

Meeting of the Regional Body & Compact Council Science Team

June 15, 2022
Erie, Pennsylvania

GREAT LAKES
ST. LAWRENCE
GOVERNORS
& PREMIERS



University of Michigan L2SWBM Research Team



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Dani Cohen, MS

Ryan Armbrustmacher,
MS

Sarah Katz, Ph.D
candidate

Alex Vandeweghe

Jennani Jayaram



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Maegan Muir, MS

Justin Huber, MS

Hannah Paulson, MS



GREAT LAKES ST. LAWRENCE GOVERNORS & PREMIERS



Outline

1. Introduction to the Great Lakes Water Balance

2. Reducing uncertainty in the water balance

- Prior approaches to measure uncertainty
- Large Lake Statistical Water Balance Model (L2SWBM)

3. Climate change and the historical record

1. Linear regression
2. Reference period (1950-1979 vs 1980-2019)
 - a. Comparison of means and standard errors
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5. Smoothed moving average

4. Impacts of climate change on the future water balance

- Regional climate models
- Historical trends

5. Conclusion





Map of the North American Great Lakes drainage basin (brown-shaded region) including major cities, political boundaries, interbasin diversions, and interconnecting channels. Ji, Xialong & Gronewold, Andrew & Daher, Houraa & Rood, Richard. (2019). Modeling seasonal onset of coastal ice. *Climatic Change*. 154. 125-141. 10.1007/s10584-019-02400-1 .

https://www.researchgate.net/publication/344434900_Modeling_seasonal_onset_of_coastal_ice

Lake Water Balance Equation

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

ΔS : Change in storage (water levels)

P: Precipitation over the lake

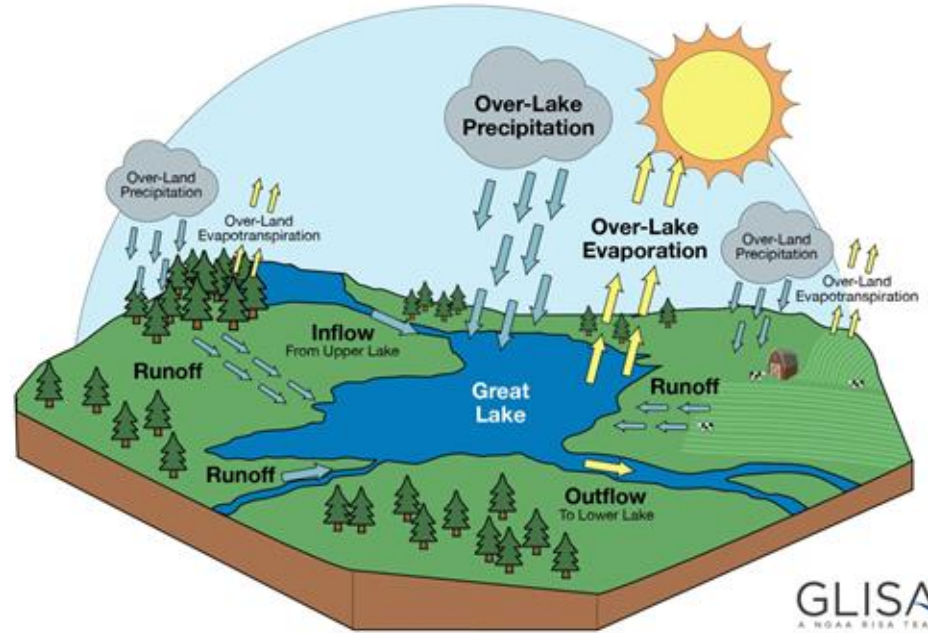
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Water balance components that affect Great Lakes water levels. <https://glisa.umich.edu/sustained-assessment/lake-levels/>

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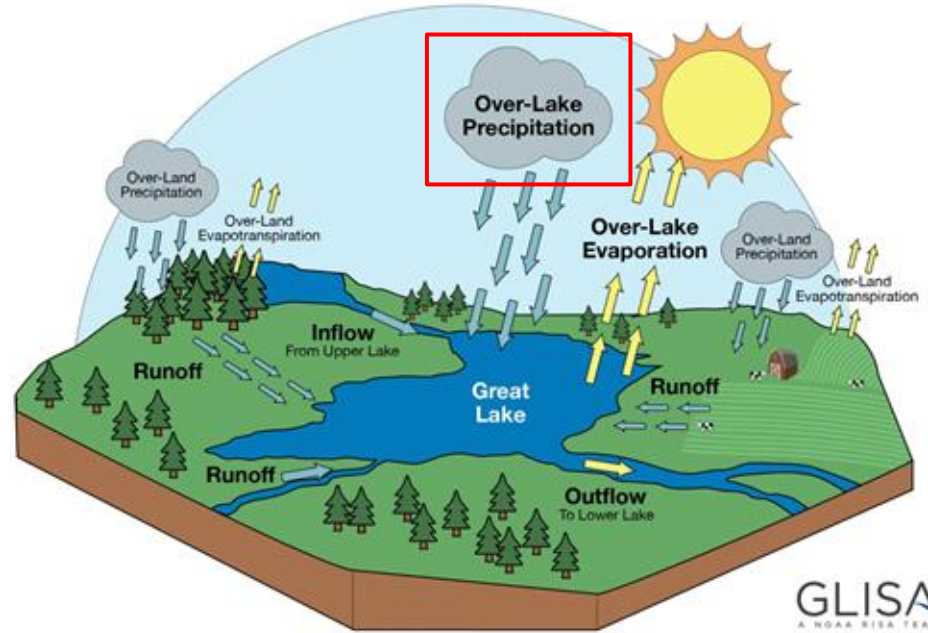
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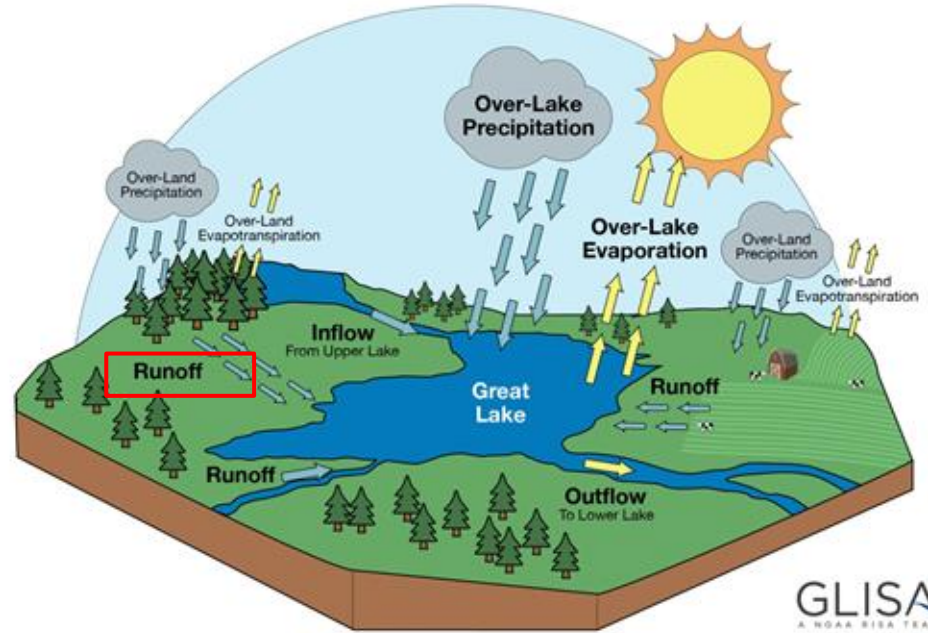
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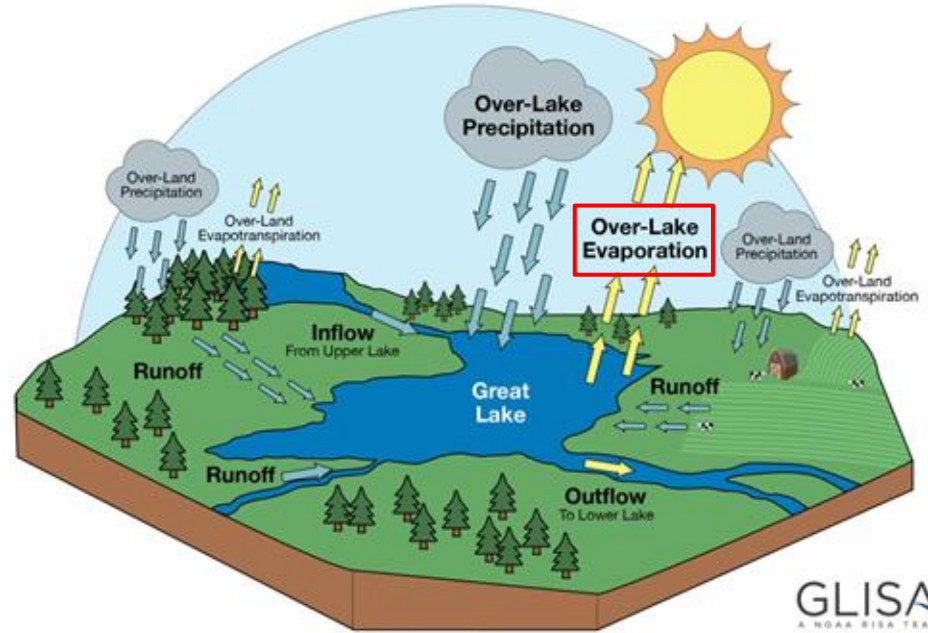
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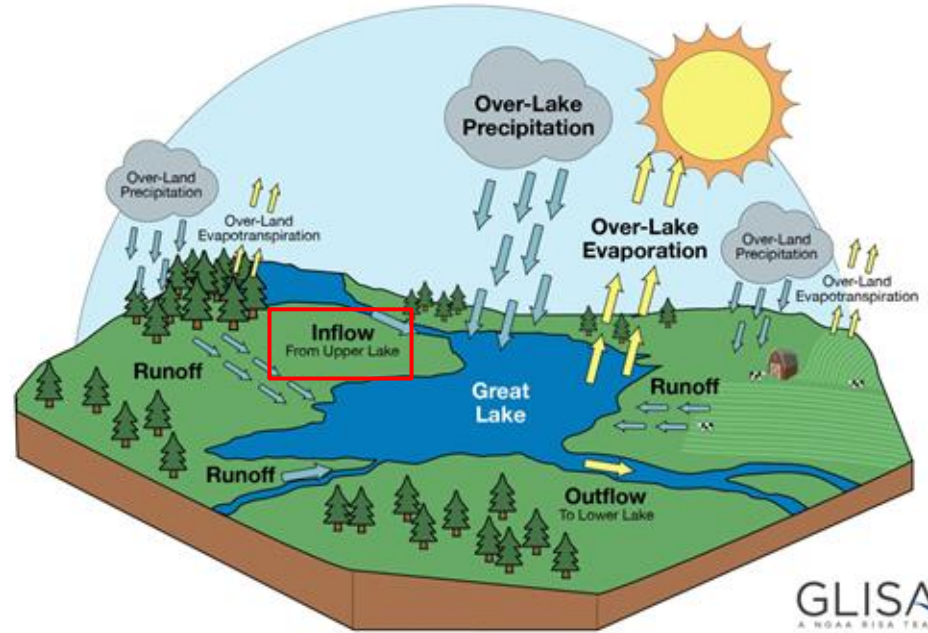
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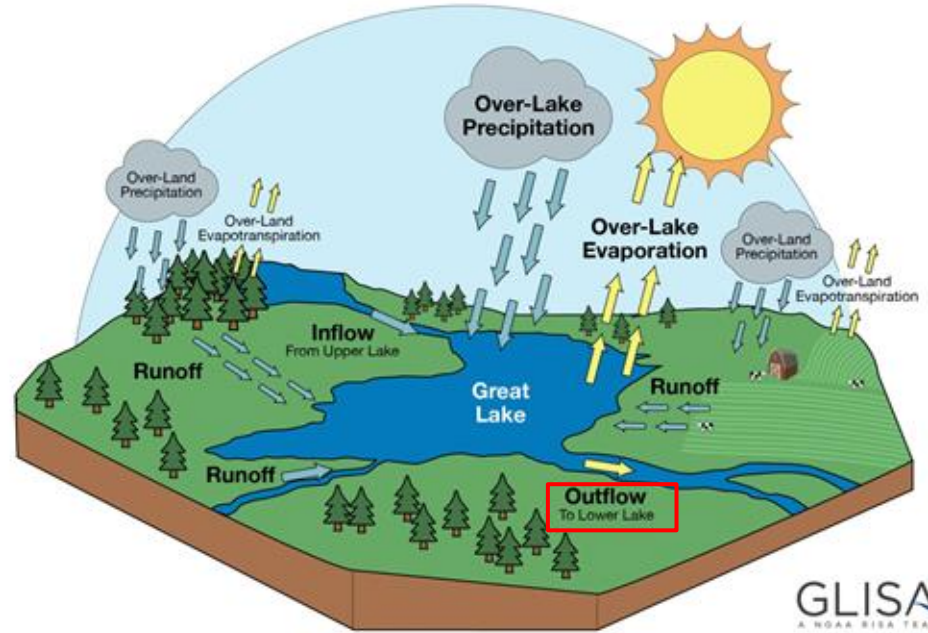
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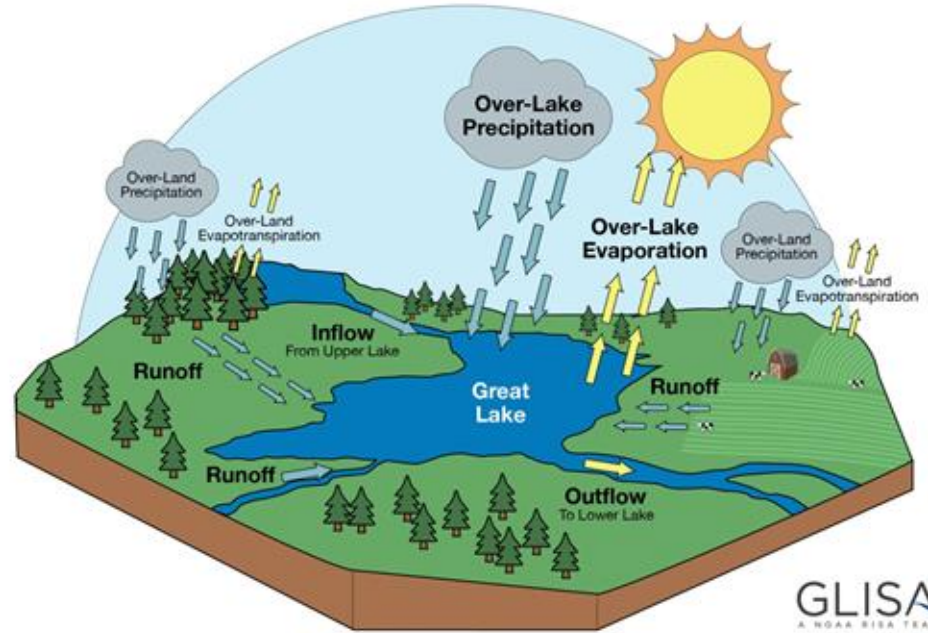
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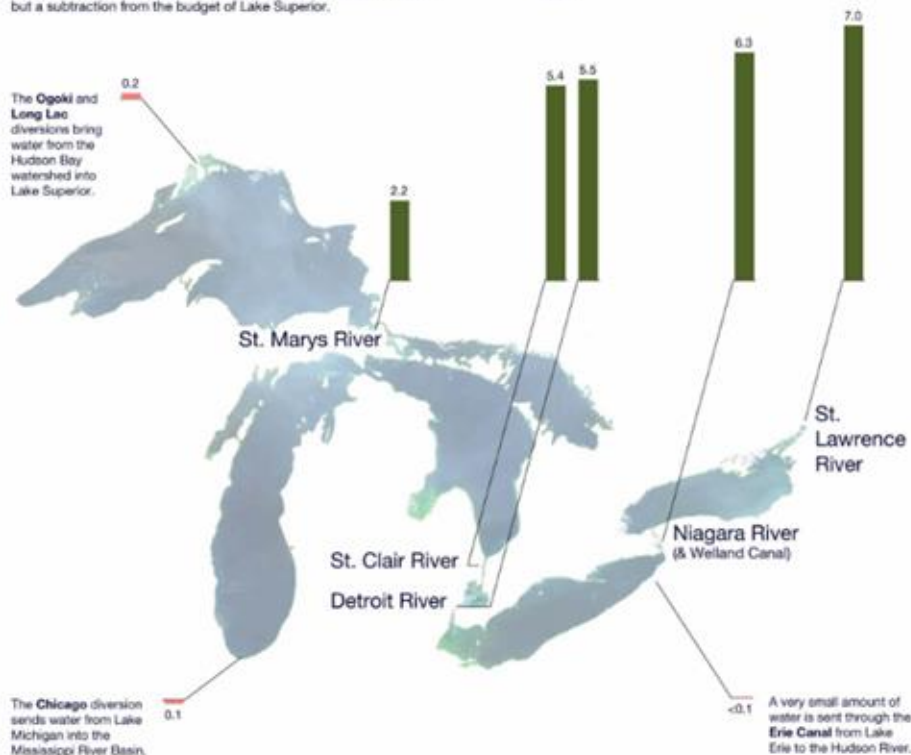
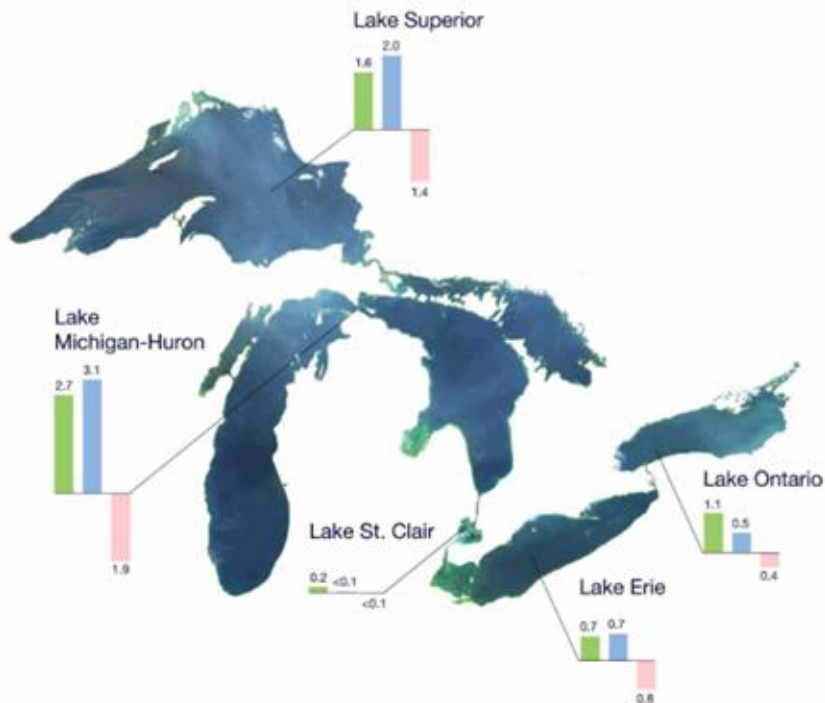
Runoff (deposit) is all of the water that runs off of land in a lake's watershed, making its way into rivers, which eventually empty into the lakes. It is impacted by precipitation over land, evaporation over land, and transpiration (the water sucked up by plants).

