L2SWBM and Copula Mini-Workshop

University of Michigan
School for Environment and Sustainability

July 2022

Outline

Outline

1. Introduction
2. Day 1 (Monday) - L2SWBM Technical Updates
   - L2SWBM background and technical overview
   - Recent and ongoing research projects
   - Version control and code repositories
   - Reality check (under the hood)
3. Day 2 (Tuesday) - Copulas and Federal Perspectives
   - Using Copulas
   - Federal Agency Partners
4. Day 3 (Wednesday) - Beyond the (Laurentian) Great Lakes
   - African Great Lakes
   - Mono Lake
   - NSF large lakes proposal (and other ideas)

University of Michigan L2SWBM Research Team

Drew Gronewold, Principal Investigator

Joseph Smith

Hong Do, Ph.D

Dani Cohen, MS

Ryan Armbrustmacher, MS

Sarah Katz, Ph.D candidate

Alex Vandeweghe

Jennani Jayaram

Yifan Luo, MS

Maegan Muir, MS

Justin Huber, MS

Hannah Paulson, MS

SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

GREAT LAKES
ST. LAWRENCE
GOVERNORS
& PREMIERS

MDOT
Michigan Department of Transportation

UNIVERSITY OF
MICHIGAN

USGS

GLPF

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE
1909

Outline

Outline

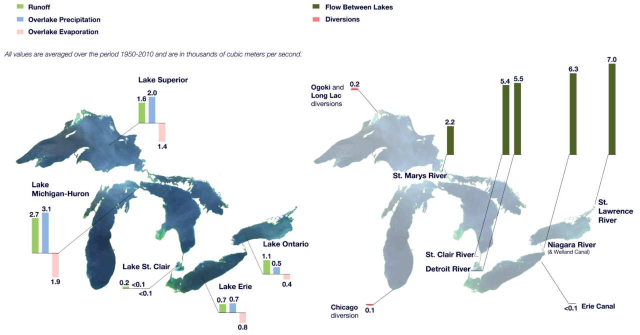
1. Introduction
2. Day 1 (Monday) - L2SWBM Technical Updates
   - L2SWBM background and technical overview
   - Recent and ongoing research projects
   - Version control and code repositories
   - Reality check (under the hood)
3. Day 2 (Tuesday) - Copulas and Federal Perspectives
   - Using Copulas
   - Federal Agency Partners
4. Day 3 (Wednesday) - Beyond the (Laurentian) Great Lakes
   - African Great Lakes
   - Mono Lake
   - NSF large lakes proposal (and other ideas)

Historical Conventional Water Balance Model

$$P + R - E + Q_{in} - Q_{out} = \Delta$$

P	R	E	Qin	Qout	Δ
Over-lake precipitation	Lateral runoff	Over-lake evaporation	Channel inflow (upstream lake)	Channel outflow (downstream lake)	Change in water level

G	ε
Groundwater	Error


Runoff
Overlake Precipitation
Overlake Evaporation
Flow Between Lakes
Diversions
All values are averaged over the period 1950-2010 and are in thousands of cubic meters per second.
Lake Superior
1.6
2.0
1.4
Lake Michigan-Huron
2.7
3.1
1.9
Lake St. Clair
0.2
<0.1
<0.1
Lake Ontario
1.1
0.5
0.4
Lake Erie
0.7
0.7
0.8
Ogoki and Long Lac diversions
0.2
2.2
5.4
5.5
6.3
7.0
St. Marys River
St. Lawrence River
St. Clair River
Detroit River
Niagara River
(& Welland Canal)
Chicago diversion
0.1
<0.1
Erie Canal

Historical Conventional Water Balance Model

P + R − E + Qin − Qout = Δ

P	R	E	Qin	Qout	Δ
Over-lake precipitation	Lateral runoff	Over-lake evaporation	Channel inflow (upstream lake)	Channel outflow (downstream lake)	Change in water level

Journal of Great Lakes Research 41 (2015) 65–77

Contents lists available at ScienceDirect

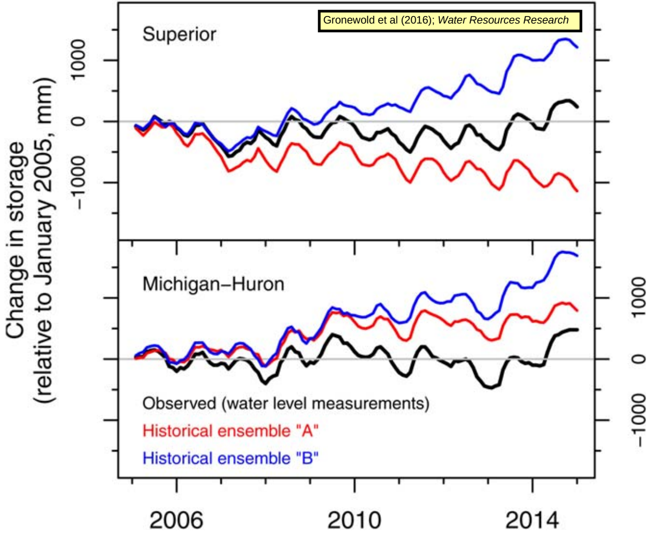
Journal of Great Lakes Research

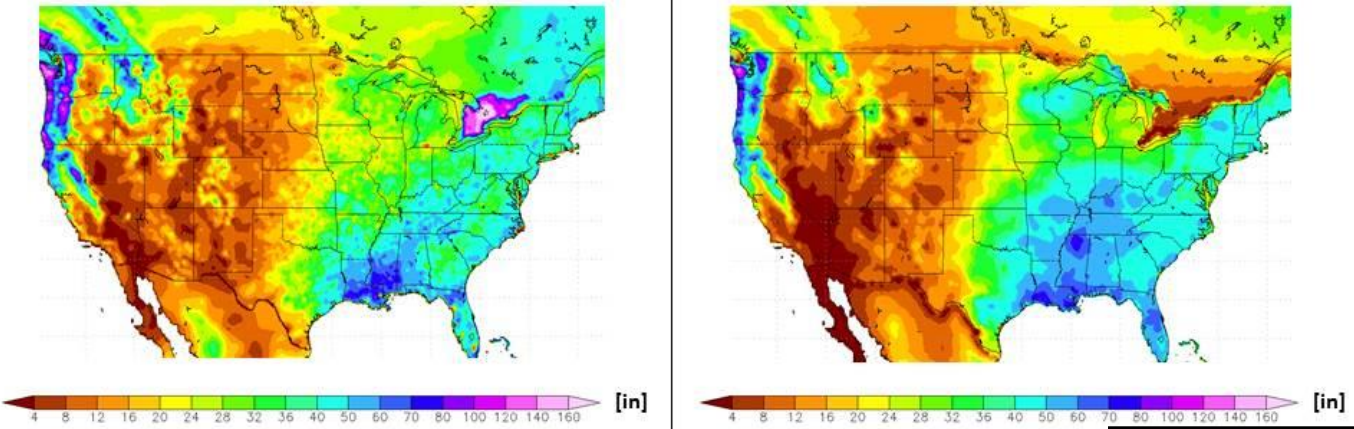
journal homepage: www.elsevier.com/locate/jglr

Development and application of a North American Great Lakes hydrometeorological database — Part I: Precipitation, evaporation, runoff, and air temperature

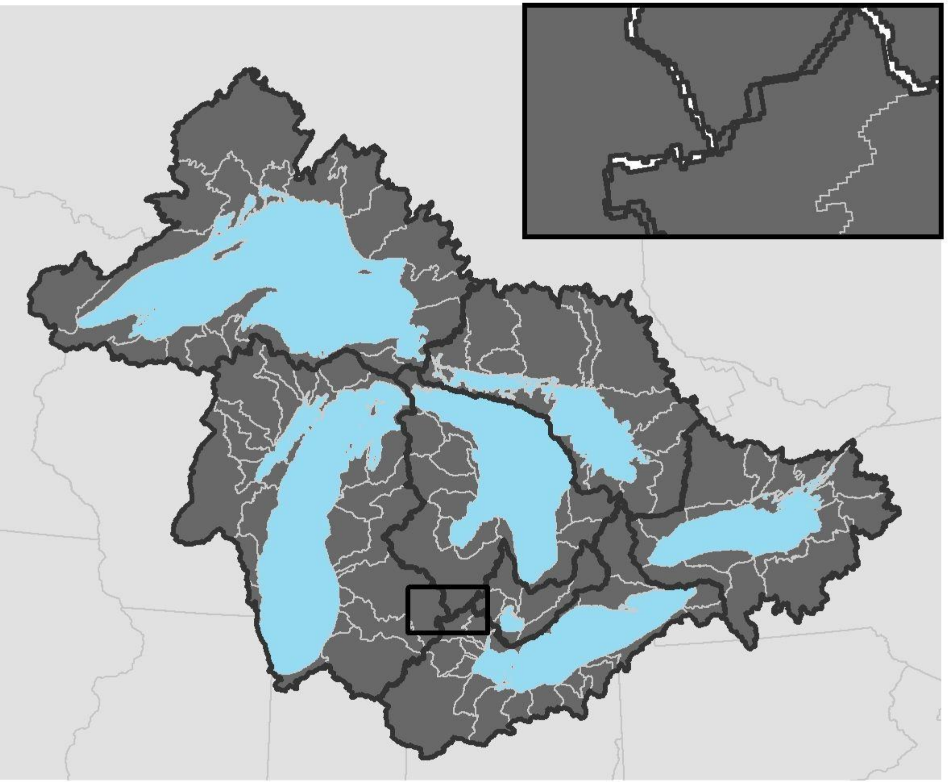
Timothy S. Hunter [a], Anne H. Clites [a], Kent B. Campbell [a,b], Andrew D. Gronewold [a,*]

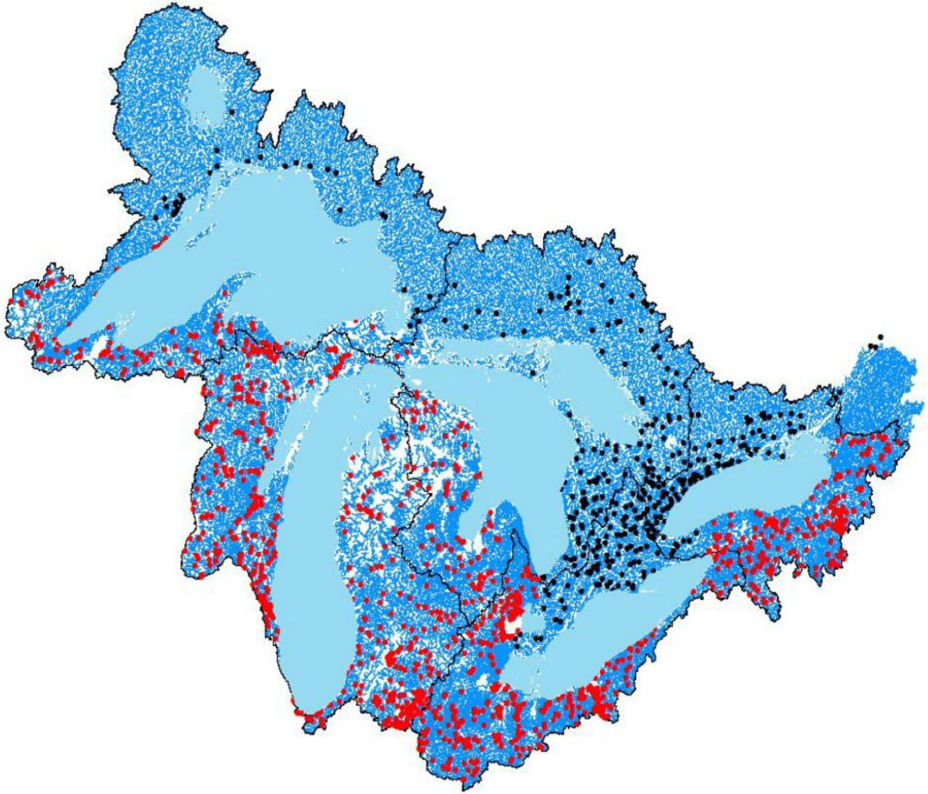
[a] Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, MI 48108, USA
[b] Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, MI 48109, USA


Gronewold et al (2016); *Water Resources Research*
Superior
Michigan–Huron
Change in storage
(relative to January 2005, mm)
1000
0
−1000
Observed (water level measurements)
Historical ensemble "A"
Historical ensemble "B"
2006
2010
2014



Gronewold et al (2018); *BAMS*





Mason et al (2019); *J. Water Resources Planning & Mgmt*


White Shoal Lighthouse: Lake Michigan
Photo courtesy Dick Moehl (Lighthouse Keepers Association)


N
Québec
Lake Superior
Ontario
Minnesota
Stannard Rock
Granite Island
Michigan
Spectacle Reef
White Shoal
Lake Huron
Lake Ontario
Wisconsin
New York
Lake Michigan
Minnesota
Michigan
Long Point
Lake Erie
Pennsylvania

24.07.2022

Product Team Enterprise Explore Marketplace Pricing Search / Sign in Sign up

dholtschlag-usgs / LakeSuperior Public

Notifications Fork 0 Star 0

Code Issues Pull requests Actions Projects Wiki Security Insights

master 1 branch 0 tags Go to file Code

dholtschlag-usgs Remove large data files b25c53e on Mar 9, 2015 17 commits

Superior	Cumulative update	8 years ago
.gitignore	Remove large data files	8 years ago
.gitignore.bak	Remove large data files	8 years ago
LaplacesDemon_15.03.01.tar.gz	Cumulative update	8 years ago
README.md	Updated Readme with waterBudgetCondLakeSupBOMLevel.R	8 years ago
README.md.bak	Updated Readme with waterBudgetCondLakeSupBOMLevel.R	8 years ago
SupMergedCMS.txt	Update with Monthly Multiple Regression Models	8 years ago
SupPrecipCMS.txt	R markdown file and output for checkCompNBS	8 years ago
Superior.Rproj	R markdown file and output for checkCompNBS	8 years ago
junkCode.R	Catchup commit	8 years ago
maacs.Rda	Catchup commit	8 years ago
stdModel.R	Catchup commit	8 years ago

