact of lakes on routing is different across 15 gauges (see Figure 5)
- ❖ The base scenario gives better performance than No-lake scenario, because the peak flow was significantly reduced and delayed by including lakes (see for example Figure 6)

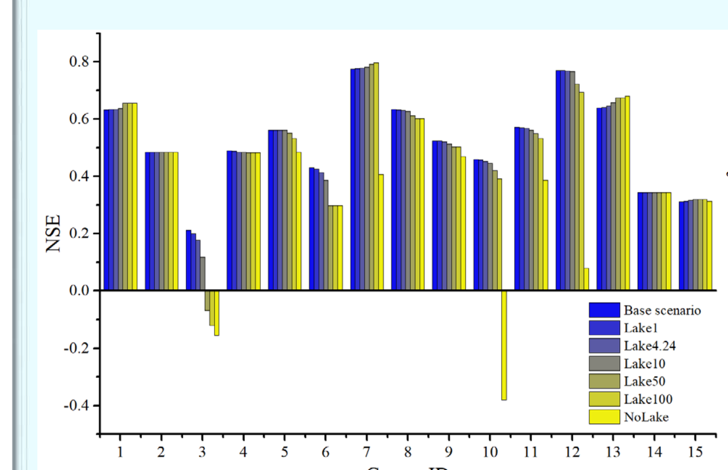

Figure 5. NSE at each gauge for each lake representation scenario. Base scenario means all lakes in the lake-river routing structure were active. Lake1 means lakes with lake area smaller than 1 km² were not explicitly modelled compared to Base scenario.

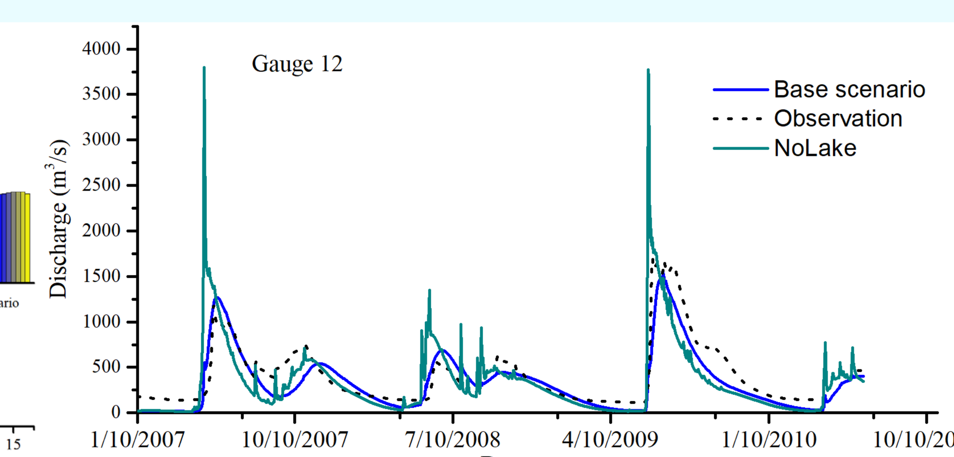

Figure 6. Example of observed hydrograph in comparison with simulated hydrographs from the Base scenario (all lakes) and the the NoLake scenario. and compared with hydrograph of observations. Lake1 means lakes with lake area smaller than 1 km² were not explicitly modelled compared to Base scenario.

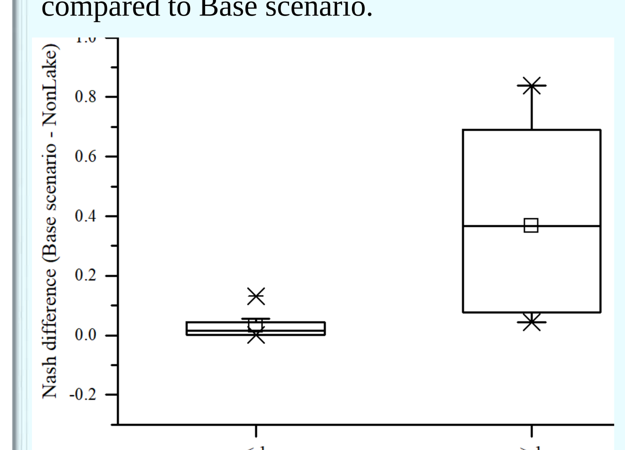

Figure 7. Relationship between Nash difference and DA ratio. DA ratio for a gauge is the ratio between total drainage area of upstream lakes with a lake area larger than 10 km² and drainage area of each gauge.

❖ Lake impact is influenced by drainage areas flowing through moderate to large lakes (Figure 7)

Conclusions

- ❖ The Pan-Canadian lake-river routing products, available as shapefiles, can support a variety of hydrologic routing and lake-focused modelling projects
- ❖ Product viability demonstrated with Raven in routing-only mode
- ❖ Routing products provide an excellent *starting point* for building your model
- ❖ Future research needed to develop objective strategies for ignoring smaller lakes
- ❖ Manuscript being submitted to CWRA journal