Overlake Precipitation (deposit) is precipitation that falls on the lake surface.

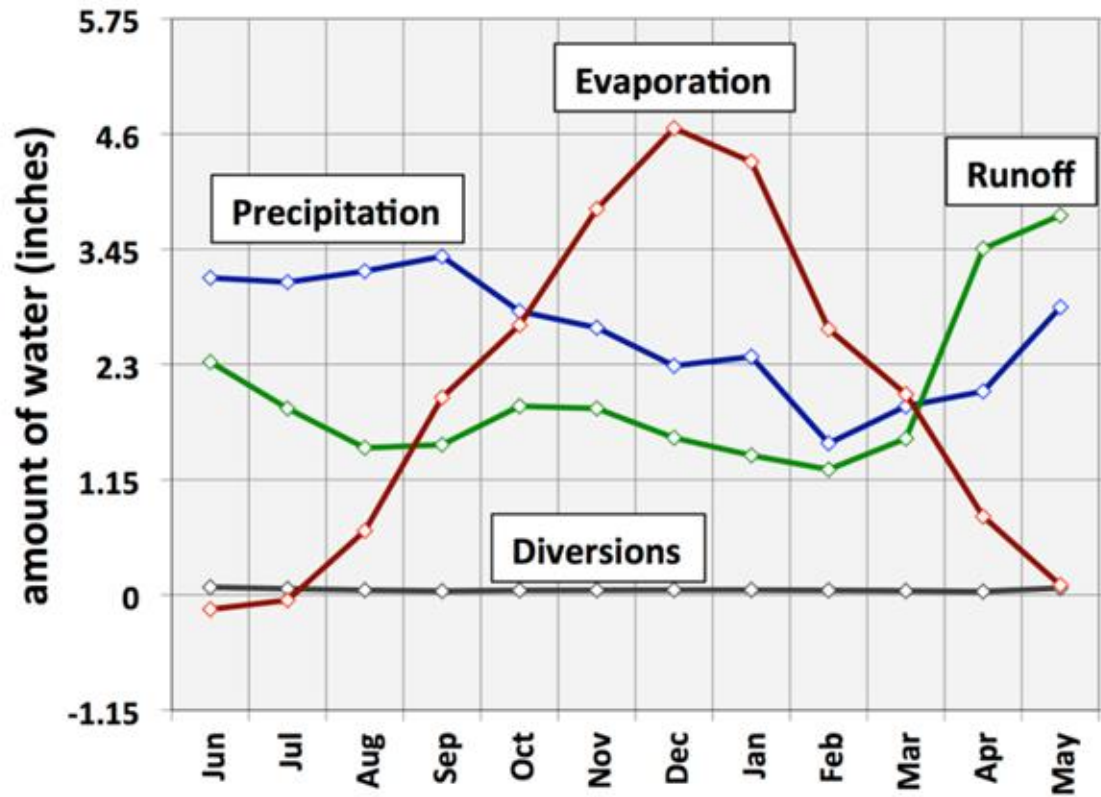
Overlake Evaporation (withdrawal) is evaporation that occurs from the lake surface.

Flow Between Lakes can be a deposit or withdrawal. For example, the St. Marys River flows between Lake Superior and Lake Huron. Its flow is an addition to the budget of Lake Michigan-Huron, but a subtraction from the budget of Lake Superior.

Diversions can be deposits or withdrawals, and are negligible relative to the internal water budget of the Great Lakes.



Lake Superior water balance



Four components of the monthly Lake Superior water balance. https://glisa.umich.edu/media/files/projectreports/GLISA_ProjRep_Lake_Evaporation.pdf

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Lake Superior	Average magnitude	Average monthly estimate uncertainty	
		Low	High
Component of water balance	ft ³ /s		
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/>

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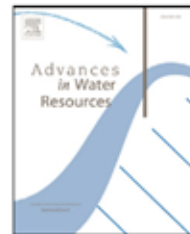
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Contents lists available at [ScienceDirect](#)

Advances in Water Resources

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



Reconciling the water balance of large lake systems

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^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