About

Water Budget for Lake Superior

Readme

0 stars

1 watching

0 forks

Releases

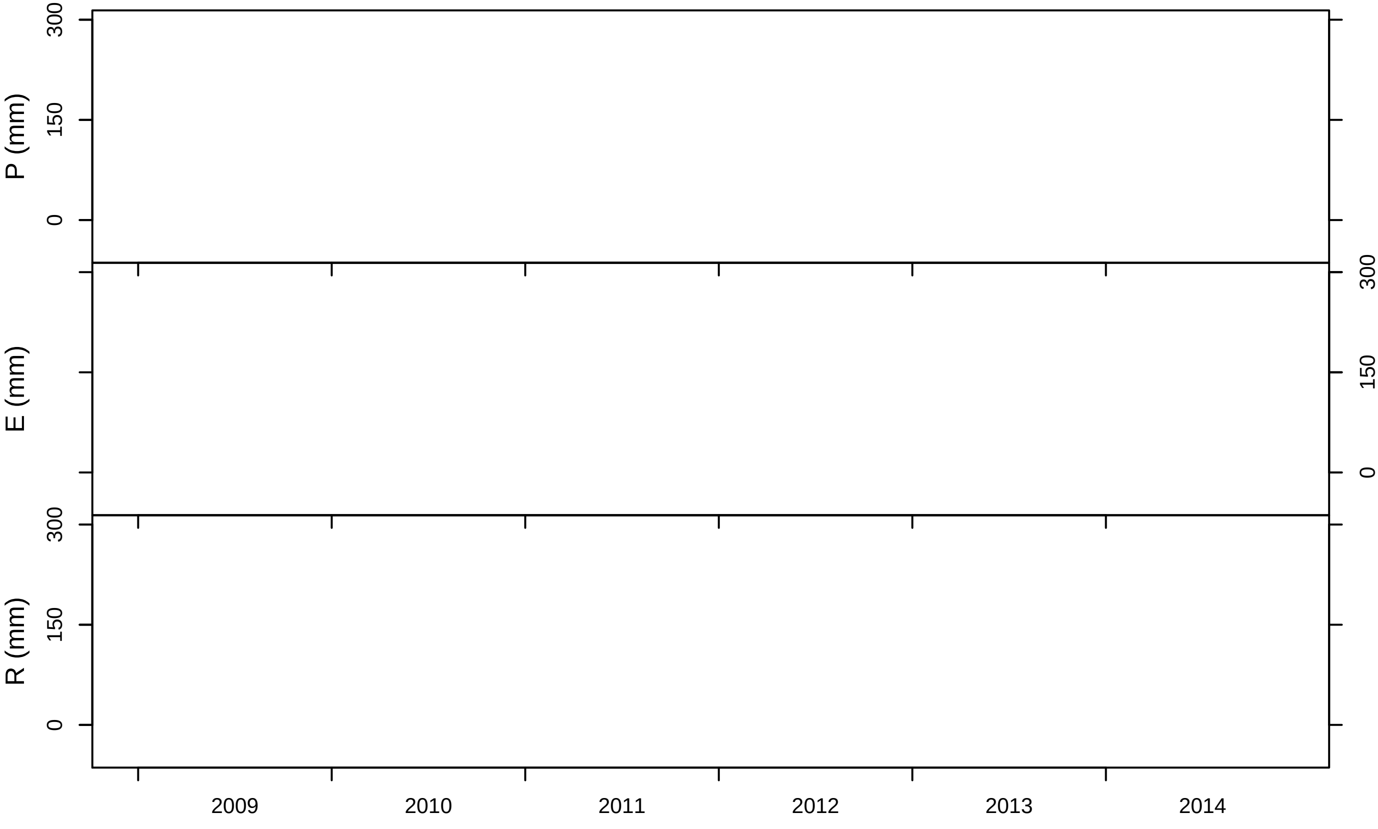
No releases published

Packages

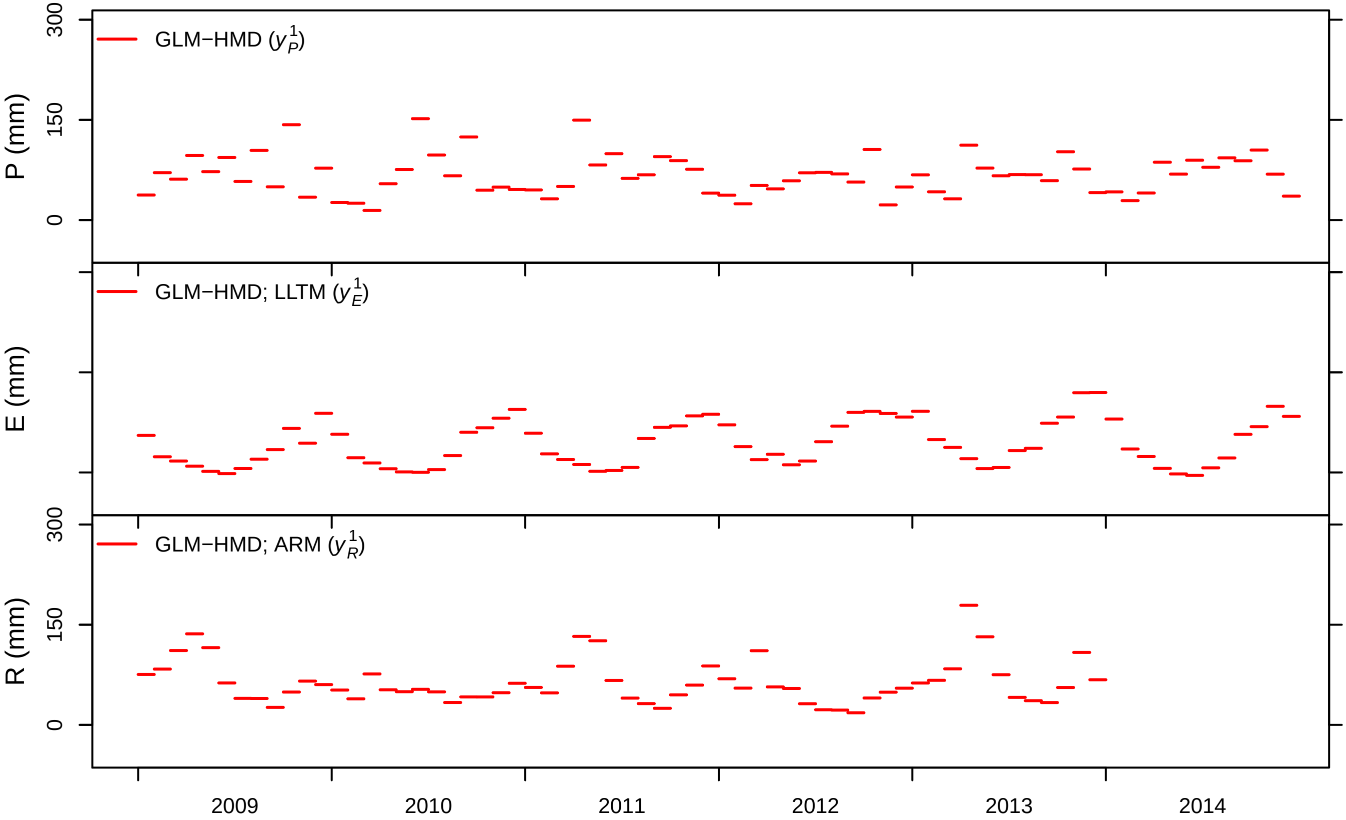
No packages published

Languages

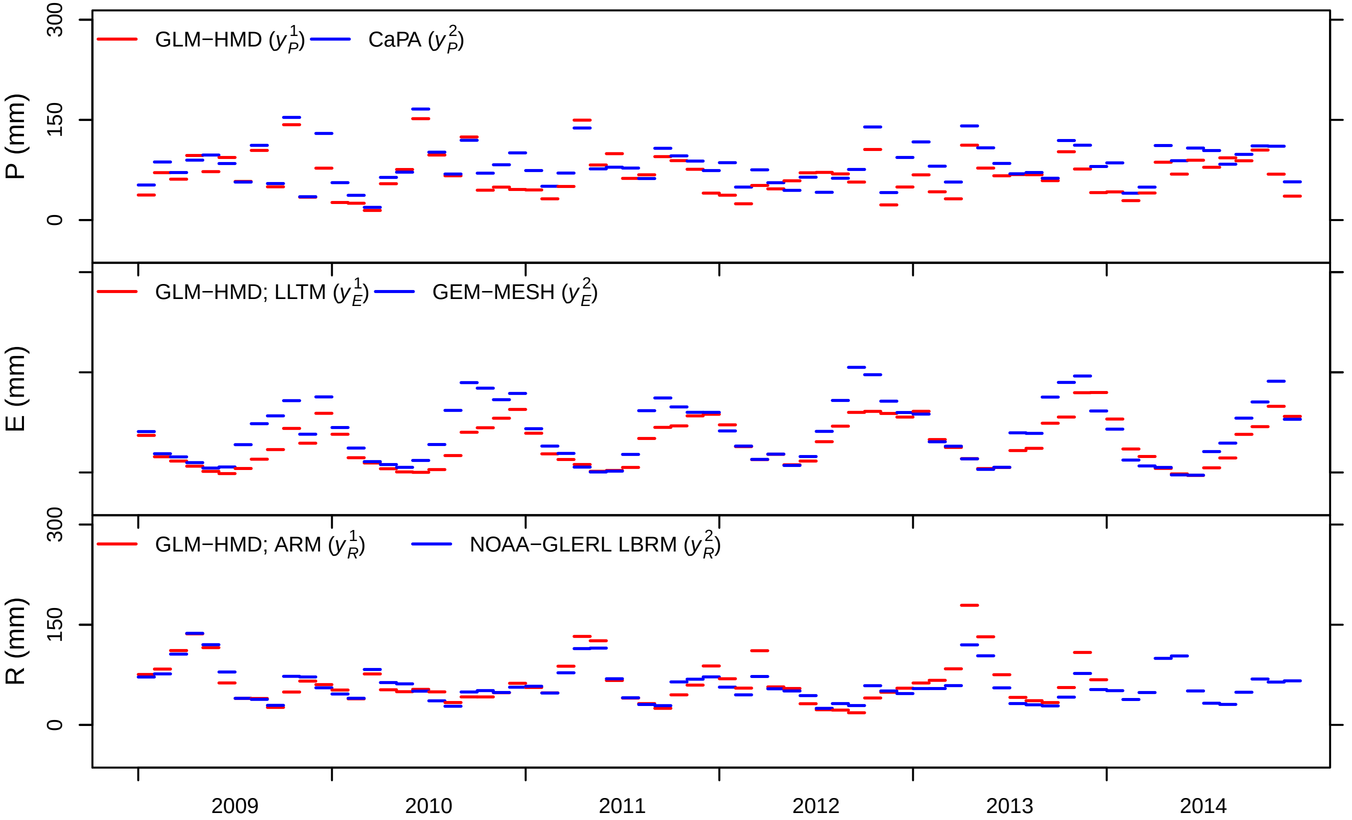
HTML 90.3% R 9.7%

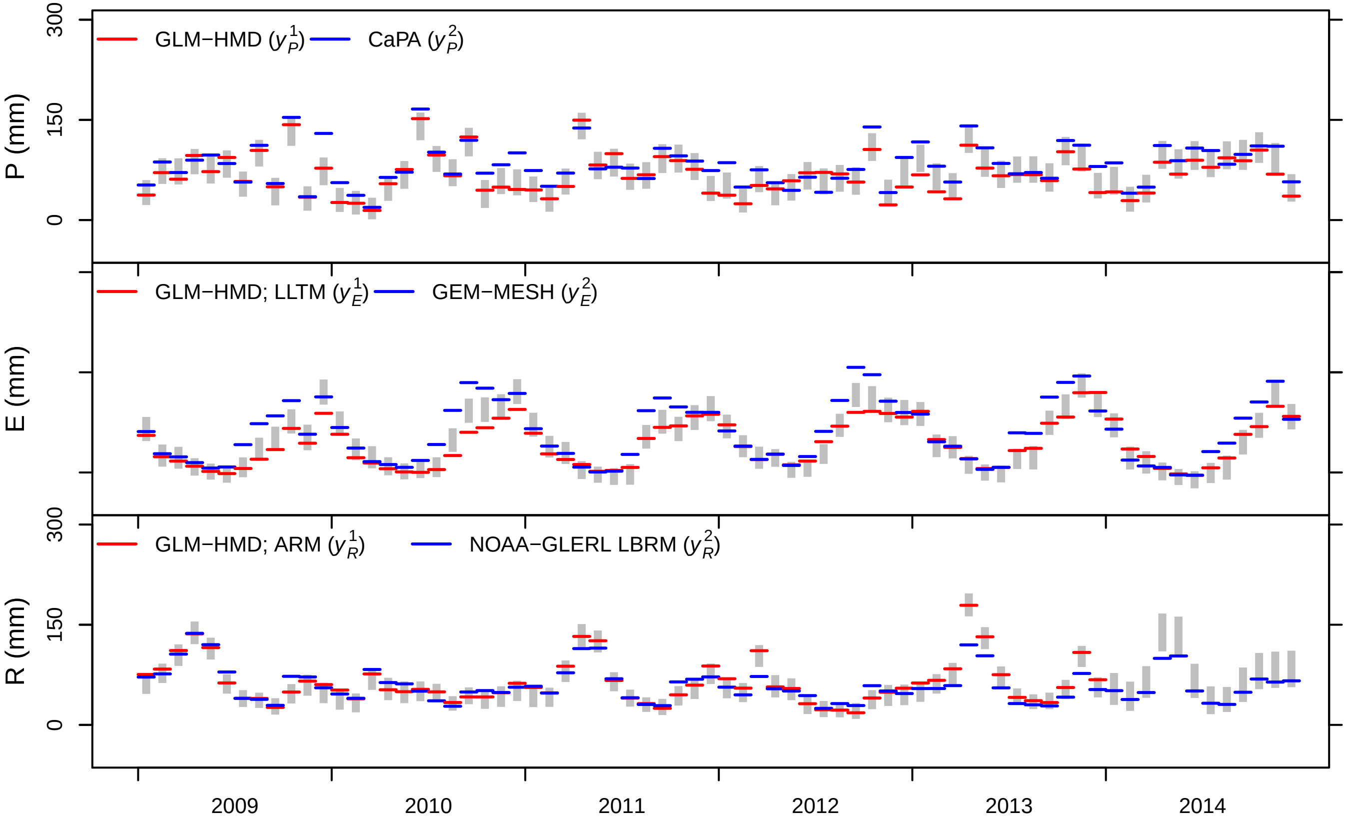


P (mm)
0
150
300
E (mm)
0
150
300
R (mm)
0
150
300
2009
2010
2011
2012
2013
2014



P (mm)
E (mm)
R (mm)
GLM−HMD (y_P^1)
GLM−HMD; LLTM (y_E^1)
GLM−HMD; ARM (y_R^1)
0
150
300
2009
2010
2011
2012
2013
2014


P (mm)
E (mm)
R (mm)
300
150
0
GLM−HMD (y_P^1)
CaPA (y_P^2)
GLM−HMD; LLTM (y_E^1)
GEM−MESH (y_E^2)
GLM−HMD; ARM (y_R^1)
NOAA−GLERL LBRM (y_R^2)
2009
2010
2011
2012
2013
2014



GLM−HMD (y_P^1)
CaPA (y_P^2)
GLM−HMD; LLTM (y_E^1)
GEM−MESH (y_E^2)
GLM−HMD; ARM (y_R^1)
NOAA−GLERL LBRM (y_R^2)
P (mm)
E (mm)
R (mm)
0
150
300
2009
2010
2011
2012
2013
2014

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR018209

Key Points:
- Between January 2013 and December 2014, the two largest lakes on Earth rose at a record-setting rate
- We developed a Bayesian MCMC routine for inferring estimates of the water budget for this period
- The cold 2013–2014 winter contributed to reduced evaporation rates and rising water levels

Hydrological drivers of record-setting water level rise on Earth's largest lake system

A. D. Gronewold[1,2], J. Bruxer[3], D. Durnford[4], J. P. Smith[5], A. H. Clites[1], F. Seglenieks[6], S. S. Qian[7], T. S. Hunter[1], and V. Fortin[4]

[1]National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, USA, [2]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan, USA, [3]Environment and Climate Change Canada, Great Lakes—St. Lawrence Regulation Office, Cornwall, Ontario, Canada, [4]Canadian Meteorological Centre, Dorval, Quebec, Canada, [5]Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, Michigan, USA, [6]Environment and Climate Change Canada, Canada Centre for Inland Waters, Burlington, Ontario, Canada, [7]Department of Environmental Sciences, University of Toledo, Toledo, Ohio, USA

$\Delta H_{j,w}$

$$\Delta H_{j,w} = H_{j+w} - H_j$$

$$\Delta H_{j,w} = H_{j+w} - H_j = \sum_{i=j}^{j+w-1} (P_i - E_i + R_i + I_i - Q_i + D_i + \epsilon_i)$$

$y_{\Delta H,j,w}$

$$y_{\Delta H,j,w} \quad = \quad y_{H,j+w} - y_{H,j}$$

$$y_{\Delta H,j,w} = y_{H,j+w} - y_{H,j} \sim \mathrm{N}$$

$$y_{\Delta H,j,w} \quad = \quad y_{H,j+w} - y_{H,j} \sim \mathsf{N}(\Delta H_{j,w},$$

$$y_{\Delta H,j,w} \;=\; y_{H,j+w} - y_{H,j} \sim \mathsf{N}(\Delta H_{j,w}, \tau_{\Delta H,w})$$

$$y^n_{t,\theta} \quad \sim \quad \mathsf{N}(\theta_t + \eta^n_{\theta,c_t}, \tau^n_{t,\theta})$$

$$
\begin{aligned}
\pi(E_t) &= \mathsf{N}(\mu_{E,c_t}, \tau_{E,c_t}/2) \\
\pi(Q'_t) &= \mathsf{N}(\mu_{Q',c_t}, \tau_{Q,c_t}) \\
\pi(D'_t) &= \mathsf{N}(\mu_{D',c_t}, \tau_{D',c_t})
\end{aligned}
$$

$$\pi(R_t) \quad = \quad \mathsf{LN}(\mu_{ln(R),c_t}, \tau_{ln(R),c_t})$$

$$
\begin{aligned}
\epsilon_t &= \epsilon_{c_t} \\
\pi(\epsilon_{c_t}) &= \mathsf{N}(0, 0.01)
\end{aligned}
$$

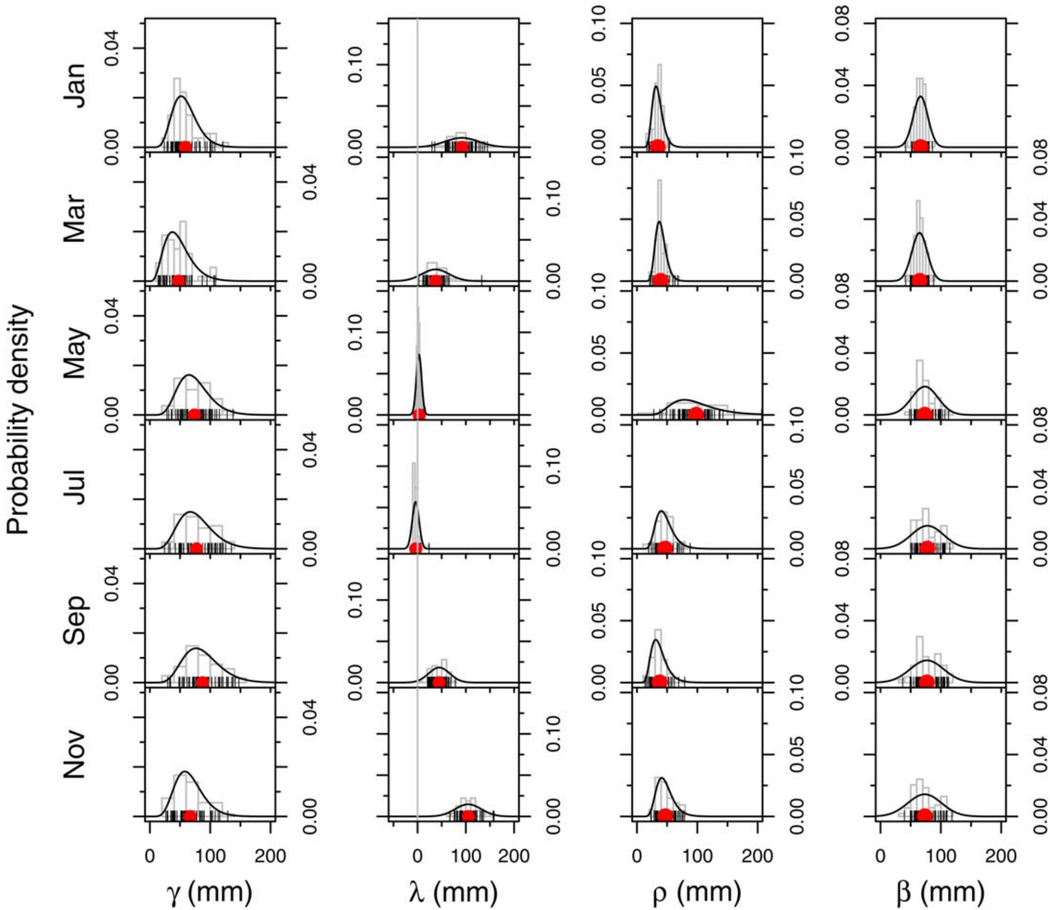
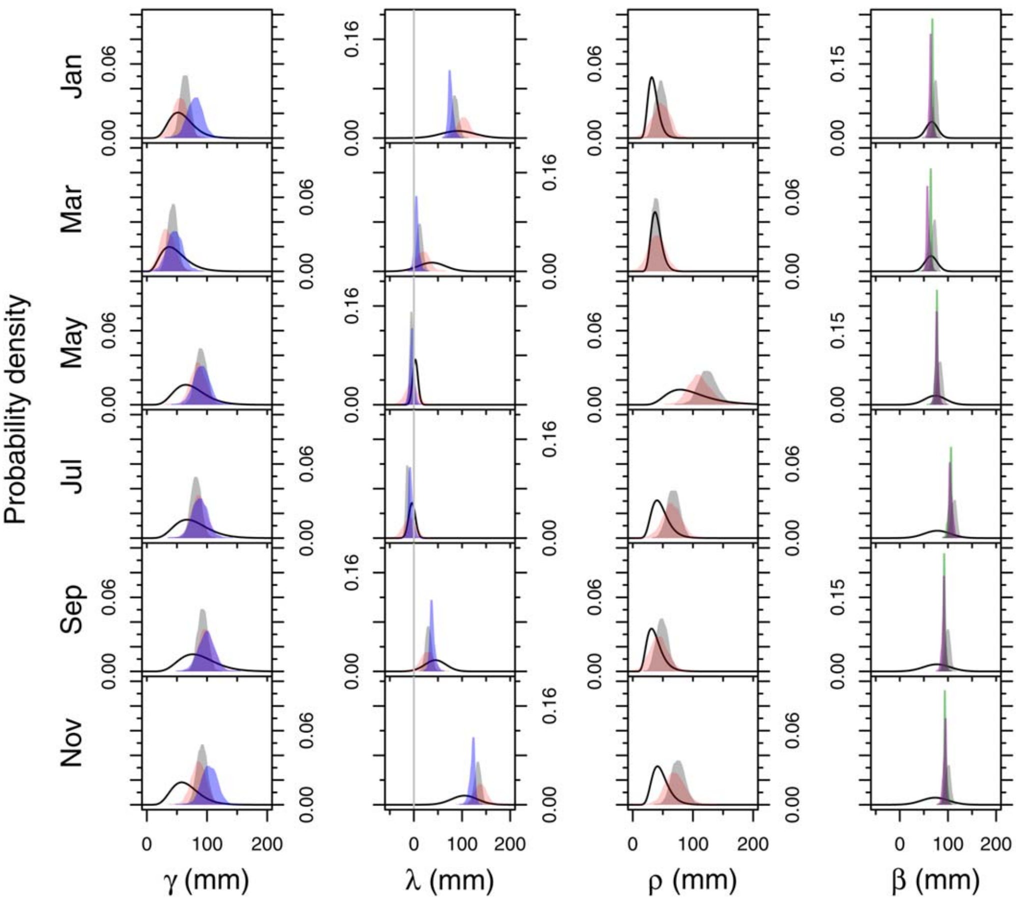


Figure 2. Development of prior probability distributions for Lake Superior monthly water budget components. Plot includes every other month (starting in January) for clarity and simplicity. Prior probability distributions for all months for both Lakes Superior and Michigan-Huron are included in supporting information Figures S1 and S2. Vertical tick marks along *x* axis and histograms in each plot are based on values from the historical record from 1950 to 2004 in the GLM-HMD [*Hunter et al.*, 2015]. Red dots represent the historical mean, and thin black curves represent the "fitted" prior probability distributions.


Probability density
Jan
Mar
May
Jul
Sep
Nov
0.00
0.06
0.16
0.15
0
100
200
γ (mm)
λ (mm)
ρ (mm)
β (mm)

Advances in Water Resources 137 (2020) 103505

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Reconciling the water balance of large lake systems

Andrew D. Gronewold[a,b,*], Joeseph P. Smith[c], Laura K. Read[d], James L. Crooks[e,f]

[a] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA
[c] Cooperative Institute for Great Lakes Research, University of Michigan, Ann Arbor, MI 48109, USA
[d] National Center for Atmospheric Research, Boulder, CO 80307, USA
[e] Division of Biostatistics and Bioinformatics, National Jewish Health, Denver, CO 80206, USA
[f] Department of Epidemiology, Colorado School of Public Health, Aurora, CO 80045, USA

A R T I C L E I N F O

Keywords:
Hydrologic cycle
Large lakes
Statistical modeling
Bayesian inference
Water balance

A B S T R A C T

Water balance models are commonly employed to improve understanding of drivers behind changes in the hydrologic cycle across multiple space and time scales. Generally, these models are physically-based, a feature that can lead to unreconciled biases and uncertainties when a model is not encoded to be faithful to changes in water storage over time. Statistical methods represent one approach to addressing this problem. We find, however, that there are very few historical hydrological modeling studies in which bias correction and uncertainty quantification methods are routinely applied to ensure fidelity to the water balance. Importantly, we know of none (aside from preliminary applications of the model we advance in this study) applied specifically to large lake systems. We fill this gap by developing and applying a Bayesian statistical analysis framework for inferring water balance components specifically in large lake systems. The model behind this framework, which we refer to as the L2SWBM (large lake statistical water balance model), includes a conventional water balance model encoded to iteratively close the water balance over multiple consecutive time periods. Throughout these iterations, the L2SWBM can assimilate multiple preliminary estimates of each water balance component (from either historical model simulations or interpolated *in situ* monitoring data, for example), and it can accommodate those estimates even if they span different time periods. The L2SWBM can also be executed if data for a particular water balance component are unavailable, a feature that underscores its potential utility in data scarce regions. Here, we demonstrate the utility of our new framework through a customized application to the Laurentian Great Lakes, the largest system of lakes on Earth. Through this application, we find that the L2SWBM is able to infer new water balance component estimates that, to our are knowledge, are the first ever to close the water balance over a multi-decadal historical period for this massive lake system. More specifically, we find that posterior predictive intervals for changes in lake storage are consistent with observed changes in lake storage across this period over simulation time intervals of both 6 and 12 months. In additional to introducing a framework for developing definitive long-term hydrologic records for large lake systems, our study provides important insights into the origins of biases in both legacy and state-of-the-art hydrological models, as well as regional and global hydrological data sets.

1. Introduction

Hydrological models that simulate and forecast the water balance across a variety of space and time scales are needed to facilitate water resources management planning and, ultimately, to ensure human and environmental health (Vörösmarty et al., 2000; Pekel et al., 2016). This need is particularly pronounced in regions where rapid population growth coincides with changes in the spatiotemporal distribution of fresh water, and where the sustainability of future water supplies is uncertain (Schewe et al., 2014). To address this need, hydrological models need to clearly differentiate components of the hydrologic cycle that are often confounded (including, for example, evapotranspiration and irrigation water demand) and to quantify changes in those components over time (Nijssen et al., 2001; Kebede et al., 2006; Raes et al., 2006; Li et al., 2007; Gronewold and Stow, 2014).

Global, continental, and basin-scale water balance modeling research typically focuses on improving representation of terrestrial and atmospheric physical processes collectively governing precipitation, evapotranspiration, and streamflow (Crow et al., 2008; Kim and Stricker, 1996; Milly and Dunne, 2017; Senay et al., 2011; Vörösmarty et al., 1998). This body of research, while providing foundational hydrologic data for much of the planet's land surface, rarely explicitly

* Corresponding author: School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, USA.
E-mail address: drewgron@umich.edu (A.D. Gronewold).

https://doi.org/10.1016/j.advwatres.2020.103505
Received 14 June 2019; Received in revised form 26 November 2019; Accepted 2 January 2020
Available online 10 January 2020

SCIENTIFIC DATA

Check for updates

OPEN

DATA DESCRIPTOR

Seventy-year long record of monthly water balance estimates for Earth's largest lake system

Hong X. Do[1,2] ✉, Joeseph P. Smith[3], Lauren M. Fry[4,5] & Andrew D. Gronewold[1]

We develop new estimates of monthly water balance components from 1950 to 2019 for the Laurentian Great Lakes, the largest surface freshwater system on Earth. For each of the Great Lakes, lake storage changes and water balance components were estimated using the Large Lakes Statistical Water Balance Model (L2SWBM). Multiple independent data sources, contributed by a binational community of research scientists and practitioners, were assimilated into the L2SWBM to infer feasible values of water balance components through a Bayesian framework. A conventional water balance model was used to constrain the new estimates, ensuring that the water balance can be reconciled over multiple time periods. The new estimates are useful for investigating changes in water availability, or benchmarking new hydrological models and data products developed for the Laurentian Great Lakes Region. The source code and inputs of the L2SWBM model are also made available, and can be adapted to include new data sources for the Great Lakes, or to address water balance problems on other large lake systems.