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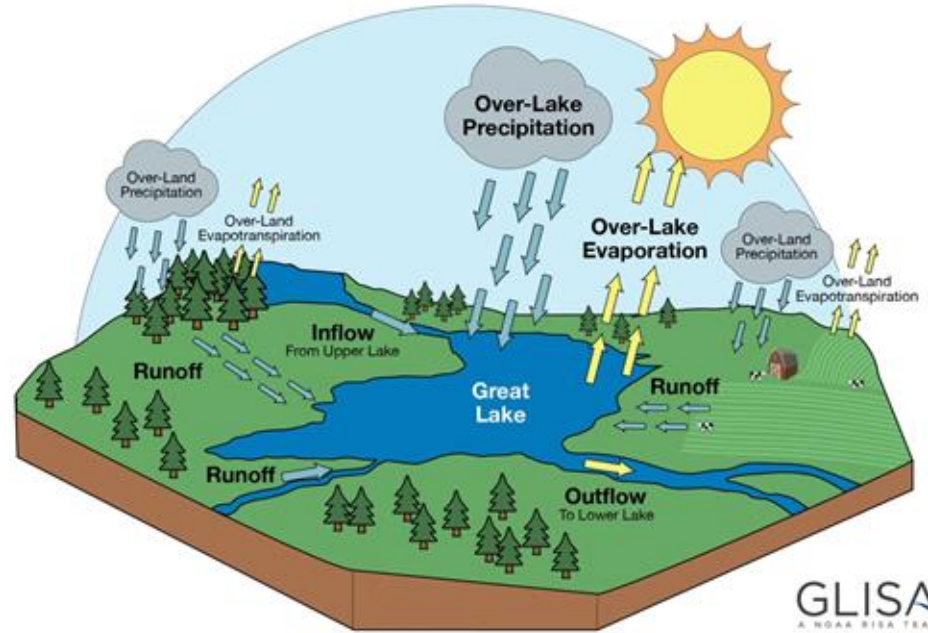
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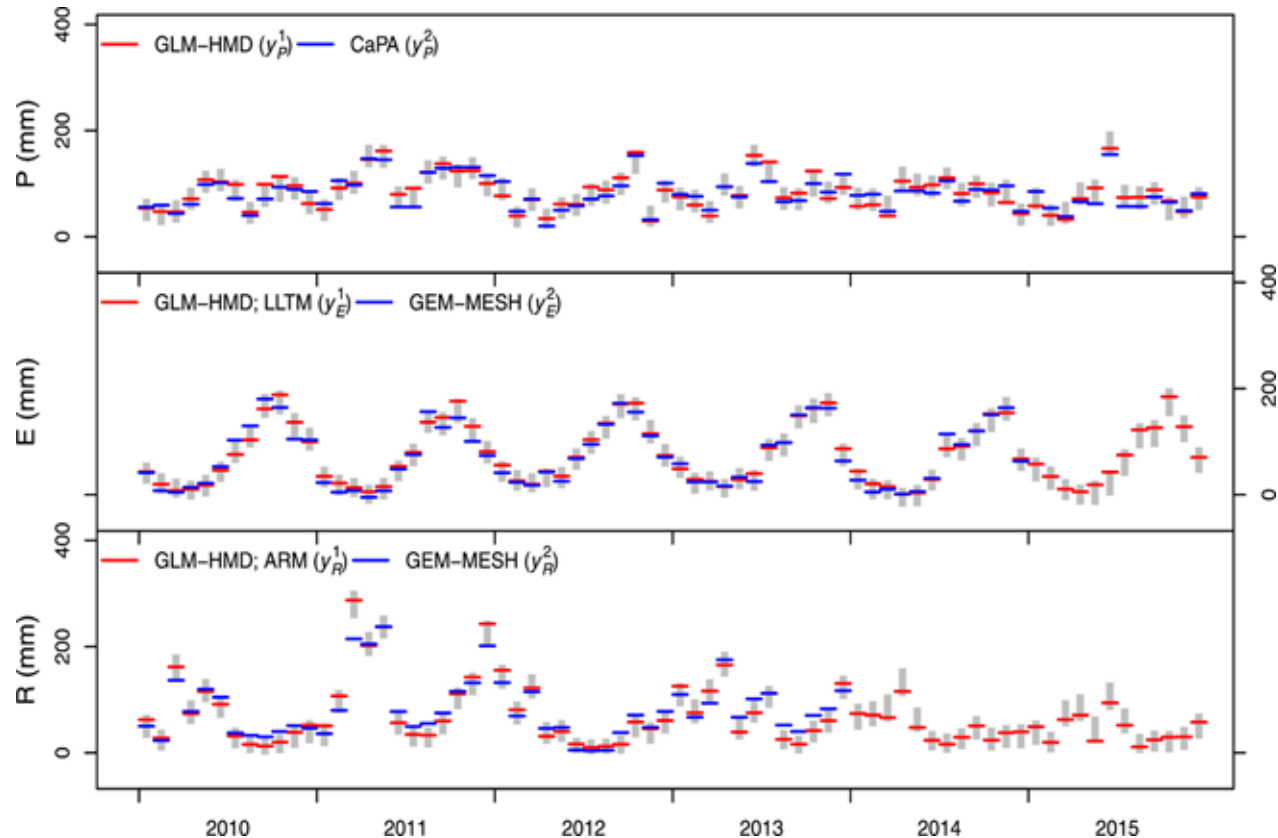
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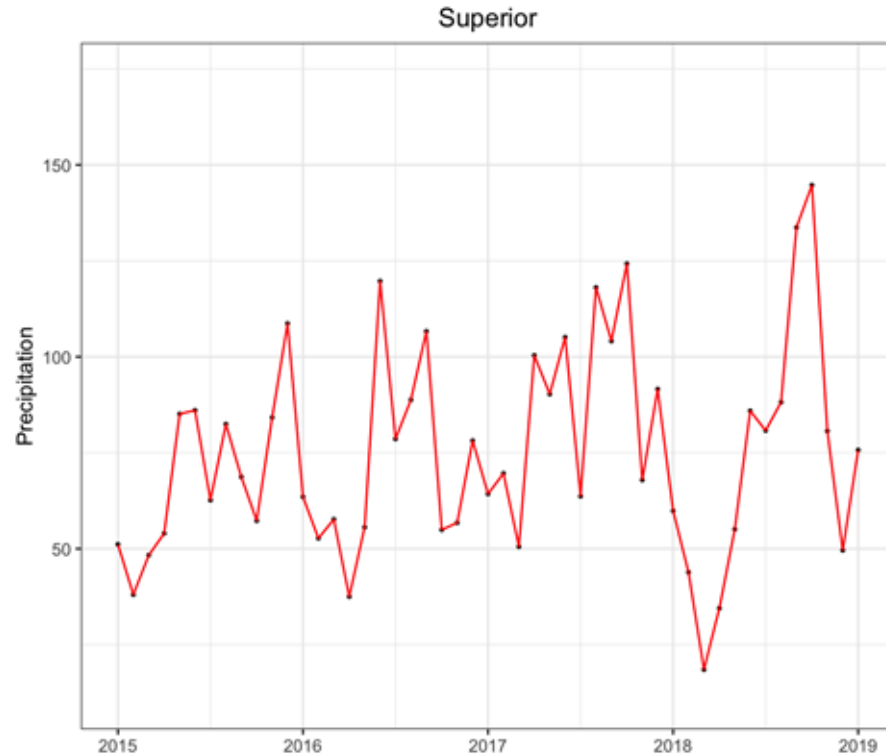


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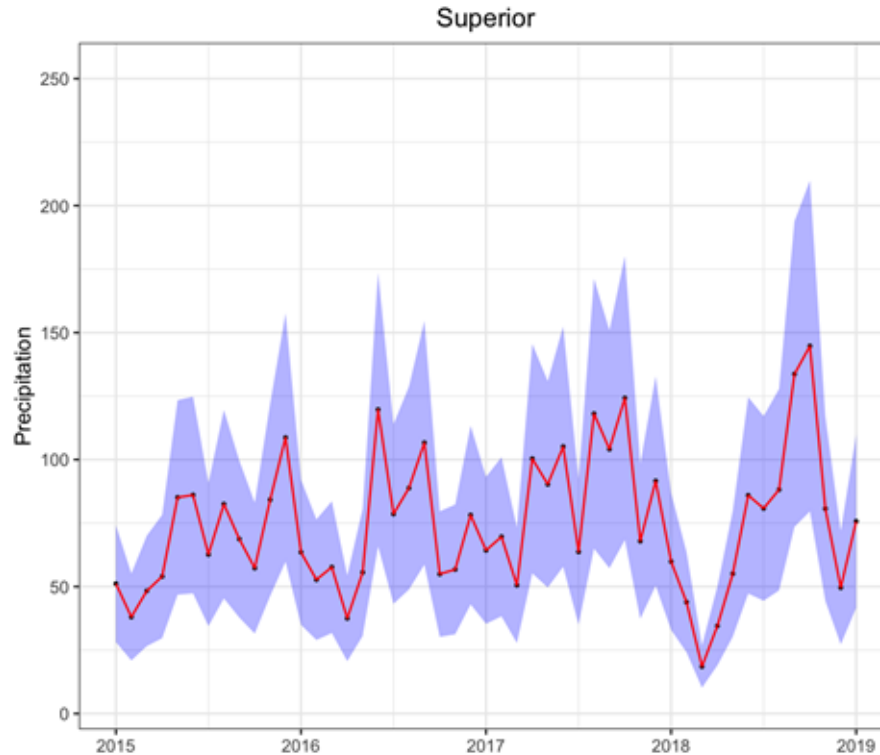
L2SWBM output sample: Lake Superior (2010-2015)



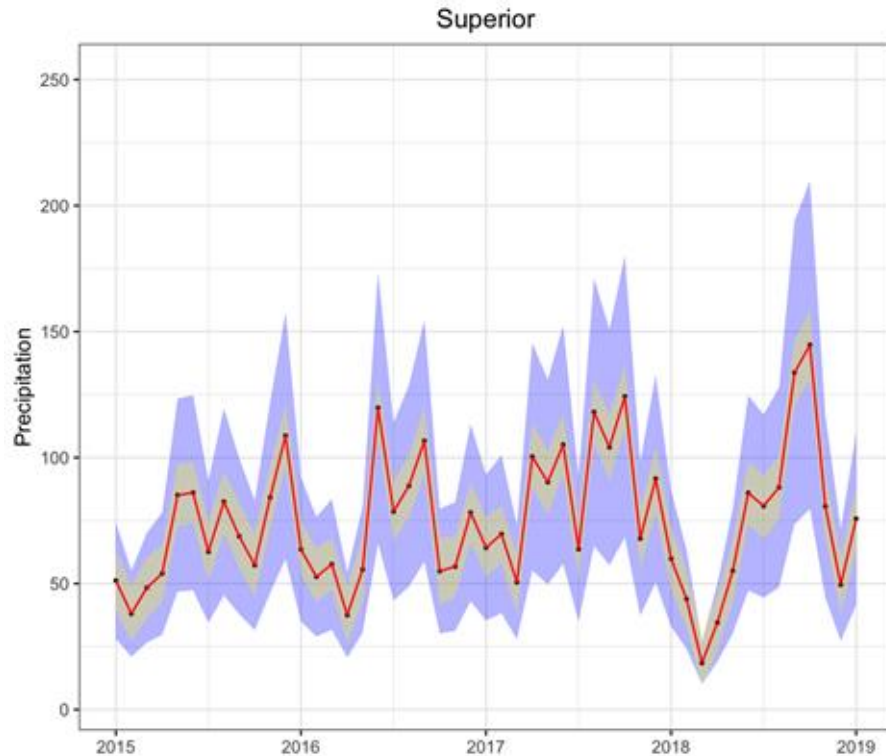
L2SWBM output: Lake Superior precipitation (2015-2019)