Outline

UNIVERSITY OF MICHIGAN

Project Updates: Investigating Uncertainty Associated with the Great Lakes Water Balance

Fall 2021 Coordinating Committee Hydrology Subcommittee Meeting

Thursday, October 21st, 2021

Sarah Katz, Jennani Jayaram, Drew Gronewold

https://www.lre.usace.army.mil/Missions/Operations/Lake-St-Clair-MI/

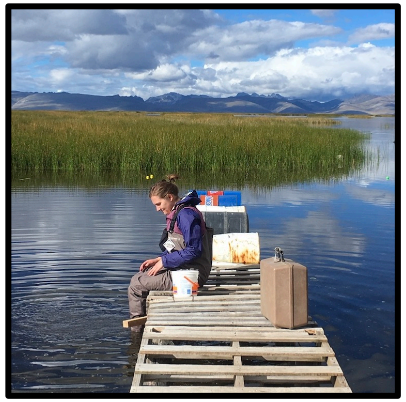
L2SWBM Background

- Large Lakes Statistical Water Balance Model
  - Originally developed at NOAA-GLERL
  - Continued development by the SEAS Hydro Team at the University of Michigan
- Assimilates data on water budget components to provide new estimates of water budget components that are faithful to the Great Lakes water balance.


Drew Gronewold


Hong Do


Dani Cohen


Sarah Katz


Jennani Jayaram


Ryan Armbrustmacher

$$\Delta H_{j,w} = H_{j+w} - H_j = \sum_{i=j}^{j+w-1} (P_i - E_i + R_i + I_i - Q_i + D_i + \epsilon_i)$$

$$\Delta H_{j,w} = H_{j+w} - H_j = \sum_{i=j}^{j+w-1} (P_i - E_i + R_i + I_i - \boxed{Q_i} + D_i + \epsilon_i)$$

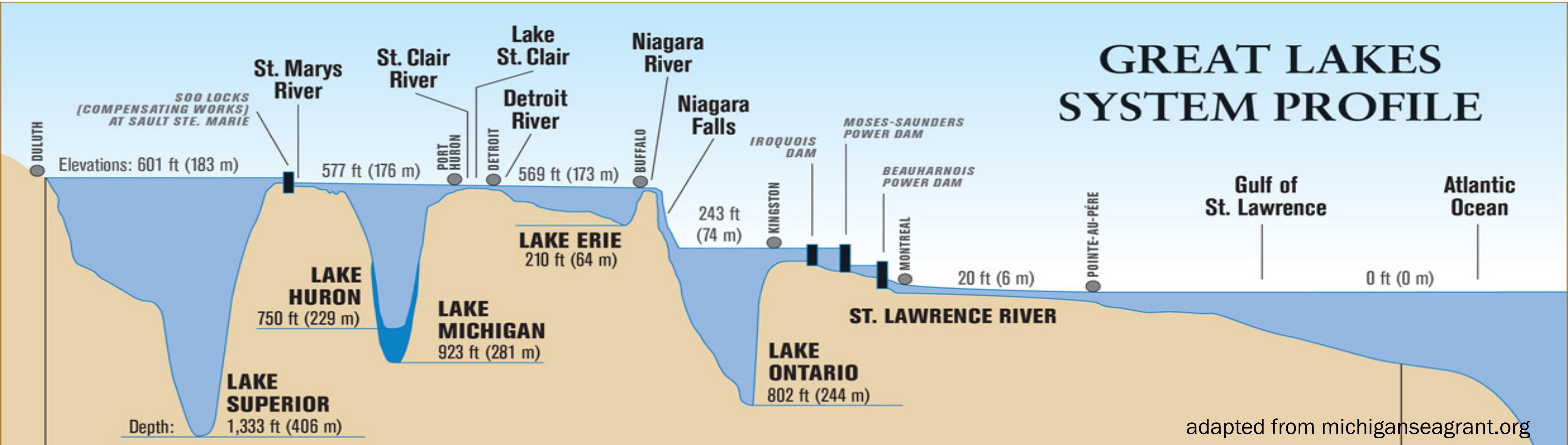
Encoding Lake-to-Lake routing equations

$$Q_{STC} = c\left(\frac{(z_1 + z_2)}{2} - y_m\right)^d$$

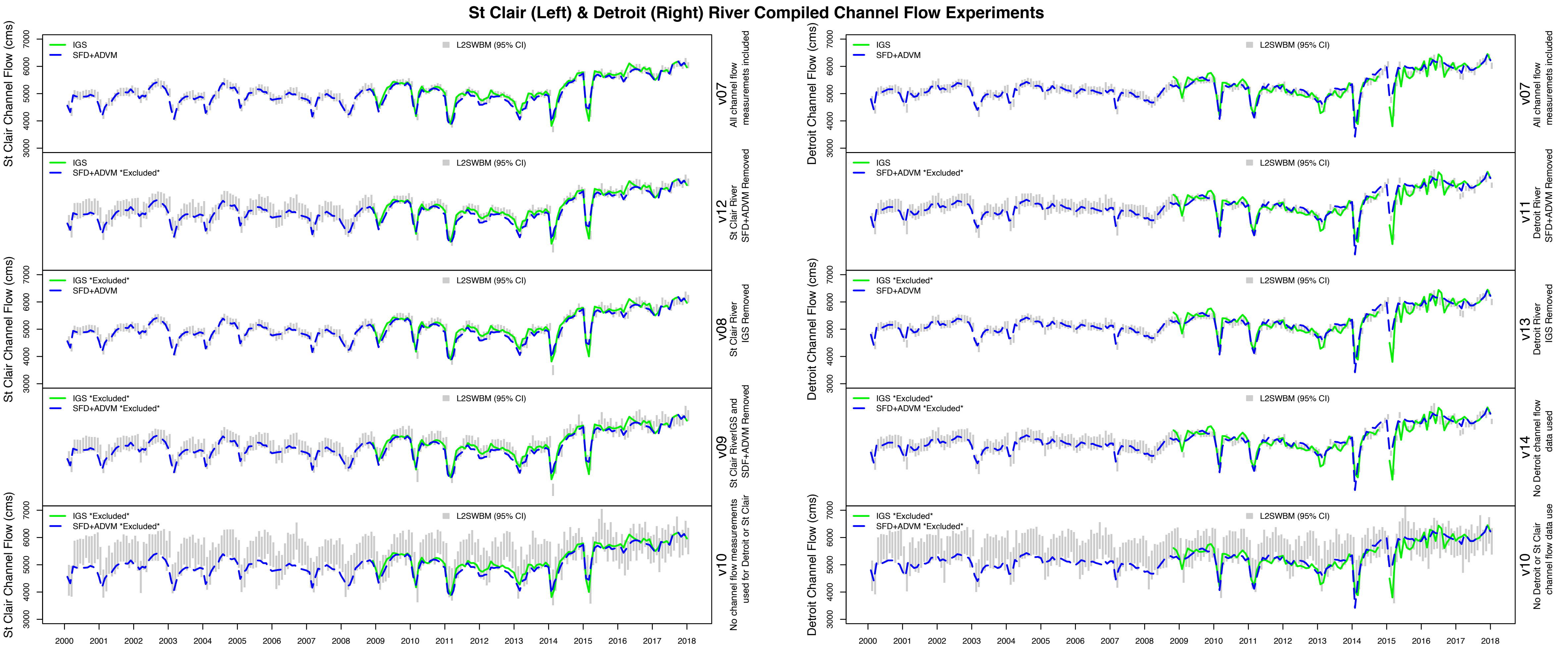
z_1 = MH BOM water levels
z_2 = STC BOM water levels
Q_{STC} = St Clair River channel flow
c = coefficient term
d = exponent term
y_m = 167

* This formulation used for initial tests, additional runs forthcoming with fall component

* L2SWBM can be used to iteratively solve for coefficient values that are faithful to the water balance



adapted from michiganseagrant.org



* Large uncertainties in L2SWBM when channel flow is unconstrained by observations (4th and 5th rows)

* Incorporating channel flow datasets improves L2SWBM performance and reduces model uncertainties (top row)

Lake-to-Lake Routing Status

Priors for this run:

c : mean = 250 ; SD = 50

d : mean = 1.6 ; SD = 2

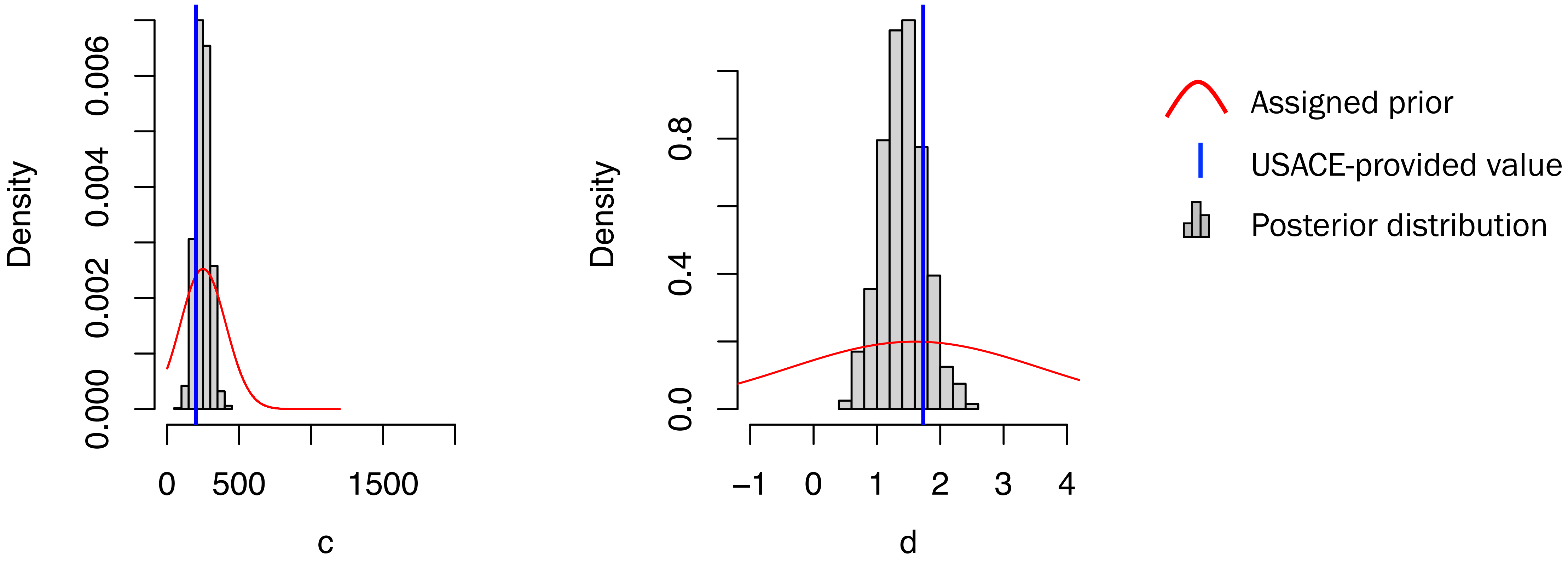
Posteriors for this run:

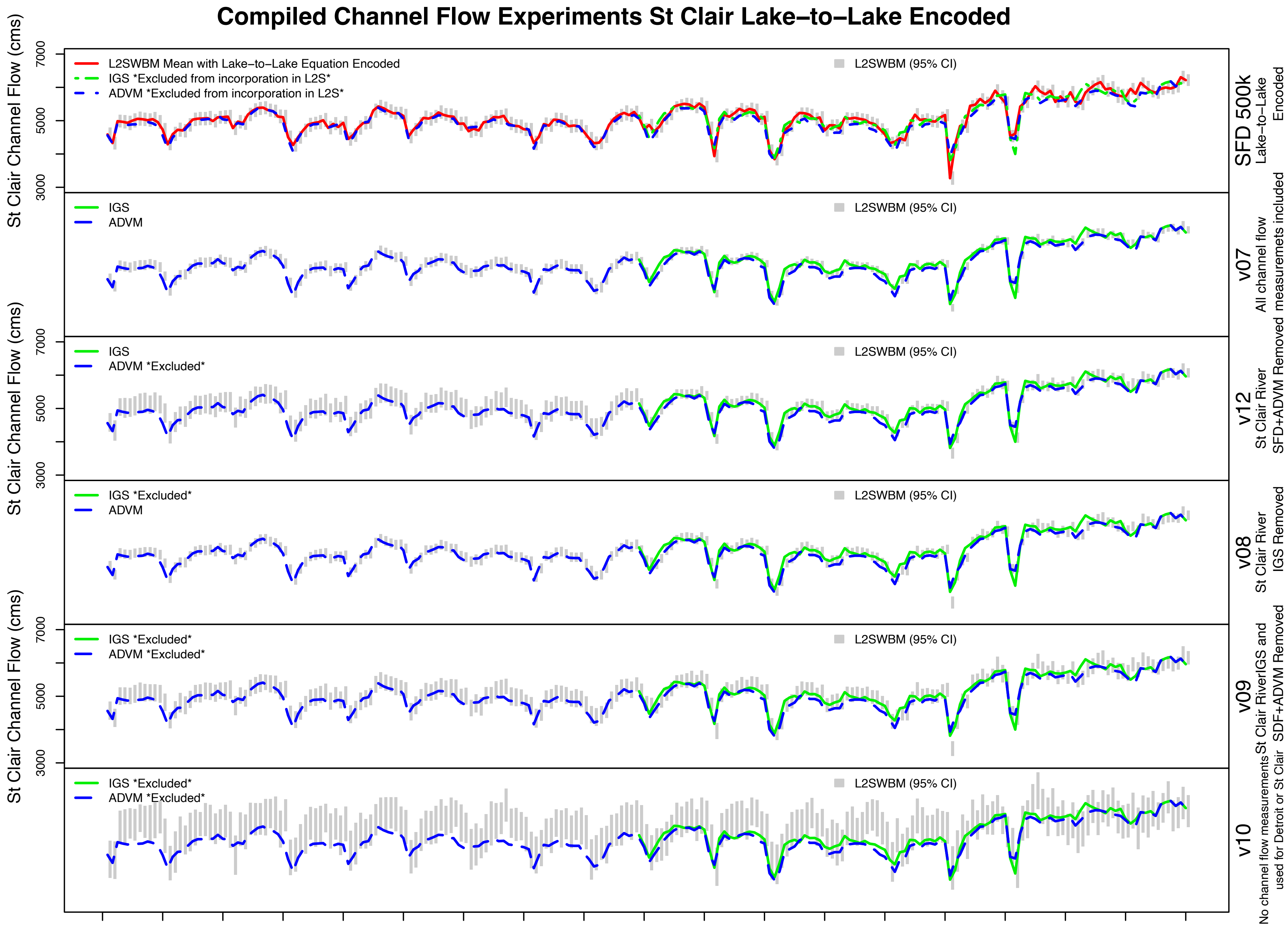
c : mean = 249.7 ; 95% CI = 152.2 – 349.3

d : mean = 1.41 ; 95% CI = 0.77 – 2.05

Iterations: 500,000

Chains: 3





New result constrained by MH & STC BOM and Lake-to-Lake equation

Fully constrained by St Clair & Detroit River observations

Unconstrained by St Clair River observations

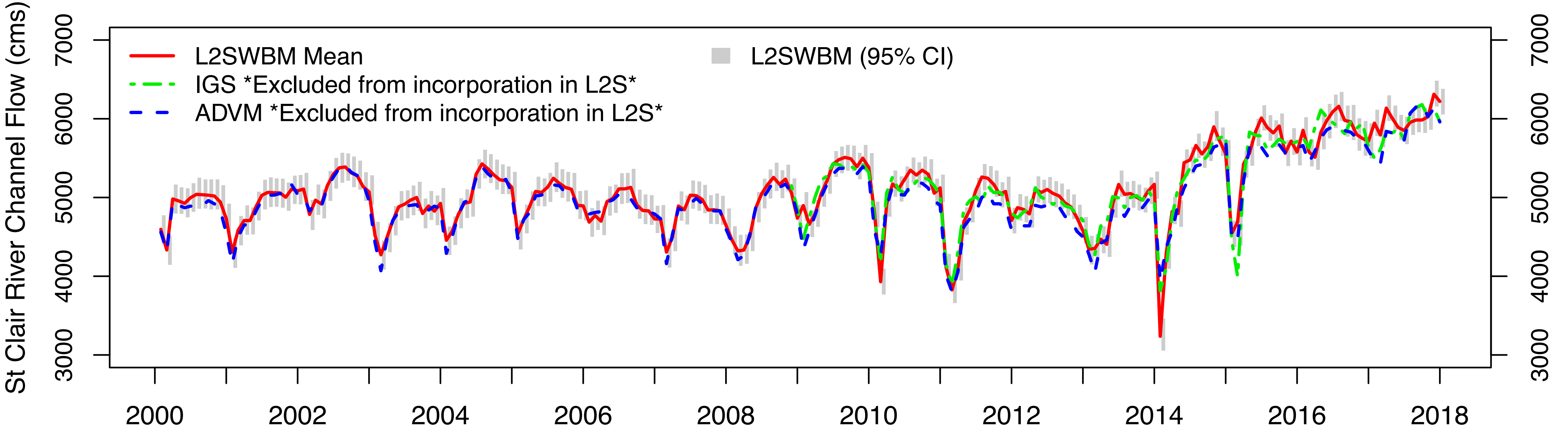
Unconstrained by St Clair & Detroit River observations

Lake-to-Lake Routing Status

Priors for this run:
c : mean = 250 ; SD = 50
d : mean = 1.6 ; SD = 2

Posteriors for this run:
c : mean = 249.7 ; 95% CI = 152.2 – 349.3
d : mean = 1.41 ; 95% CI = 0.77 – 2.05

Iterations: 500,000
Chains: 3



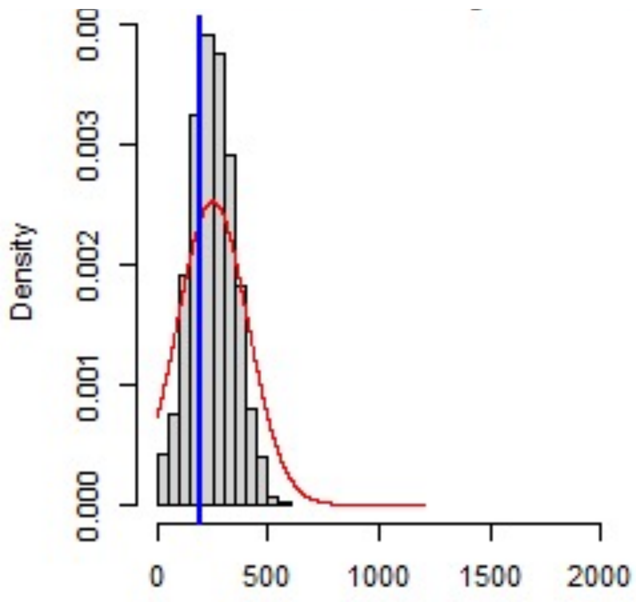
Lake-to-Lake Routing Status

Assigned prior

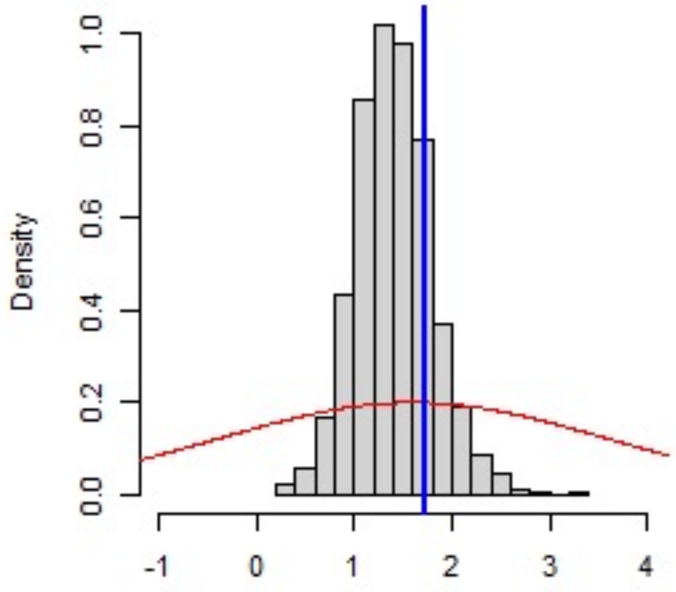
USACE-provided value

Posterior distribution

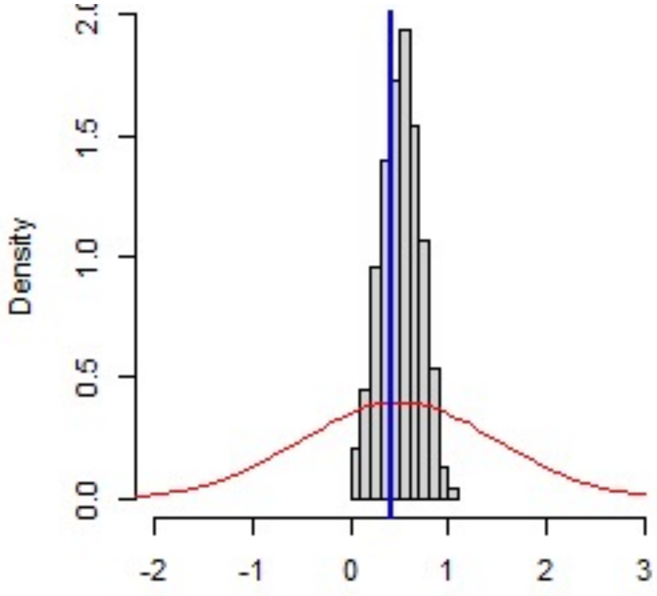
** Using a formulation of Lake-to-Lake equation incorporating fall
→ Note: Small number of iterations, more testing needed!!



c



d



f

Improving representation of groundwater in foundational Great Lakes hydrologic and hydrodynamic models and data sets

ACTIVE

By John Wesley Powell Center for Analysis and Synthesis September 30, 2020

Groundwater plays a critical role in the water balance, however the groundwater component of the hydrologic cycle is frequently overlooked at basin scales because it is difficult to observe and quantify. We address this problem through a novel framework that combines existing hydrological models and data sets with groundwater flux estimates across Earth's largest system of lakes; the Laurentian Great Lakes. Aside from serving as a template for combining surface and ground water data and models, the Laurentian Great Lakes recently transitioned from a period characterized by water scarcity (water levels on the lakes were persistently below average from 1998 through 2013) to extreme water abundance (all-time high water levels were set in 2017 and 2019). Throughout this transition, we know of no comprehensive data record or modeling system that explicitly linked changes in observed land surface hydrology with critical subsurface groundwater processes. In addition to utilizing our novel framework for combining existing surface and ground water data sets and model simulations, we will also demonstrate the impact of ground water representation in existing lake physics models that serve as the basis for understanding lake evaporation, circulation patterns, and pollutant fate and transport dynamics.

Principal Investigators:
Andrew D. Gronewold *(University of Michigan)*
Sandra M. Eberts *(USGS - Water Mission Area)*
Juliane Mai *(Univresity of Waterloo)*
Howard W. Reeves *(USGS - Upper Midwest Water Science Center)*

The Great Lakes from space.

Contacts

John Wesley Powell Center for Earth System Analysis and Synthesis

Fort Collins Science Center (FORT)
2150 Centre Ave Building C
Fort Collins, CO 80526
United States

Email: powellcenter@usgs.gov
Phone: 970-226-9103

Howard W Reeves

Research Hydrologist
Upper Midwest Water Science Center
Email: hwreeves@usgs.gov
Phone: 517-887-8914

Journal of Hydrology 594 (2021) 125911

Contents lists available at ScienceDirect

Journal of Hydrology

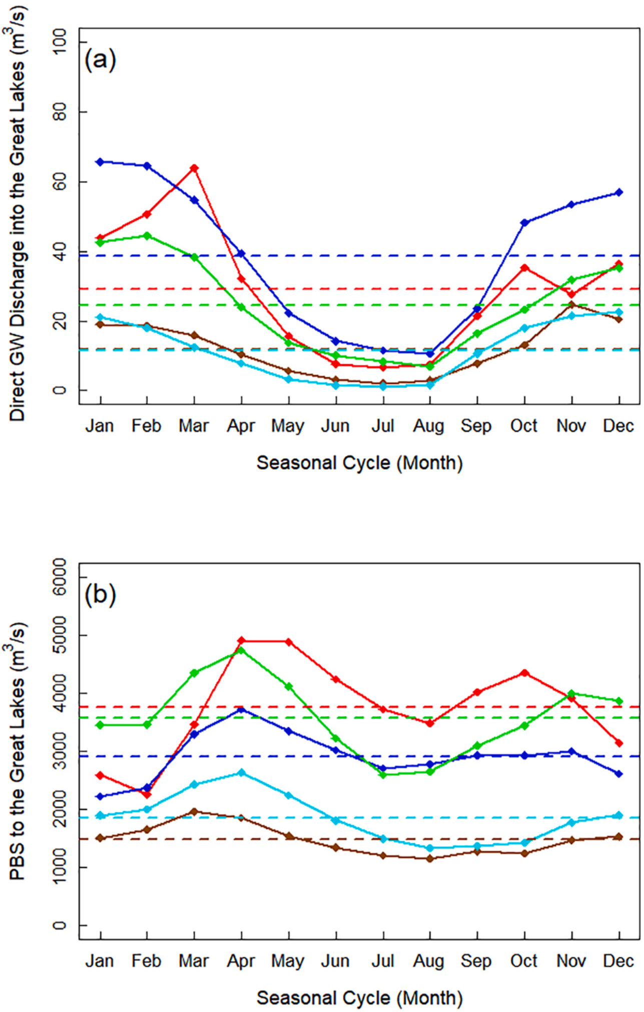
journal homepage: www.elsevier.com/locate/jhydrol