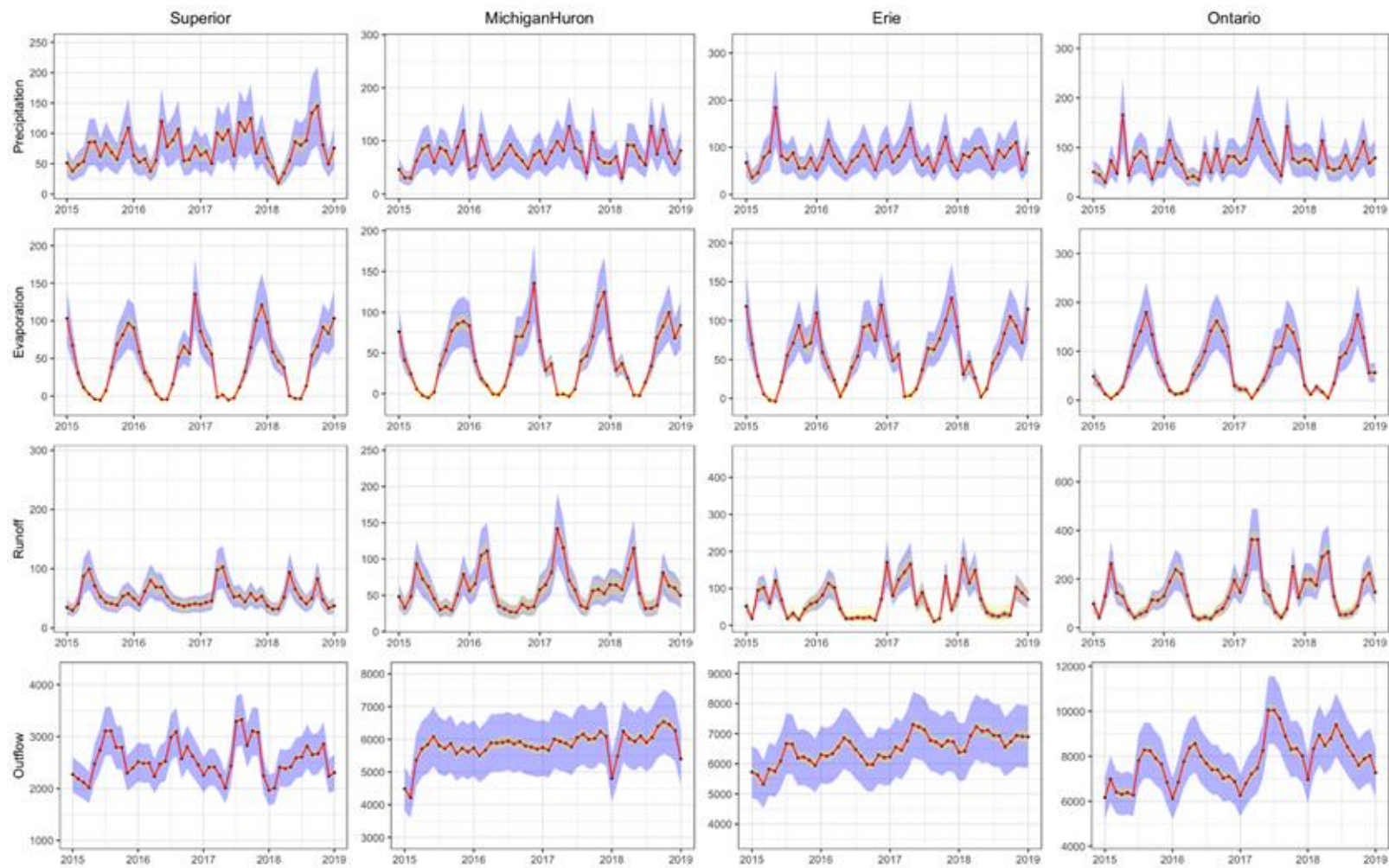


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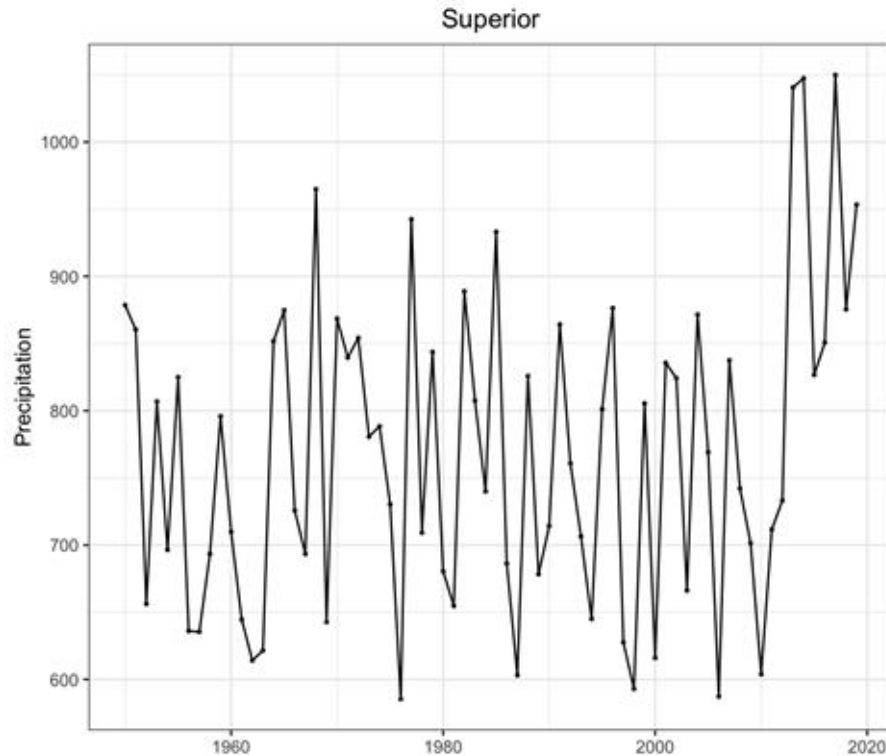


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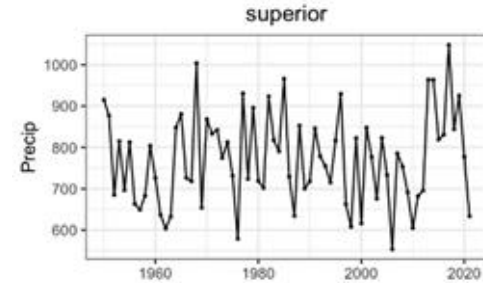
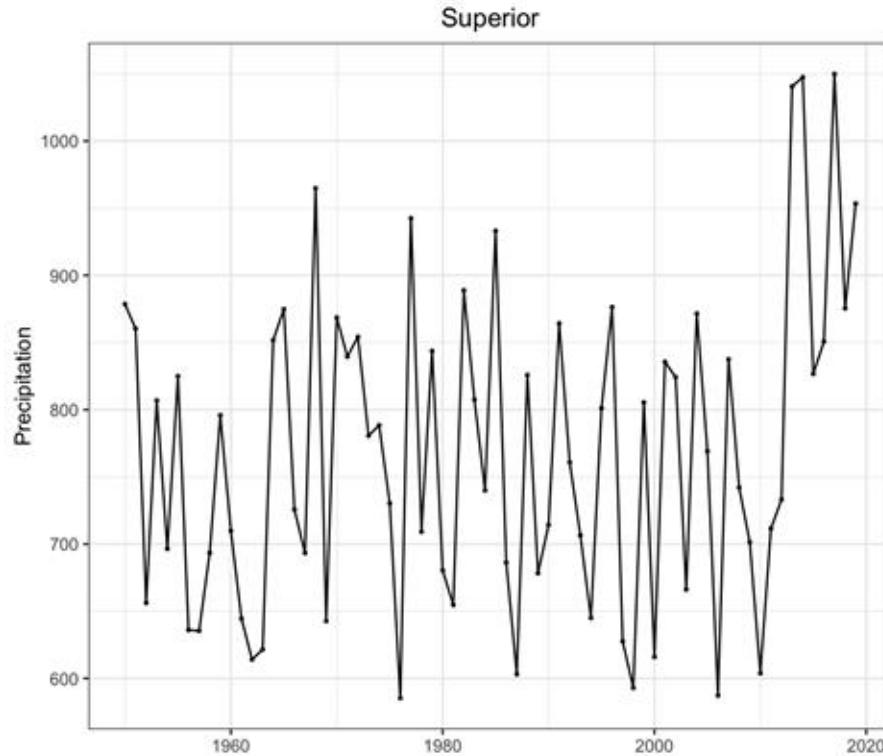




Lake Superior annual precipitation (1950-2019)



Lake Superior annual precipitation (1950-2019)

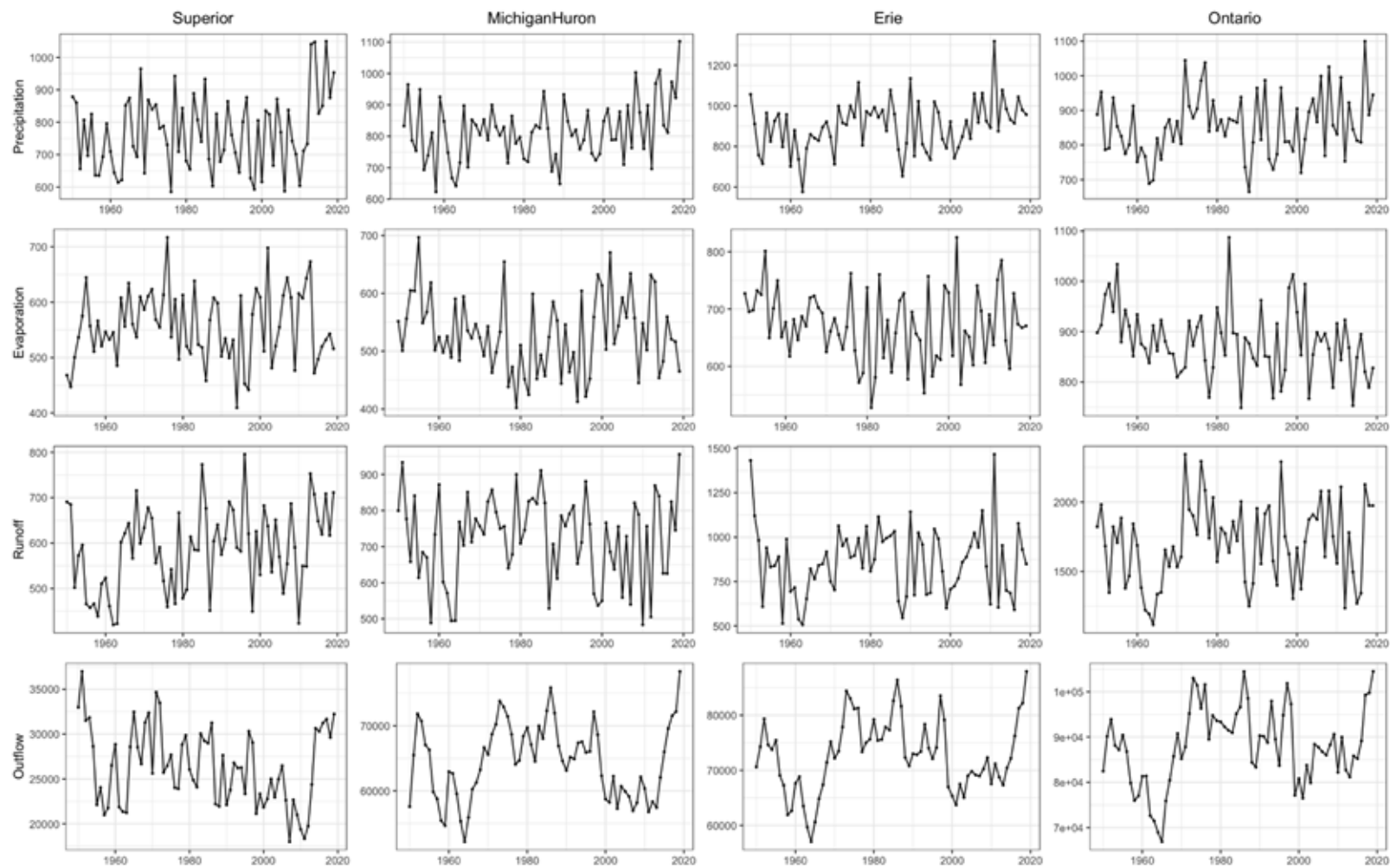


1950-2021

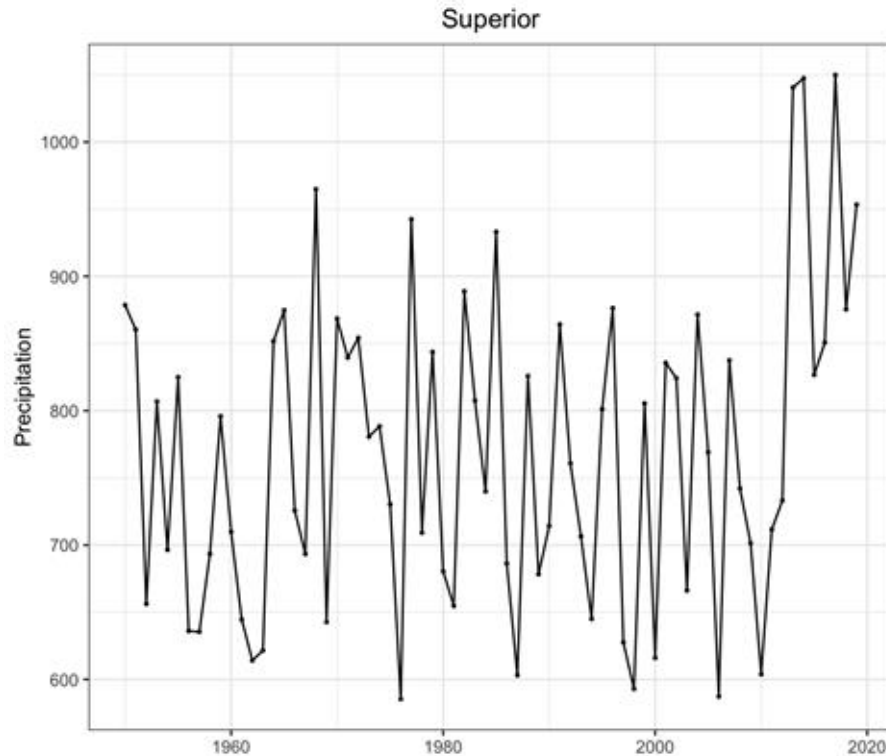
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Lake Superior annual precipitation (1950-2019)