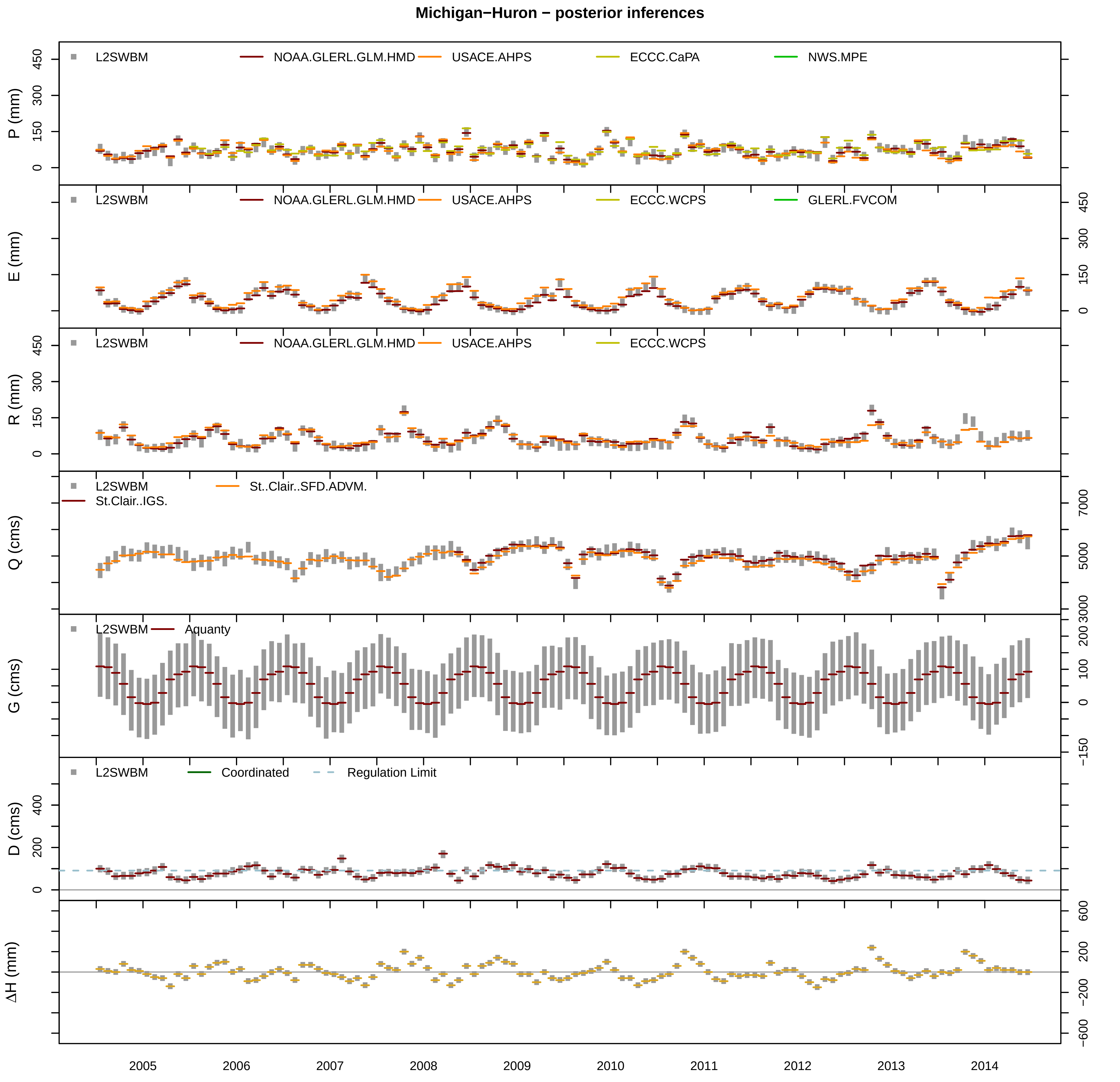
Research papers

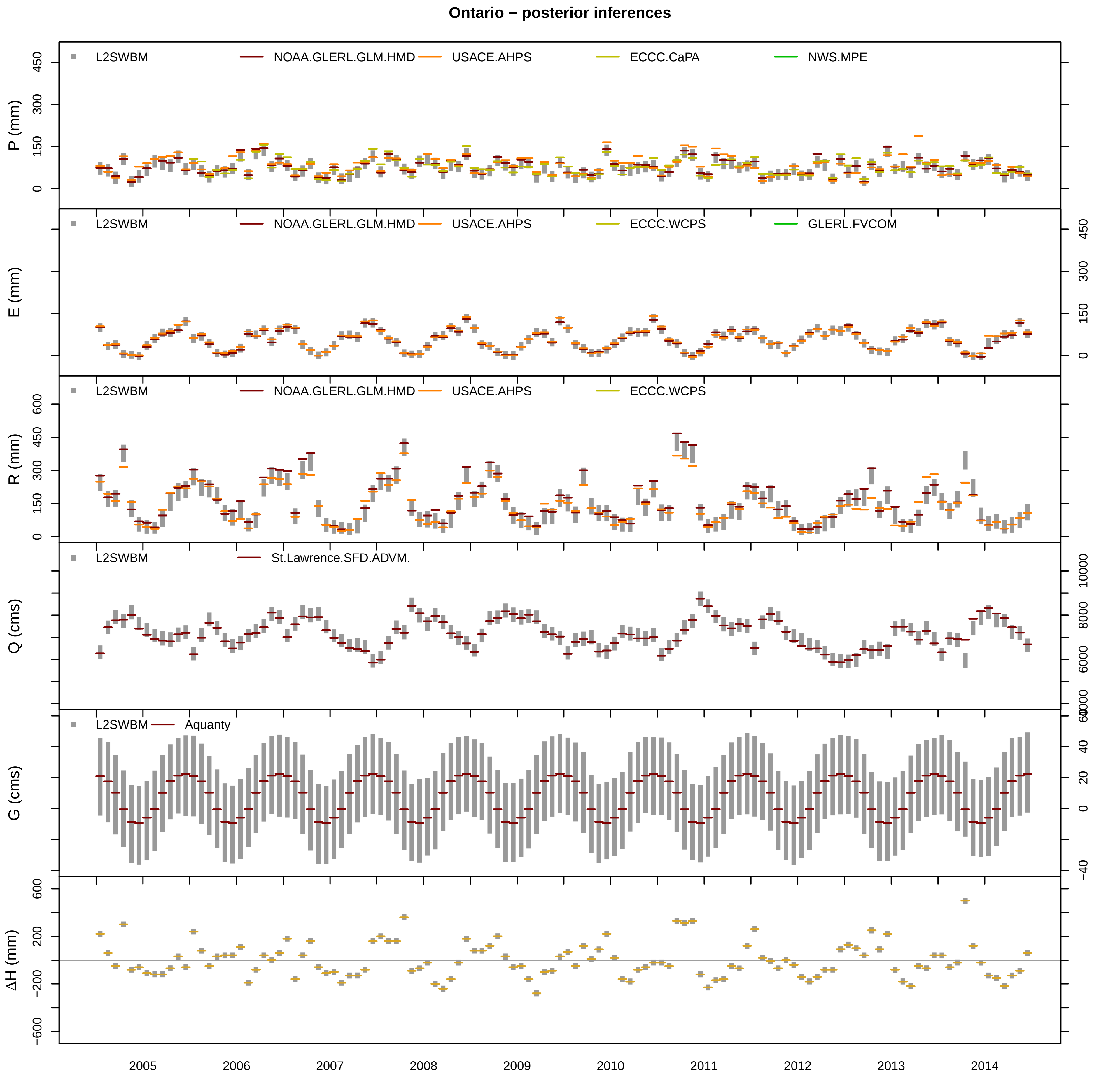
Investigating groundwater-lake interactions in the Laurentian Great Lakes with a fully-integrated surface water-groundwater model

Shu Xu [a], S.K. Frey [a,b,*], A.R. Erler [a,d], O. Khader [a], S.J. Berg [a,b], H.T. Hwang [a,b], M.V. Callaghan [a], J.H. Davison [c], E.A. Sudicky [a,b]

[a] Aquanty, 564 Weber St. N., Waterloo, ON N2L 5C6, Canada
[b] University of Waterloo, Department of Earth and Environmental Sciences, 200 University Ave. W., Waterloo, ON N2L 3G1, Canada
[c] The Catholic University of America, Department of Civil and Environmental Engineering, 620 Michigan Ave., N.E., Washington, DC 20064, United States
[d] University of Waterloo, Department of Geography and Environmental Management, 200 University Ave. W., Waterloo, ON N2L 3G1, Canada


(a)
Direct GW Discharge into the Great Lakes (m^3/s)
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Seasonal Cycle (Month)
(b)
PBS to the Great Lakes (m^3/s)
0
1000
2000
3000
4000
5000
6000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Seasonal Cycle (Month)


Michigan−Huron − posterior inferences
P (mm)
L2SWBM
NOAA.GLERL.GLM.HMD
USACE.AHPS
ECCC.CaPA
NWS.MPE
E (mm)
ECCC.WCPS
GLERL.FVCOM
R (mm)
Q (cms)
St..Clair..SFD.ADVM.
St.Clair..IGS.
G (cms)
Aquanty
D (cms)
Coordinated
Regulation Limit
ΔH (mm)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014


Ontario − posterior inferences
P (mm)
L2SWBM
NOAA.GLERL.GLM.HMD
USACE.AHPS
ECCC.CaPA
NWS.MPE
E (mm)
ECCC.WCPS
GLERL.FVCOM
R (mm)
Q (cms)
St.Lawrence.SFD.ADVM.
G (cms)
Aquanty
ΔH (mm)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

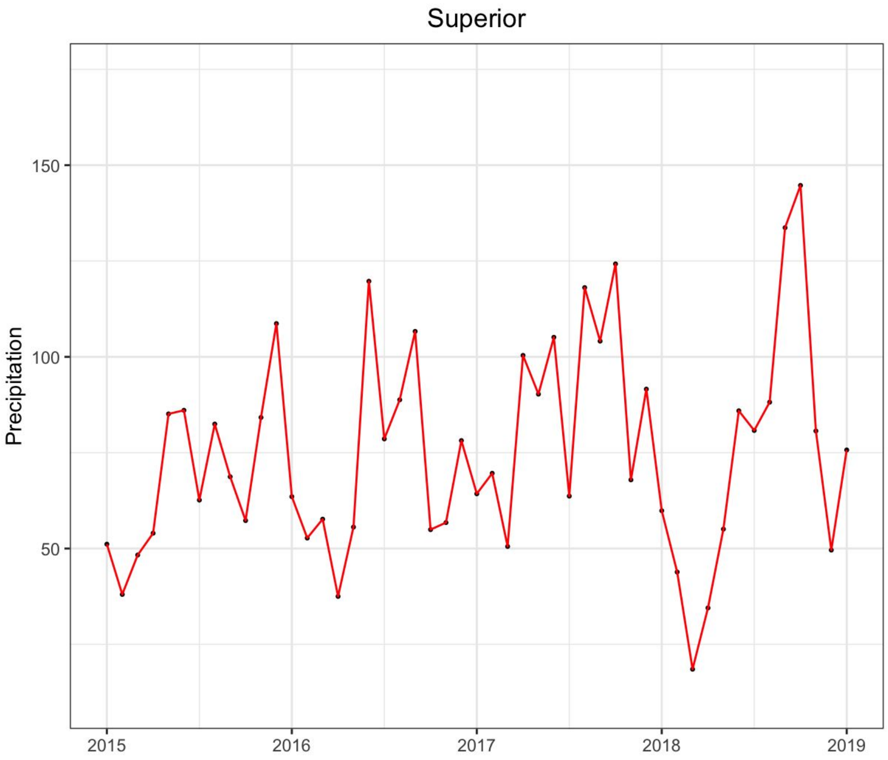
Lake Superior	**Average magnitude**		**Average monthly estimate uncertainty**
Component of water balance	ft^3/s	Low	High
Connecting-channel inflow	N/A	N/A	N/A
Connecting-channel outflow	79,118	5%	15%
Change in storage	N/A	0.12 in (3 mm)	0.47 in (12 mm)
Over-lake precipitation	73,047	15%	45%
Runoff	55,619	15%	35%
Evaporation	54,233	10%	35%
Long Lac diversion	1,412	10%	30%
Ogoki diversion	4,035	10%	30%
Ground water	Unknown	100% of 850 ft^3/s	100% of 3,500 ft^3/s
Component NBS	70,398	11%	31%
Residual NBS	73,671	4%	12%

Table extracted from: Neff, Brian P. and J. R. Nicholas, 2005, Uncertainty in the Great Lakes Water Balance, Date Posted: November 23, 2005: U.S. Geological Survey Scientific Investigations Report 2004-5100, 42 p. https://pubs.water.usgs.gov/sir2004-5100/

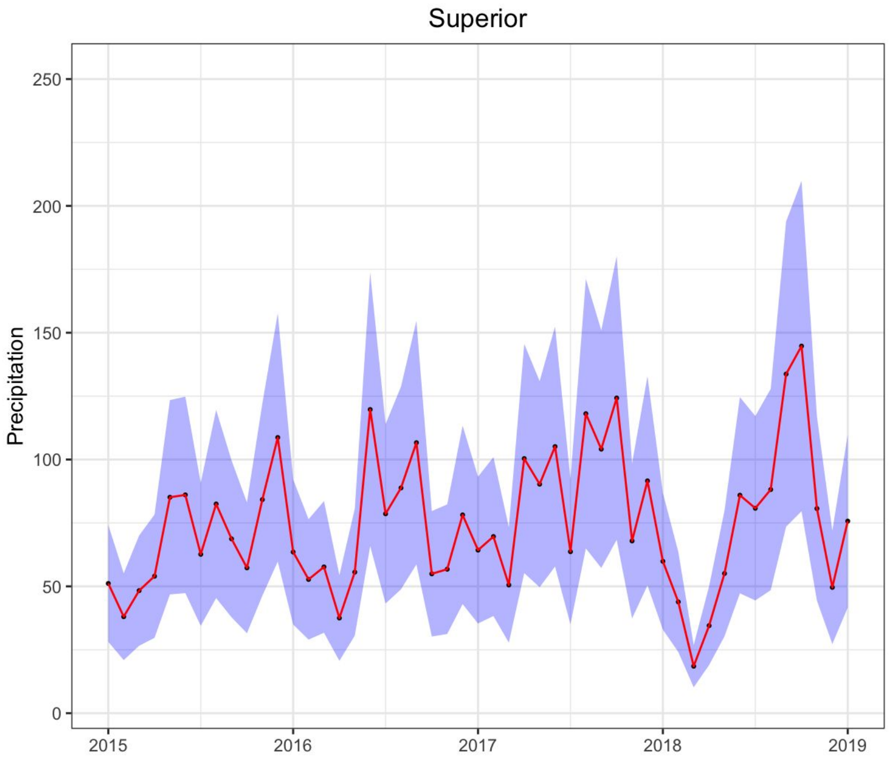
Lake Superior Component of water balance	Average magnitude ft^3/s	Average monthly estimate uncertainty Low	 High
Connecting-channel inflow	N/A	N/A	N/A
Connecting-channel outflow	79,118	5%	15%
Change in storage	N/A	0.12 in (3 mm)	0.47 in (12 mm)
Over-lake precipitation	73,047	15%	45%
Runoff	55,619	15%	35%
Evaporation	54,233	10%	35%
Long Lac diversion	1,412	10%	30%
Ogoki diversion	4,035	10%	30%
Ground water	Unknown	100% of 850 ft^3/s	100% of 3,500 ft^3/s
Component NBS	70,398	11%	31%
Residual NBS	73,671	4%	12%

Table extracted from: Neff, Brian P. and J. R. Nicholas, 2005, Uncertainty in the Great Lakes Water Balance, Date Posted: November 23, 2005: U.S. Geological Survey Scientific Investigations Report 2004-5100, 42 p. https://pubs.water.usgs.gov/sir2004-5100/

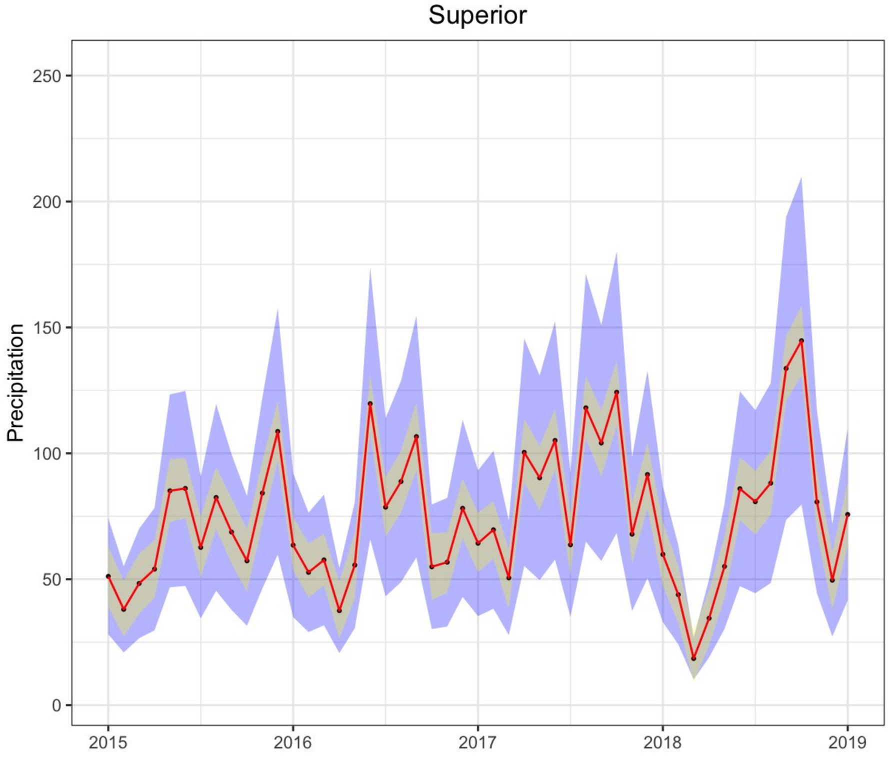
L2SWBM output: Lake Superior precipitation (2015-2019)

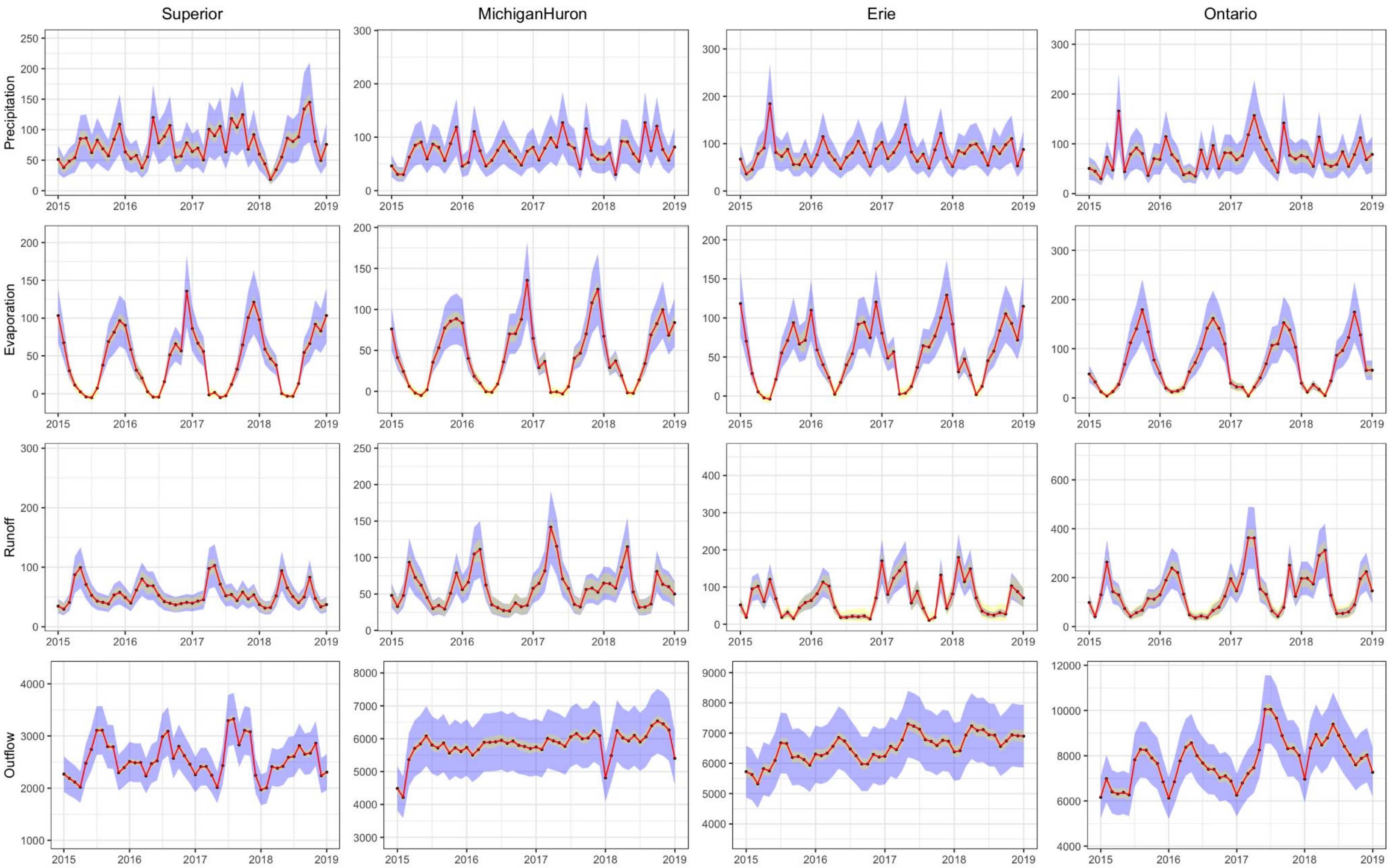


L2SWBM output: Lake Superior precipitation (2015-2019)



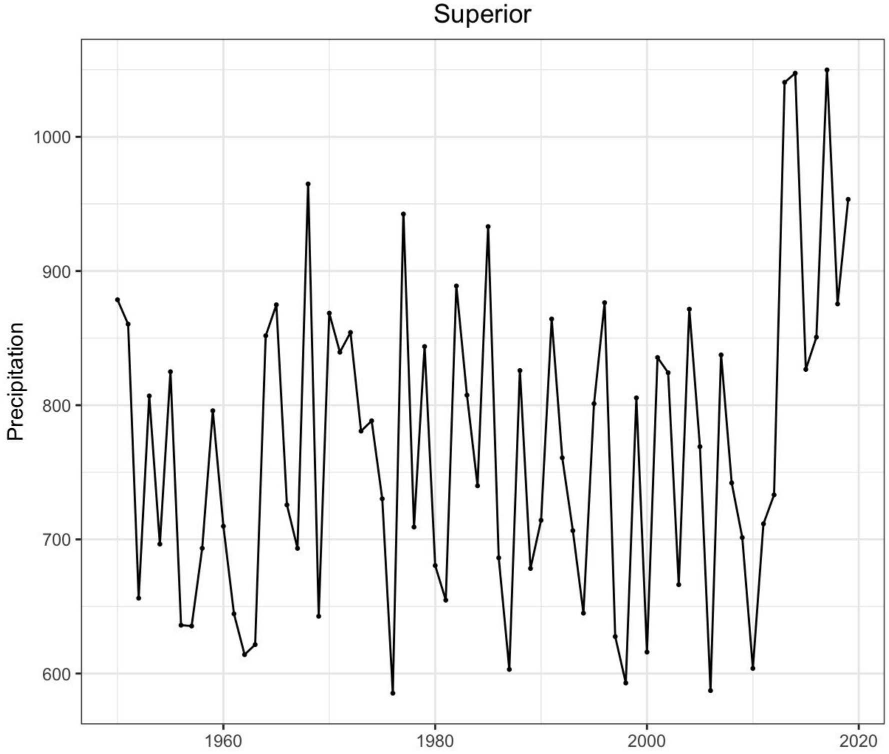
L2SWBM output: Lake Superior precipitation (2015-2019)





Superior
MichiganHuron
Erie
Ontario
Precipitation
Evaporation
Runoff
Outflow
2015
2016
2017
2018
2019

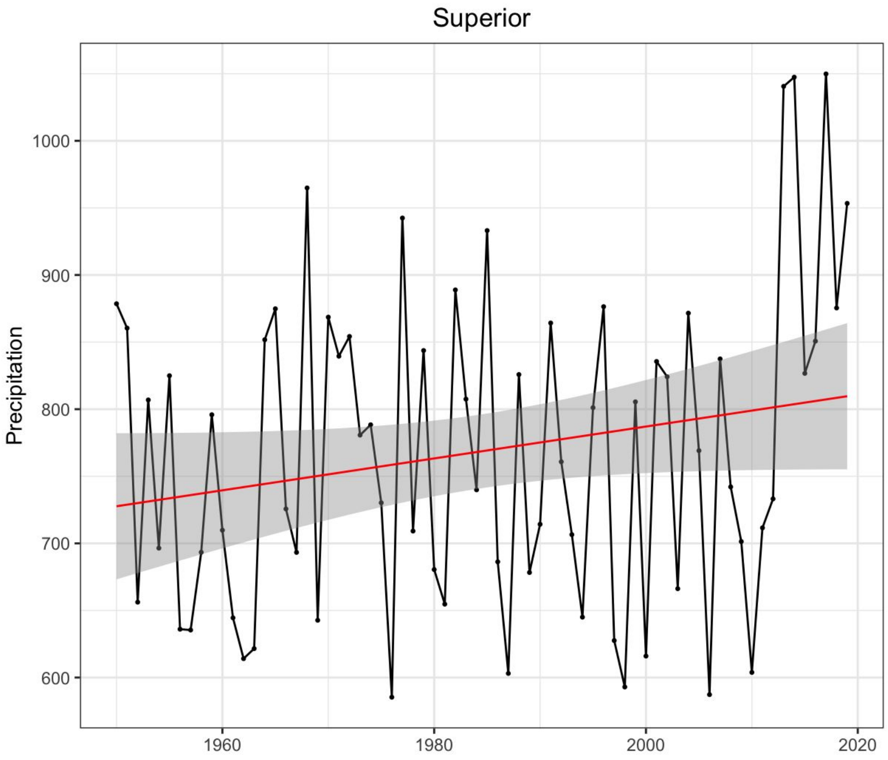
Lake Superior annual precipitation (1950-2019)



Method 1: Linear regression

- A simple and quick process of finding a line that best fits the data

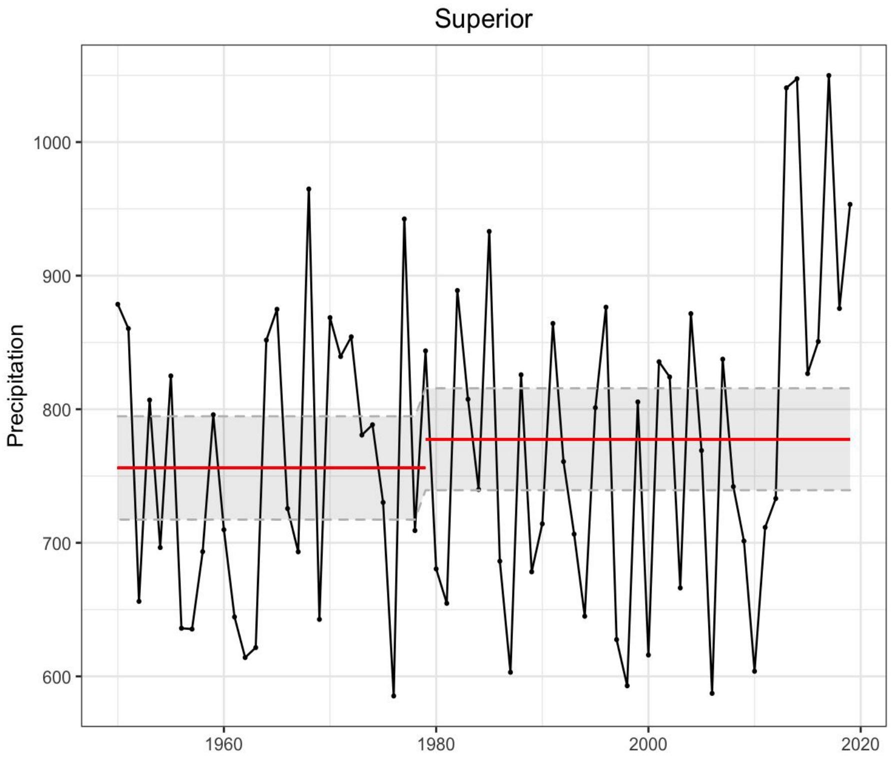
- Determines the underlying trends, and can be used to forecast future water balance



Method 2a: Fixed reference period (1950-1979 vs 1980-present)

- Filters out interannual variation or anomalies

- Shows longer climatic trends

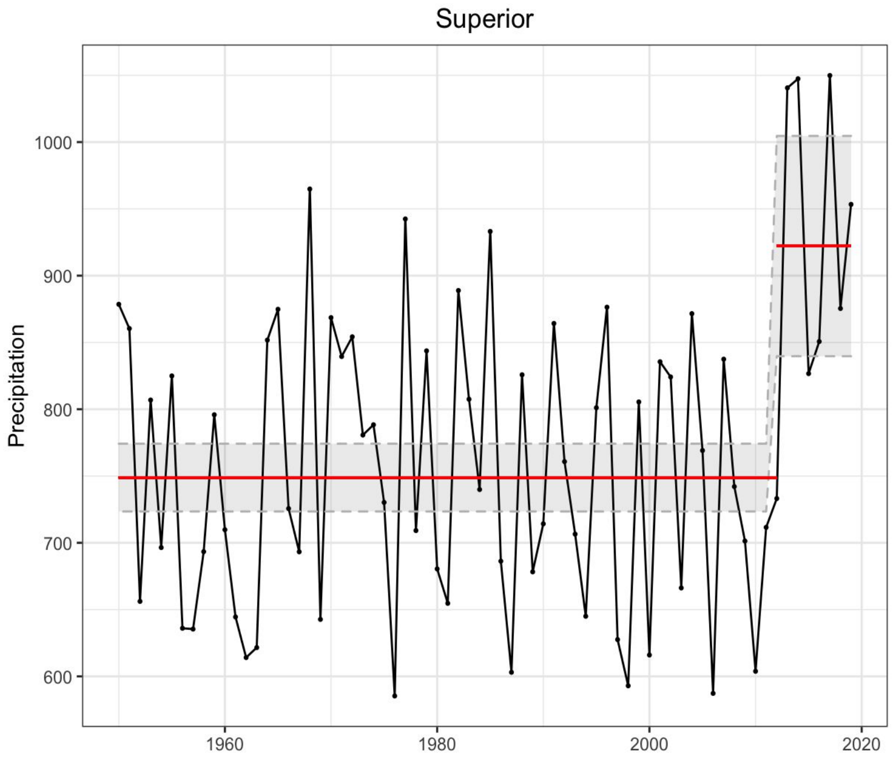


Fixed reference period

Method 3: Change point detection

- Automatically detects where a statistically significant shift in the data occurs

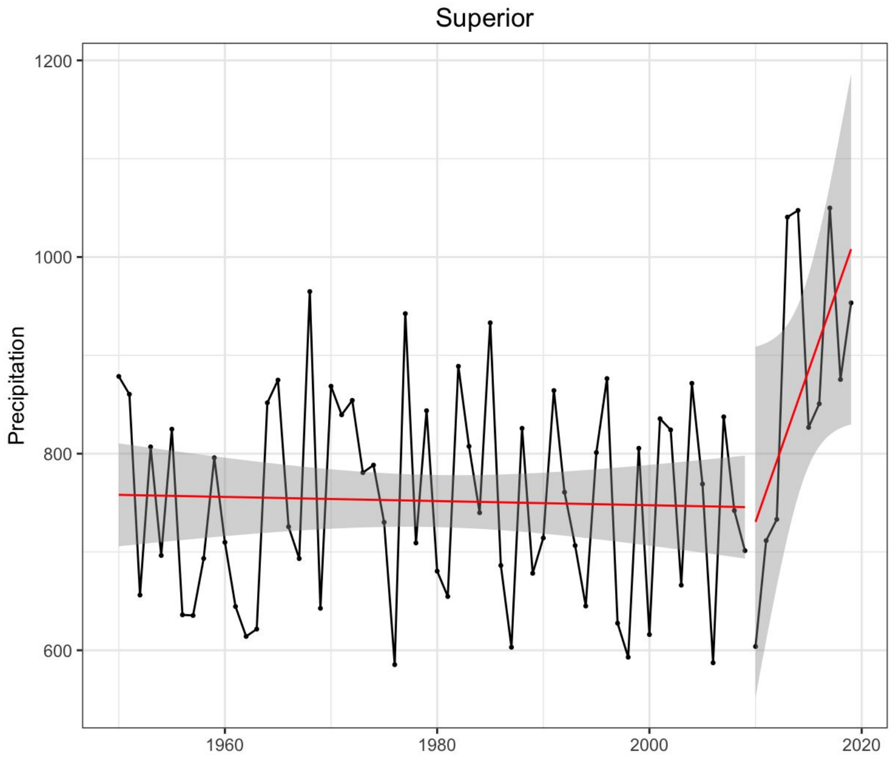
- Divides a time series into two segments with distinct statistical characteristics



Method 4: “Hockey stick” segmented regression

- Automatically selects the “best” breakpoint where there is a significant trend change over time

- Widely used in estimating intervention effects on interrupted time series studies



Outline

1. Introduction
2. Day 1 (Monday) - L2SWBM Technical Updates
   - L2SWBM background and technical overview
   - Recent and ongoing research projects
   - Version control and code repositories
   - Reality check (under the hood)
3. Day 2 (Tuesday) - Copulas and Federal Perspectives
   - Using Copulas
   - Federal Agency Partners
4. Day 3 (Wednesday) - Beyond the (Laurentian) Great Lakes
   - African Great Lakes
   - Mono Lake
   - NSF large lakes proposal (and other ideas)