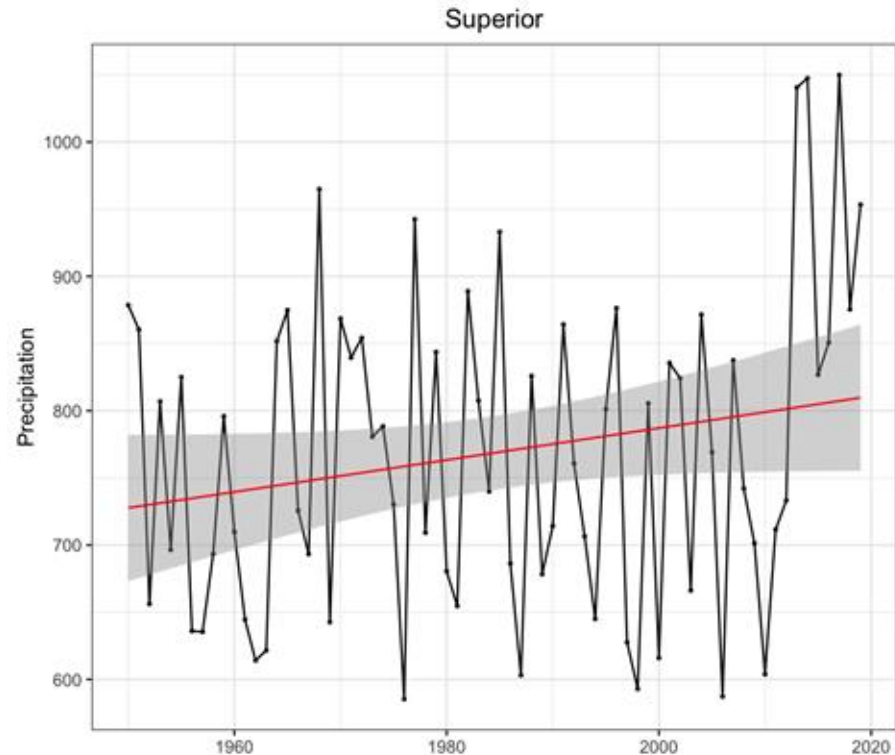
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Method 1: Linear regression

- 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



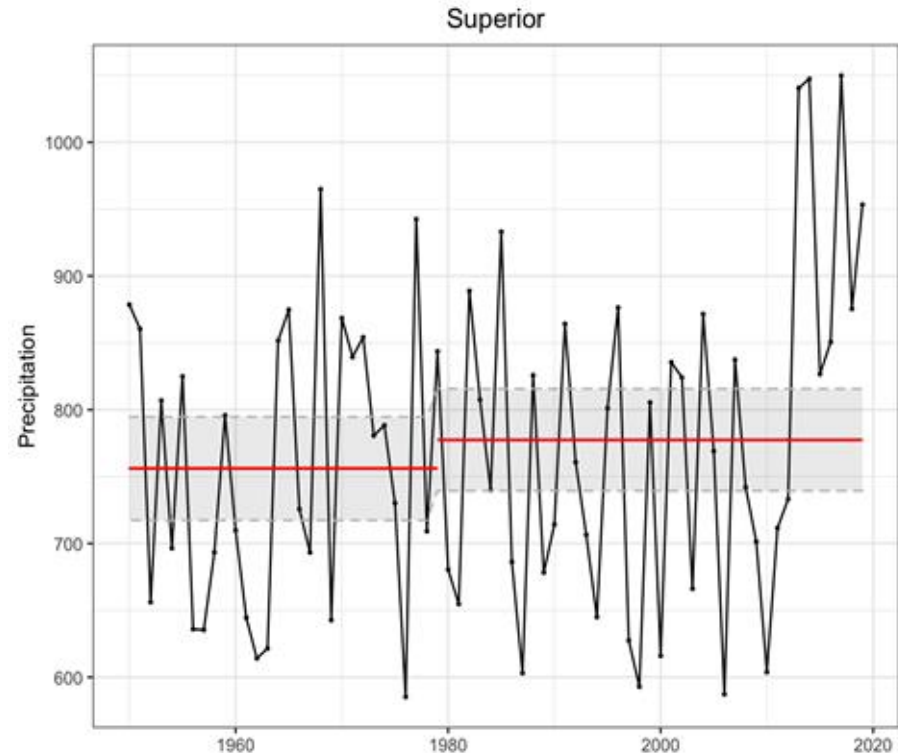
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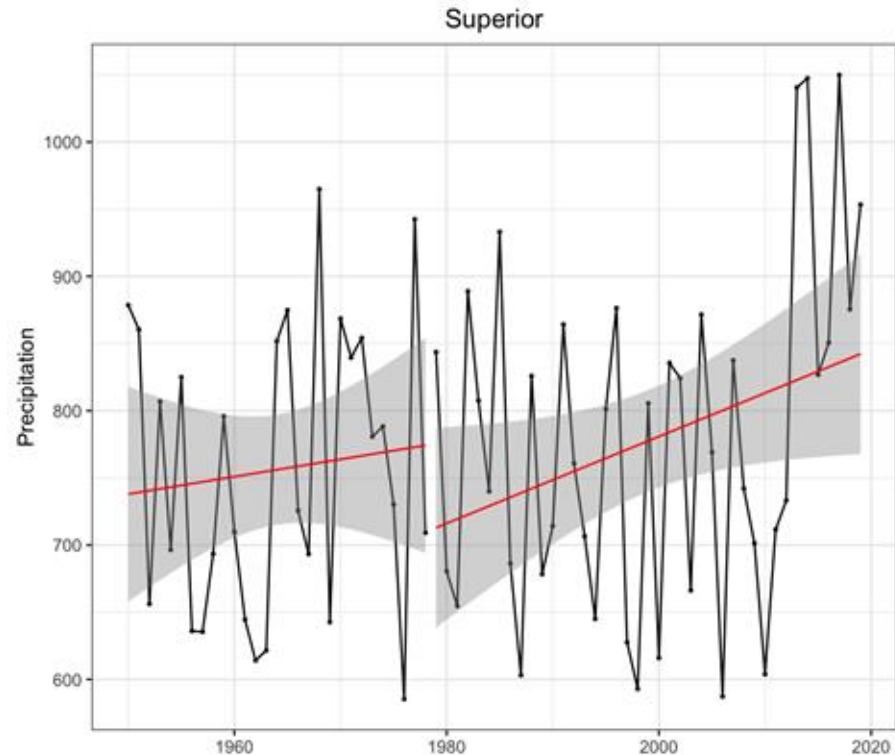
Method 2a: Fixed reference period (1950-1979 vs 1980-present)

- Filters out interannual variation or anomalies
- Shows longer climatic trends



Method 2b: Fixed reference period with linear regression

- Allows multiple linear models to be fitted to the data for different time ranges



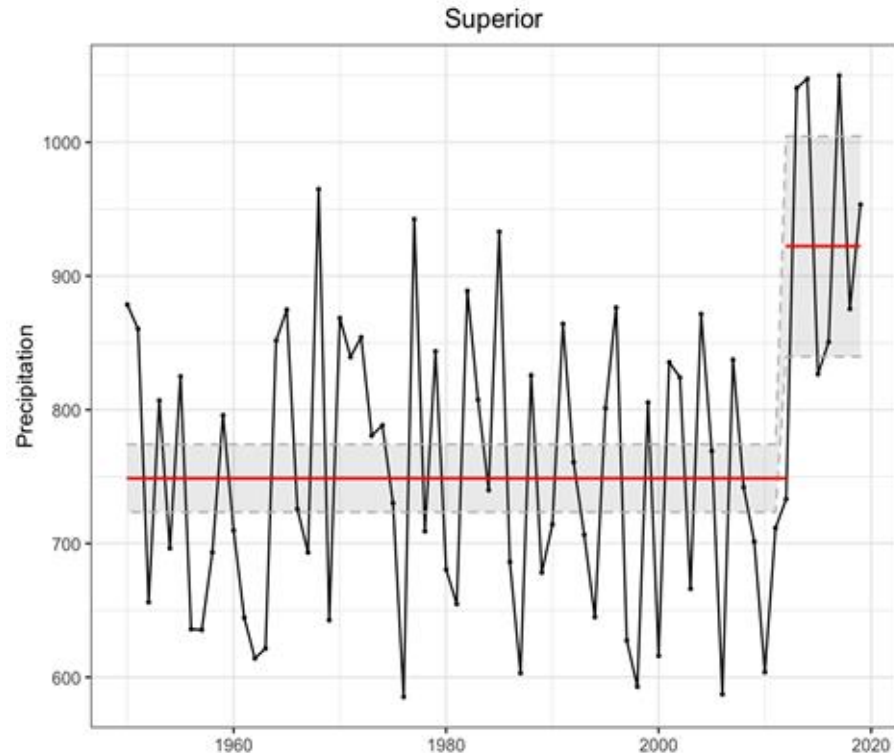
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Method 3: Change point detection

- Automatically detects where a statistically significant shift in the data occurs
- Divides a time series into two segments with distinct statistical characteristics



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Method 4: “Hockey stick” segmented regression

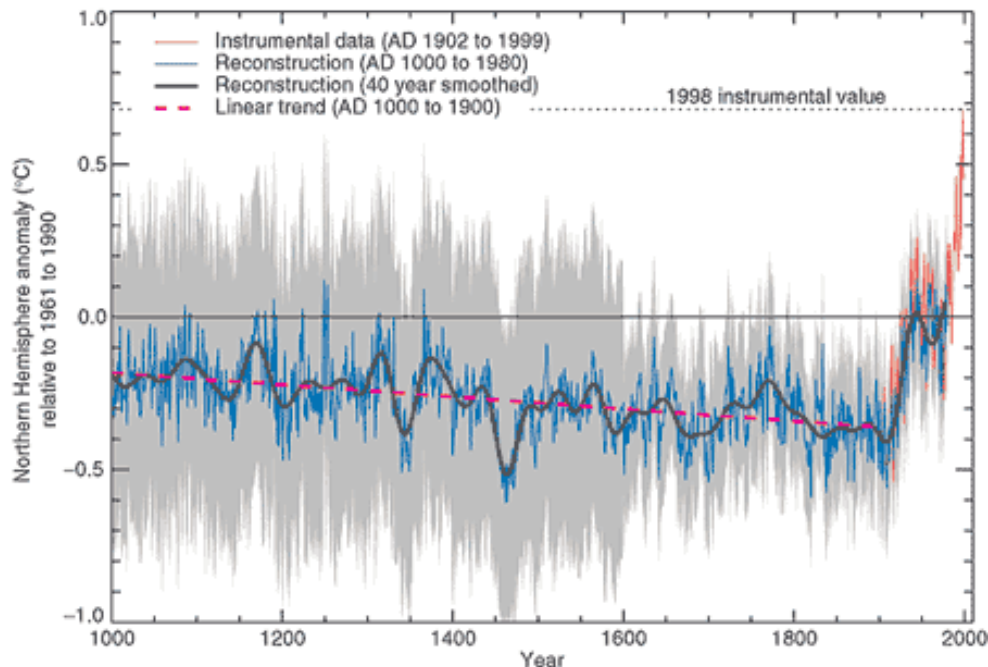
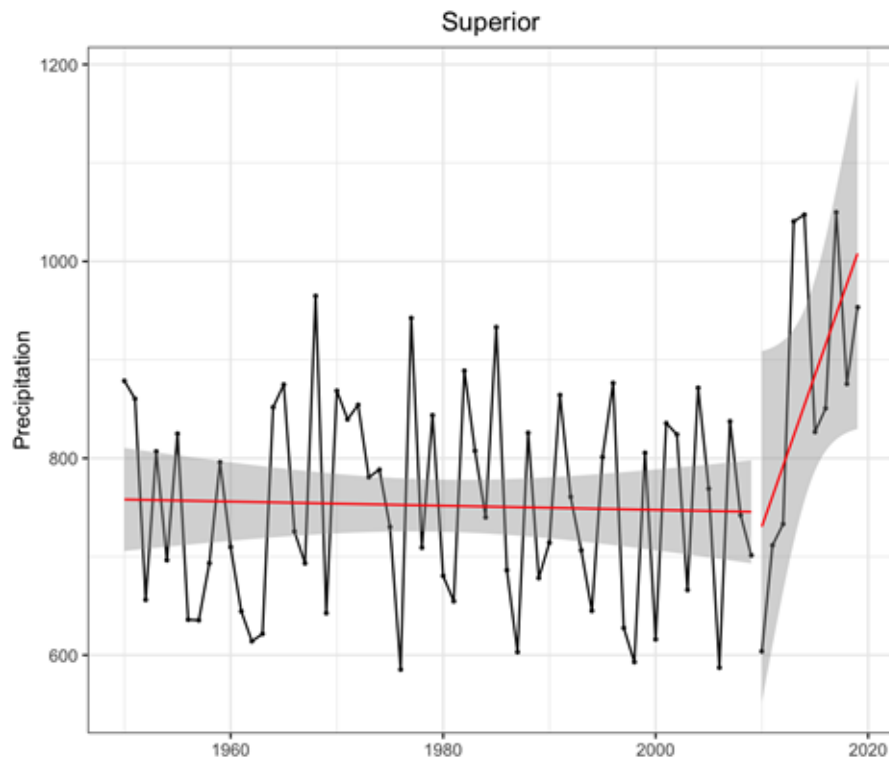