Outline

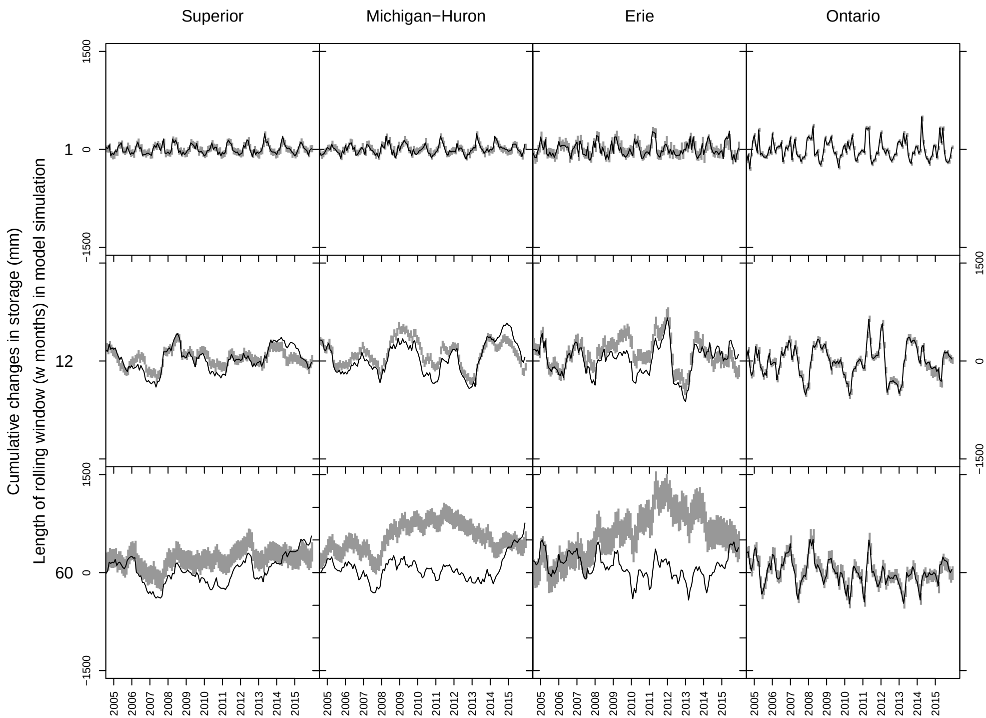


Figure 3: Water balance closure assessment for the version of our model configured with a 1-month inference window. Simulated changes in storage from the model are presented as grey bands (95% posterior predictive intervals) over cumulative one month (top row), 12 month (middle row), and 60 month periods. Observed cumulative changes in storage over corresponding time horizons are represented by a black line.

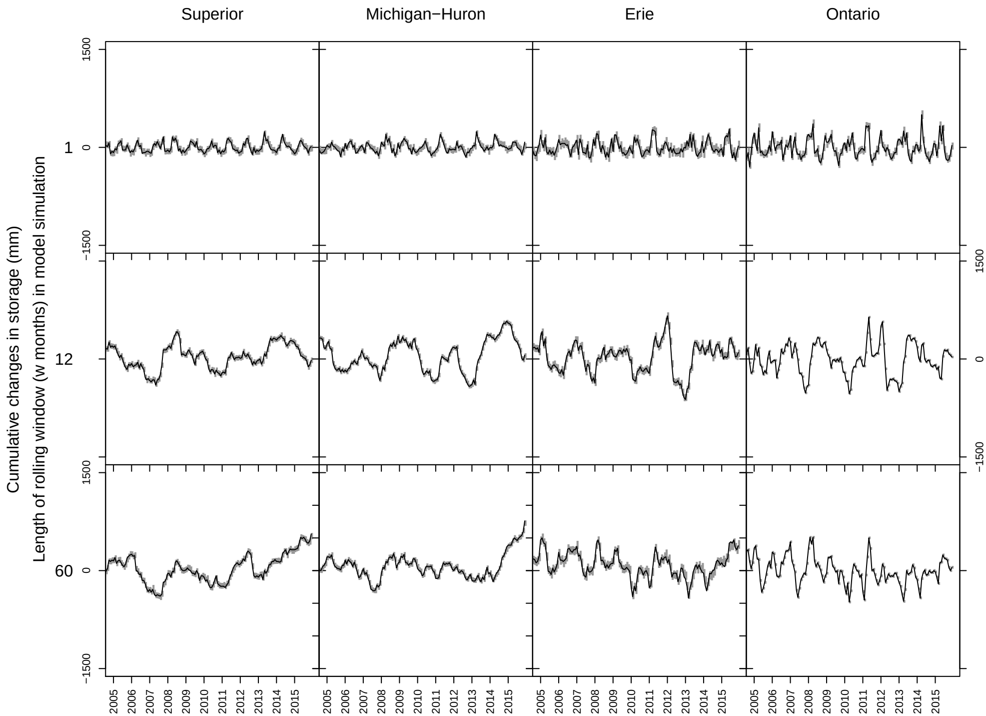


Figure 4: Water balance closure assessment for the version of our model configured with a 12-month inference window. Simulated changes in storage from the model are presented as grey bands (95% posterior predictive intervals) over cumulative one month (top row), 12 month (middle row), and 60 month periods. Observed cumulative changes in storage over corresponding time horizons are represented by a black line. Vertical axis scale in each panel is the same as in figure 3 to facilitate comparison.

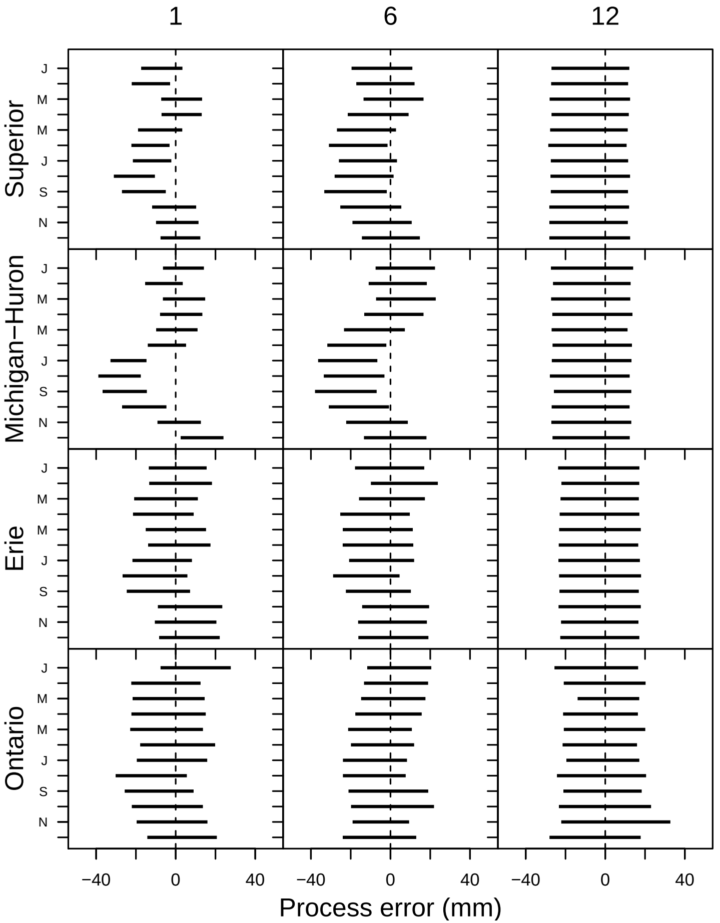


Figure 2: 95% credible intervals for model process errors ϵ_{c_t} from model configurations with a 1-month inference window (left), 6-month inference window (center), and a 12-month inference window (right).

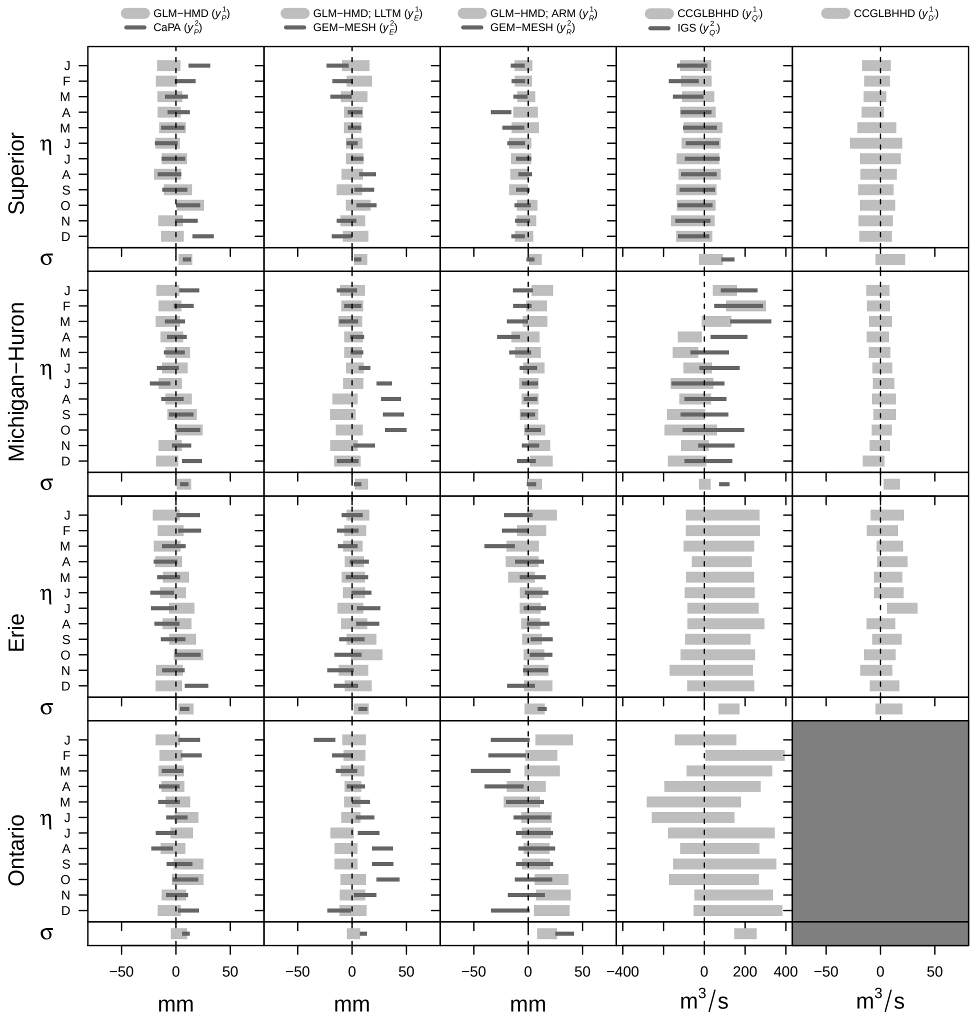
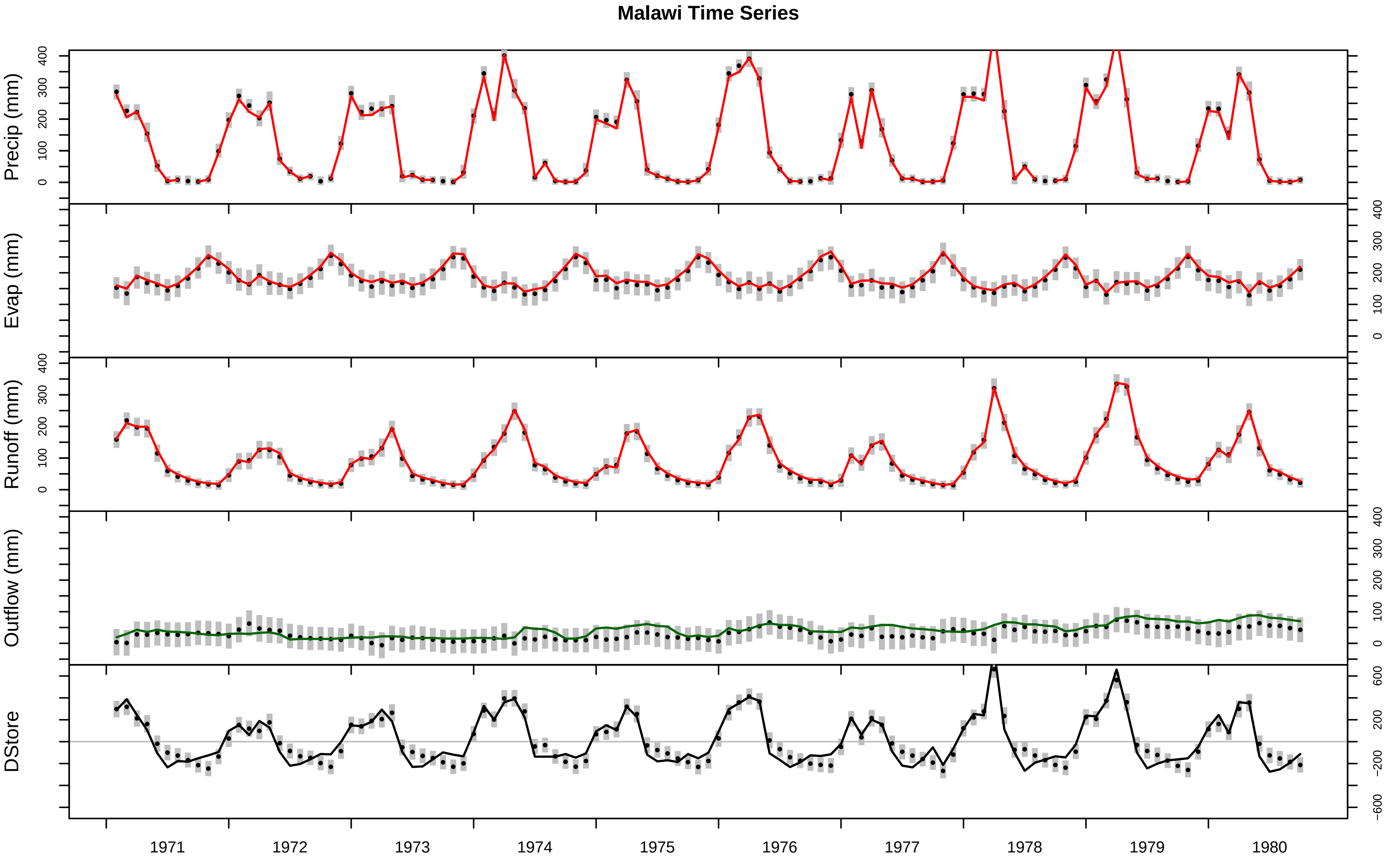


Figure 6: Inferred bias (η) and error (σ) in historical water balance component data based a configuration of our model with a 12-month inference window. Columns, from left to right, correspond to monthly data for over-lake precipitation, over-lake evaporation, lateral tributary runoff, outflow, and interbasin diversions. Horizontal bars represent 95% credible intervals. For details on data sources, see table A1.



Malawi Time Series
Precip (mm)
Evap (mm)
Runoff (mm)
Outflow (mm)
DStore
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980

Outline