Figure: Northern Hemisphere temperature changes estimated from various proxy records shown in blue, instrumental data shown in red. Note the large uncertainty (grey area) as you go further back in time. <http://www.geo.umass.edu/faculty/bradley/mann1999.pdf>

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



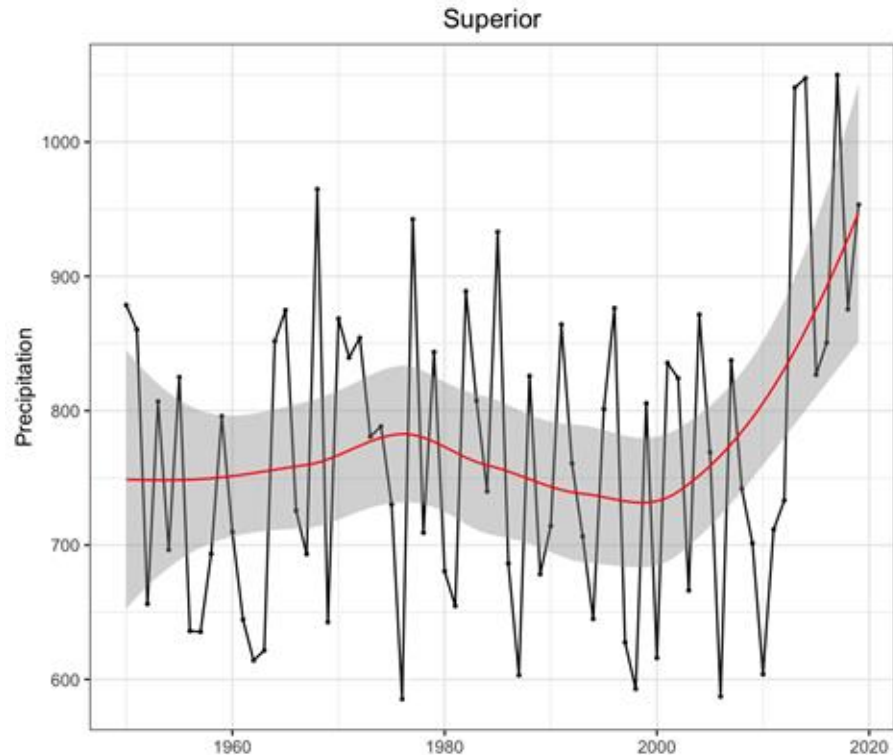
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Method 5: Smooth moving average

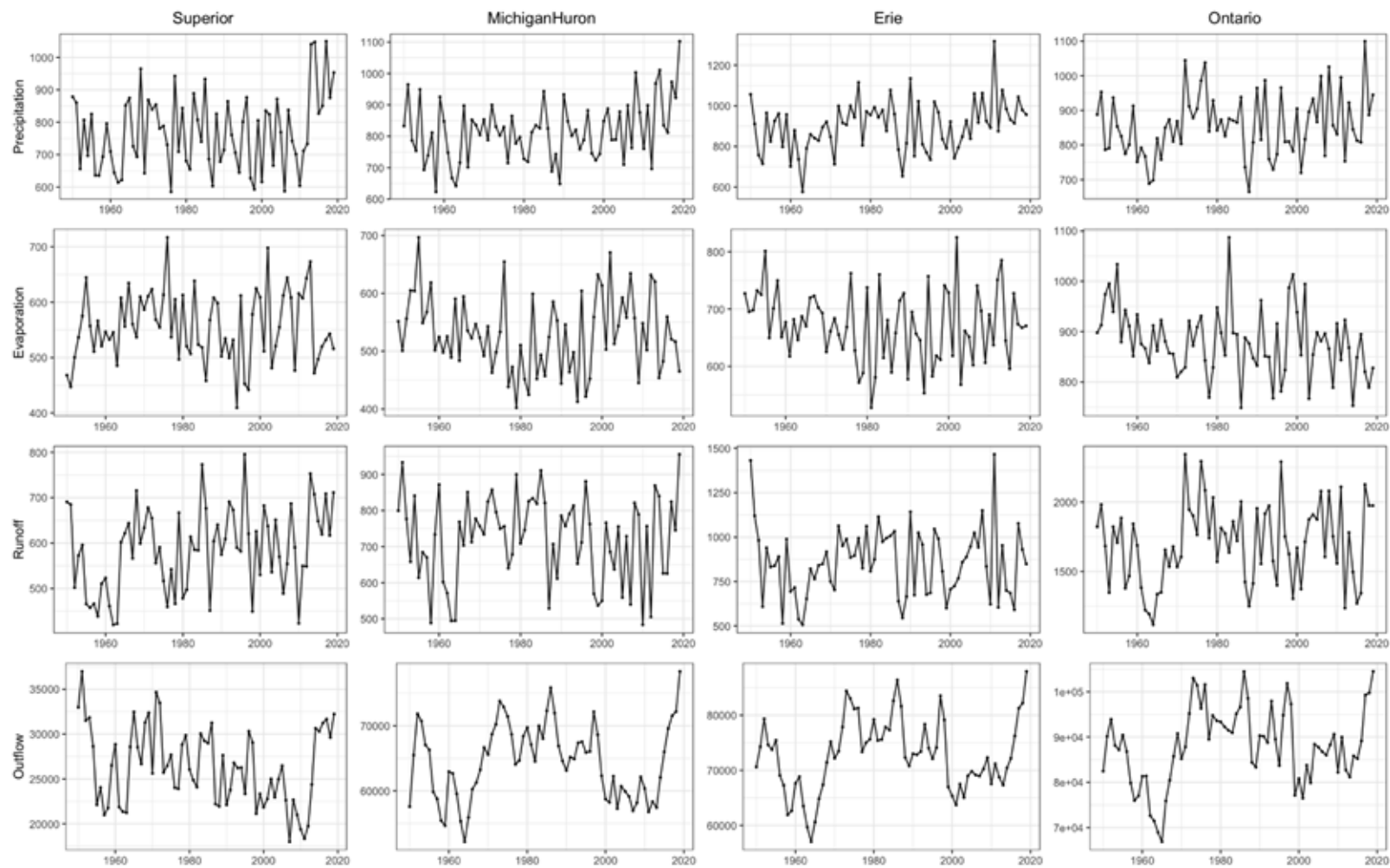
- Captures the average change over time by filtering out the noise from extreme values
- Smooths out short-term fluctuations and highlights long-term trends



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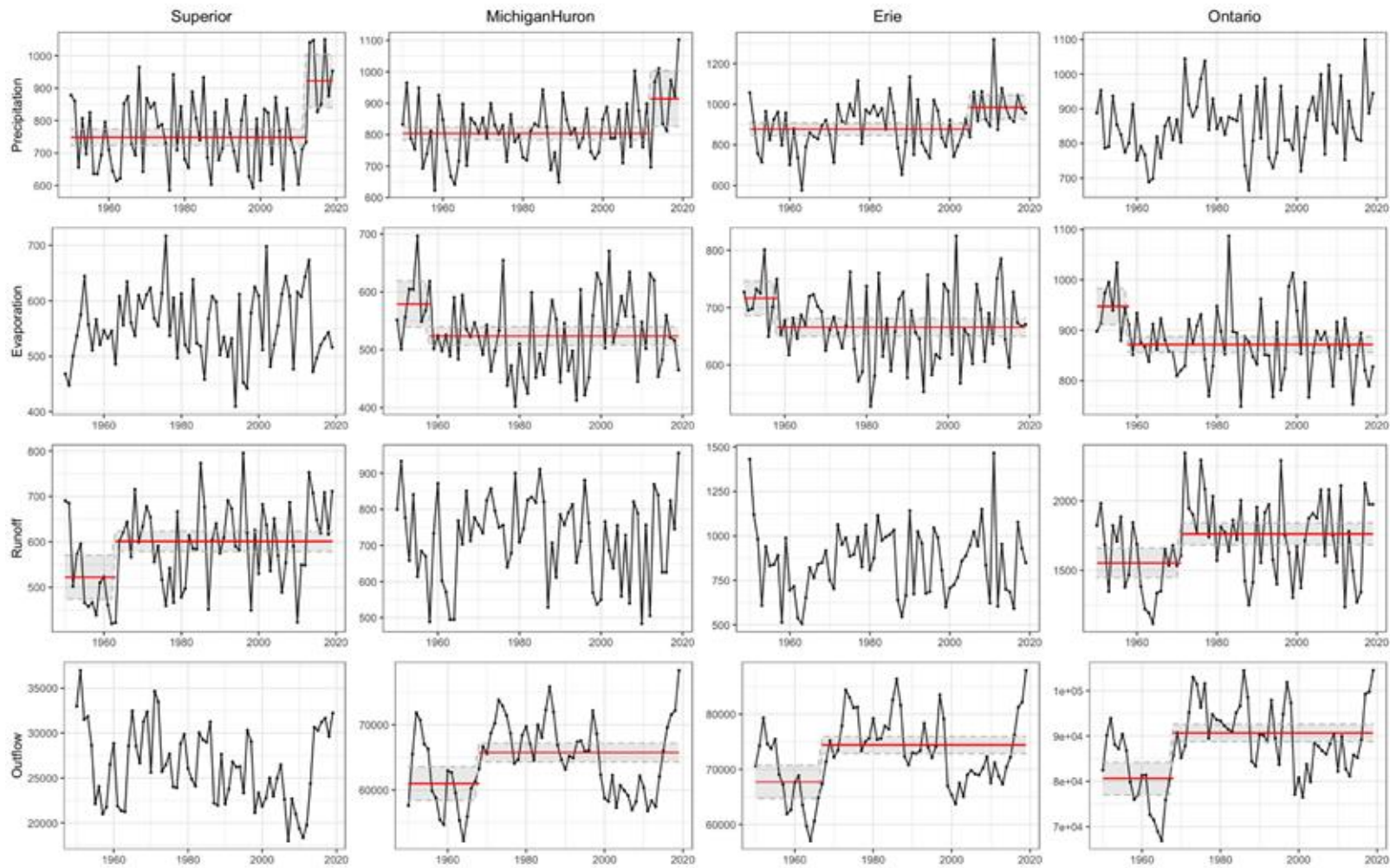


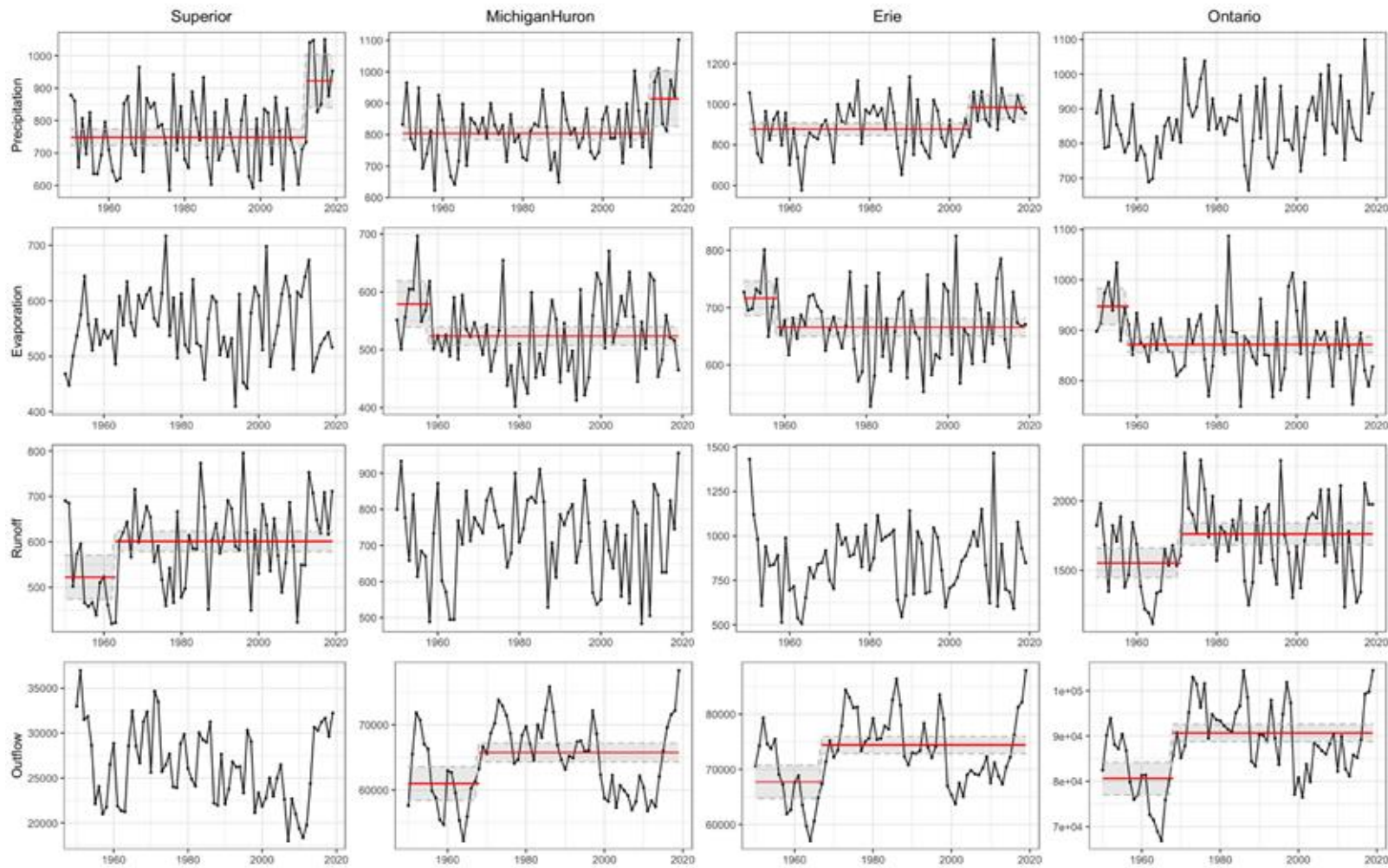


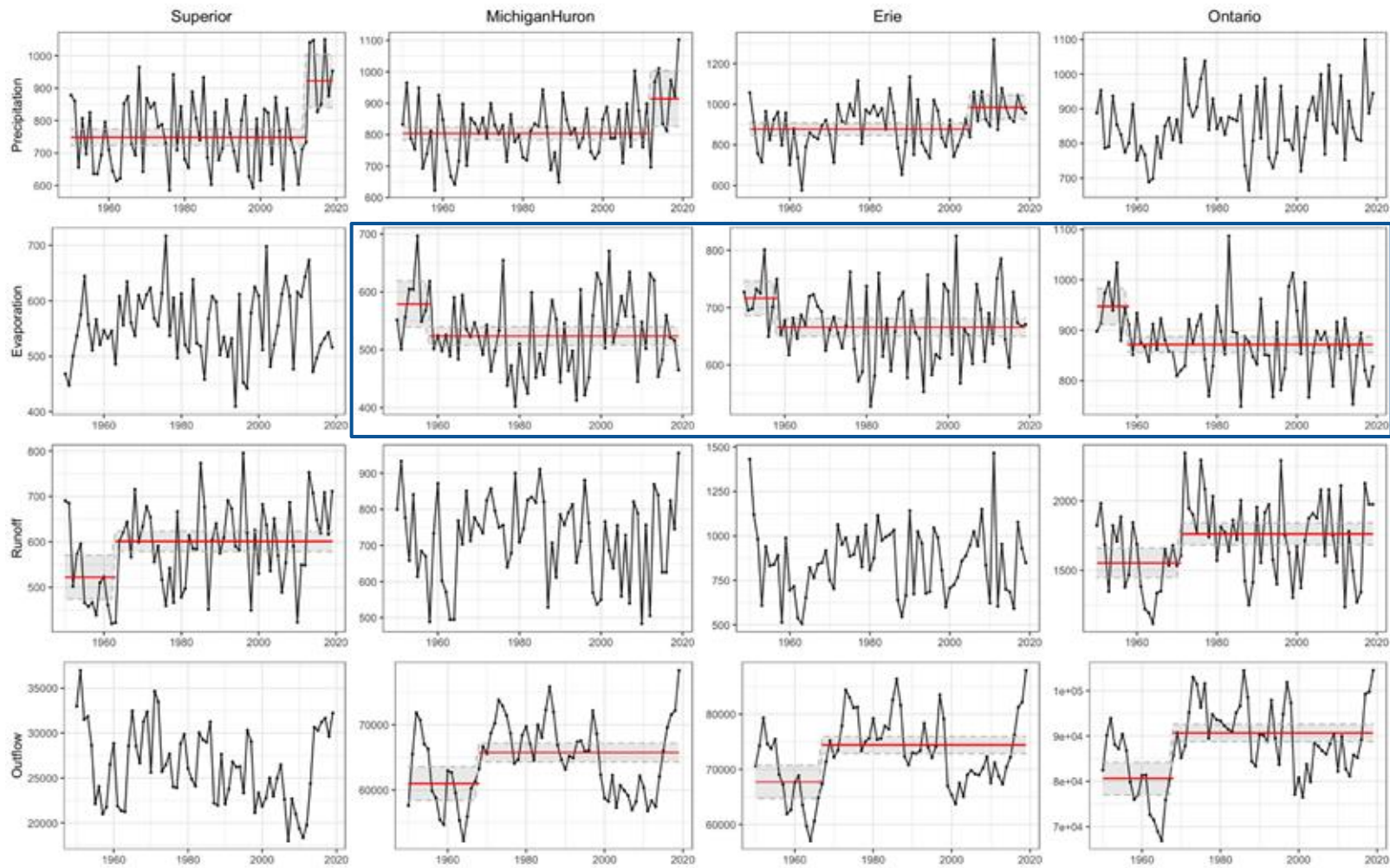
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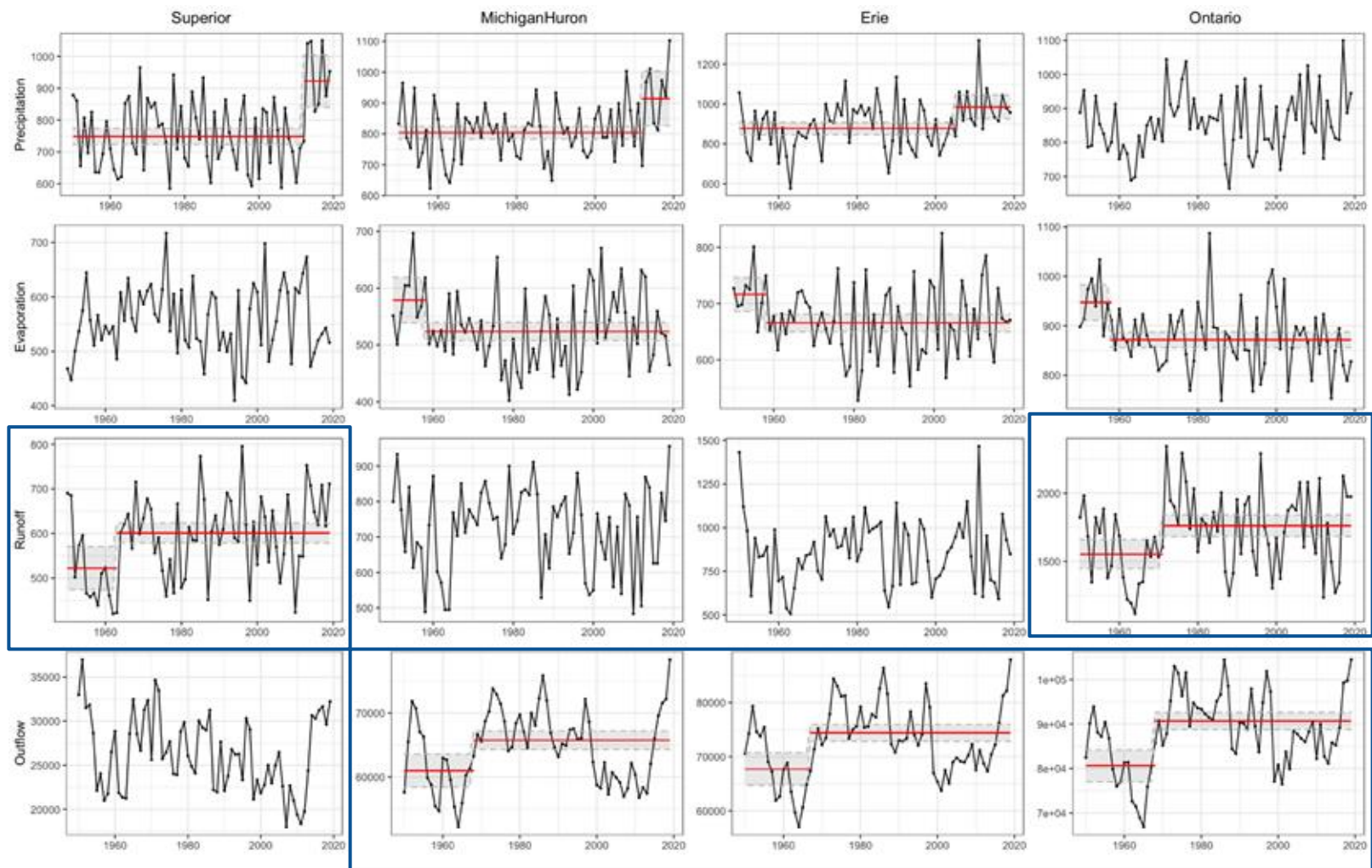
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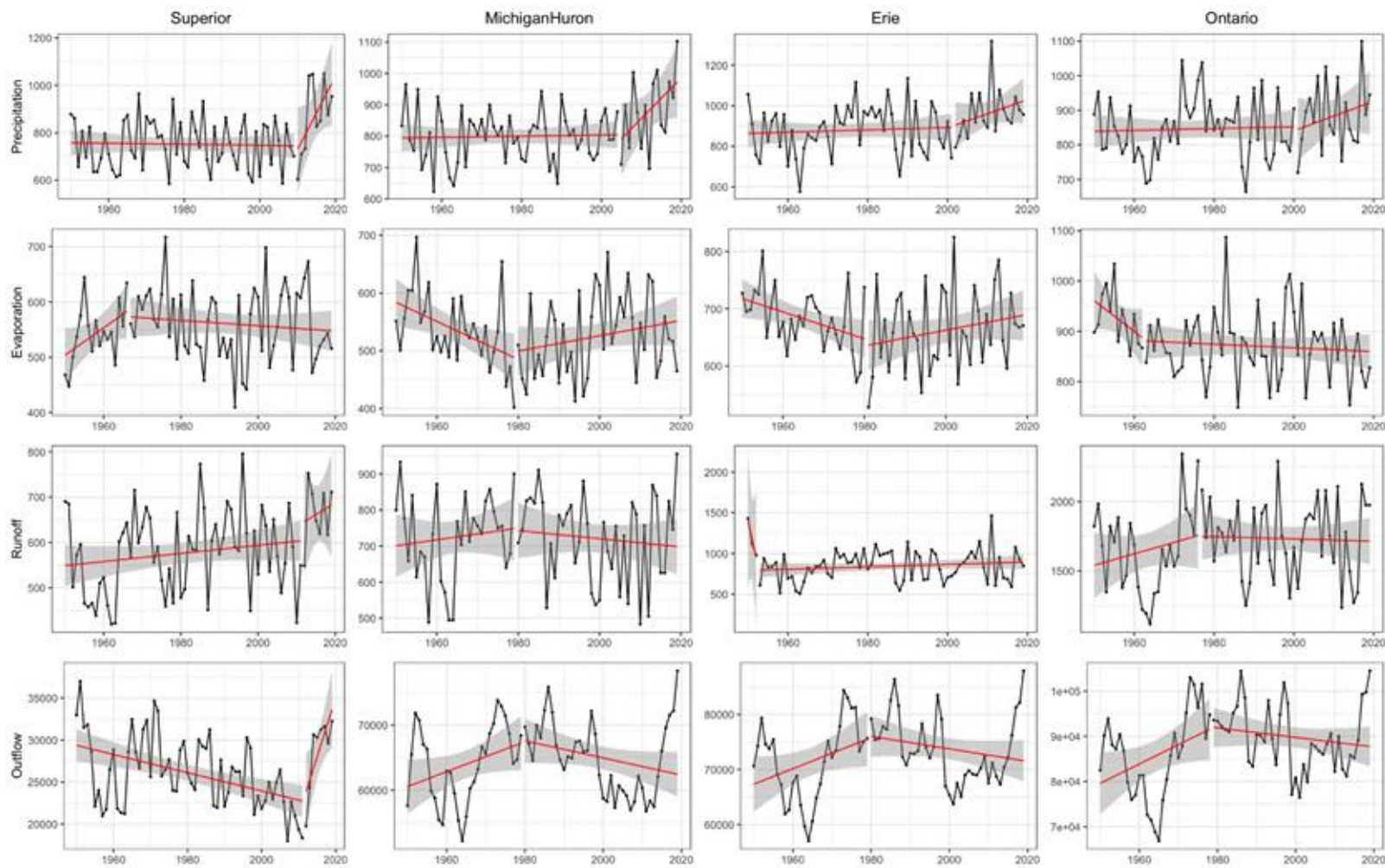


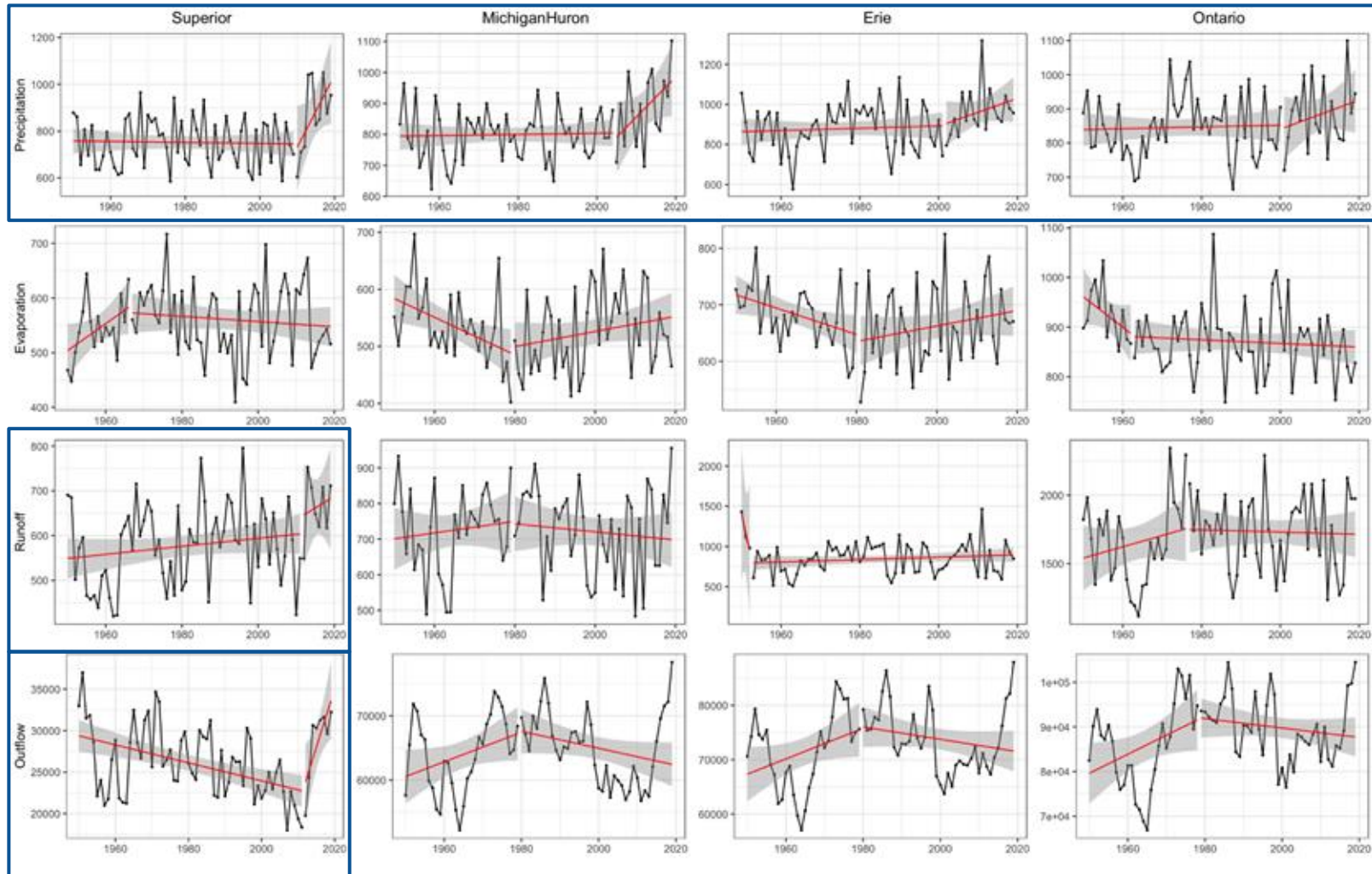


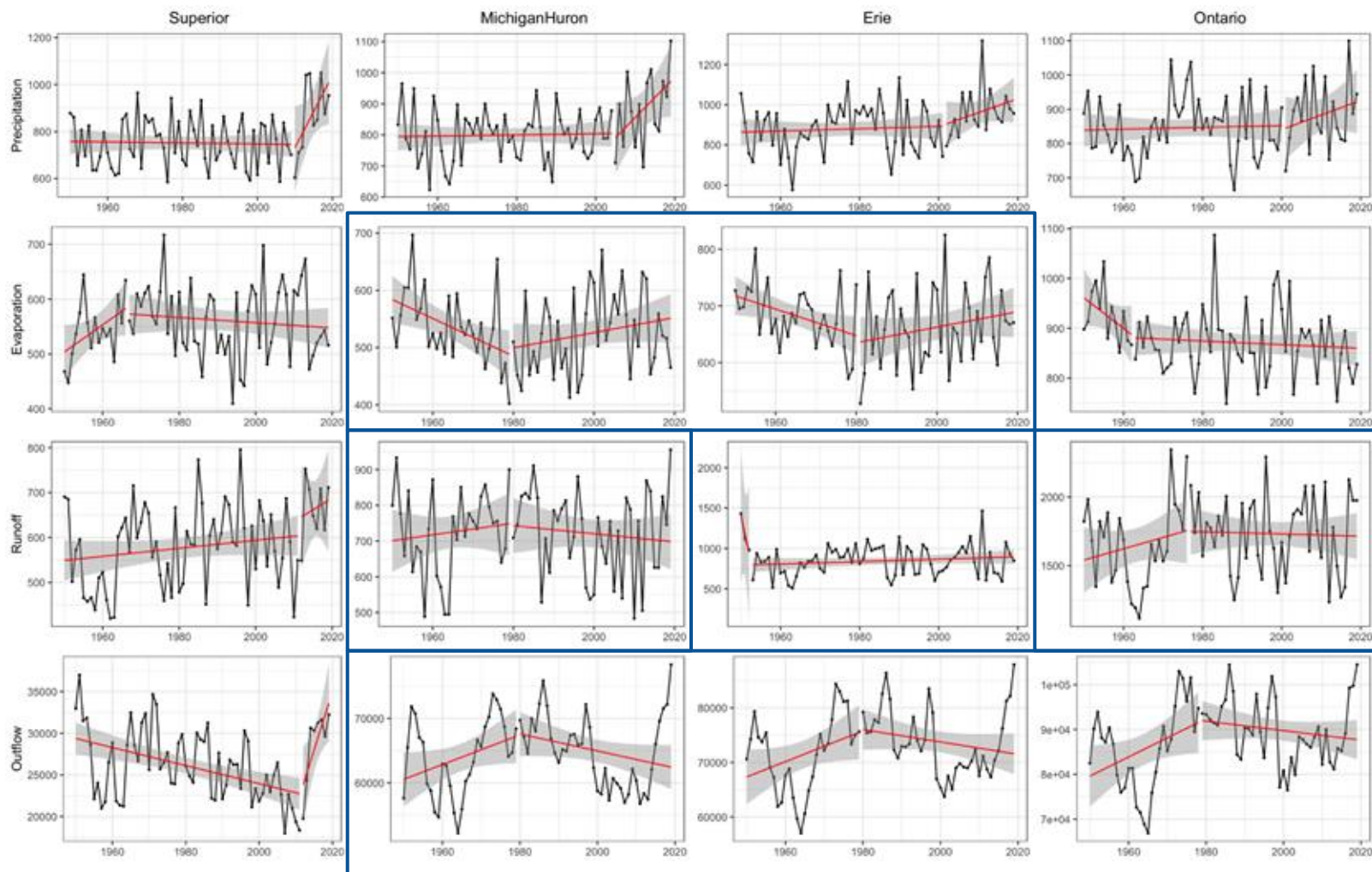
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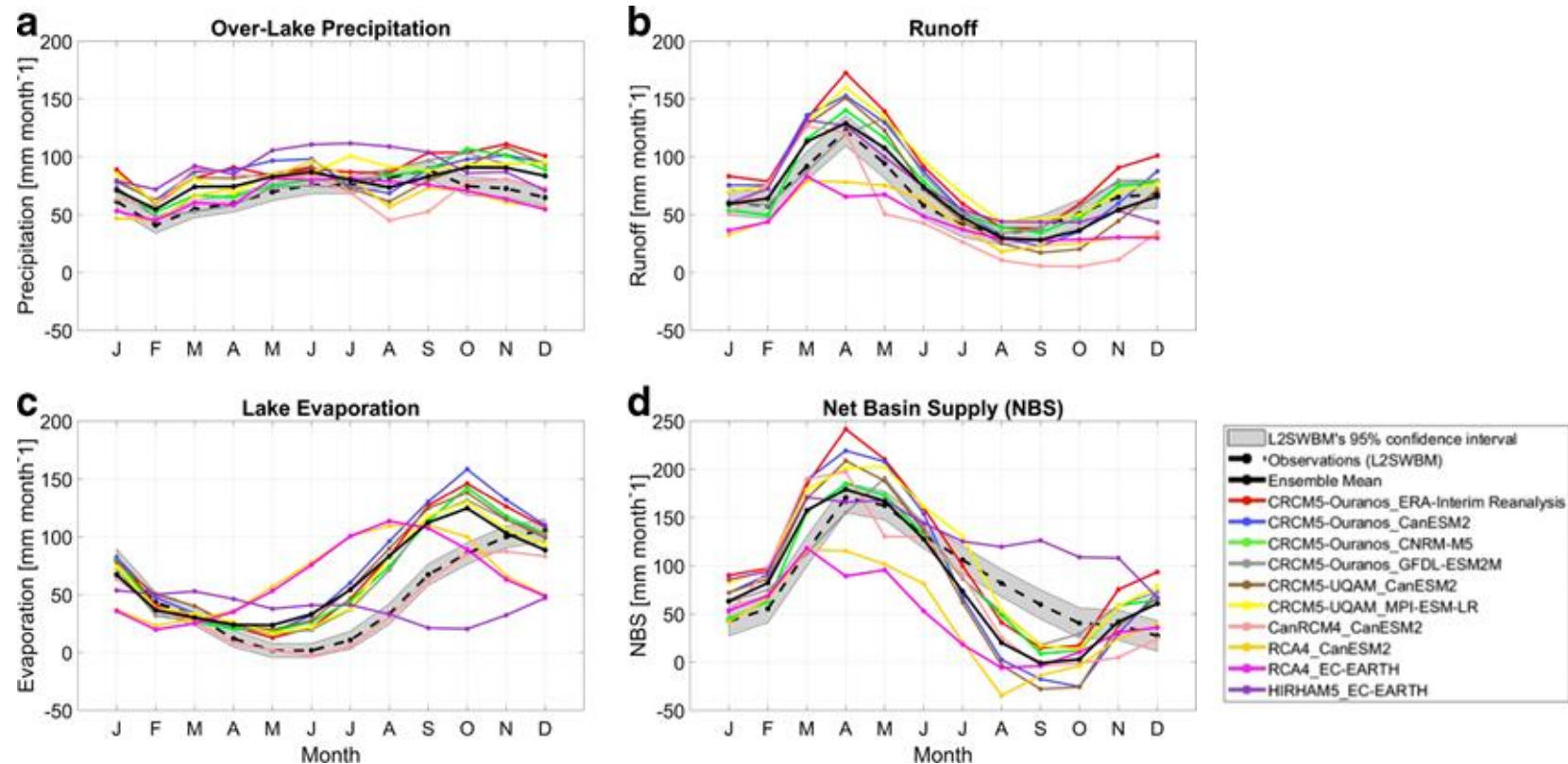


Assessment of the Laurentian Great Lakes' hydrological conditions in a changing climate

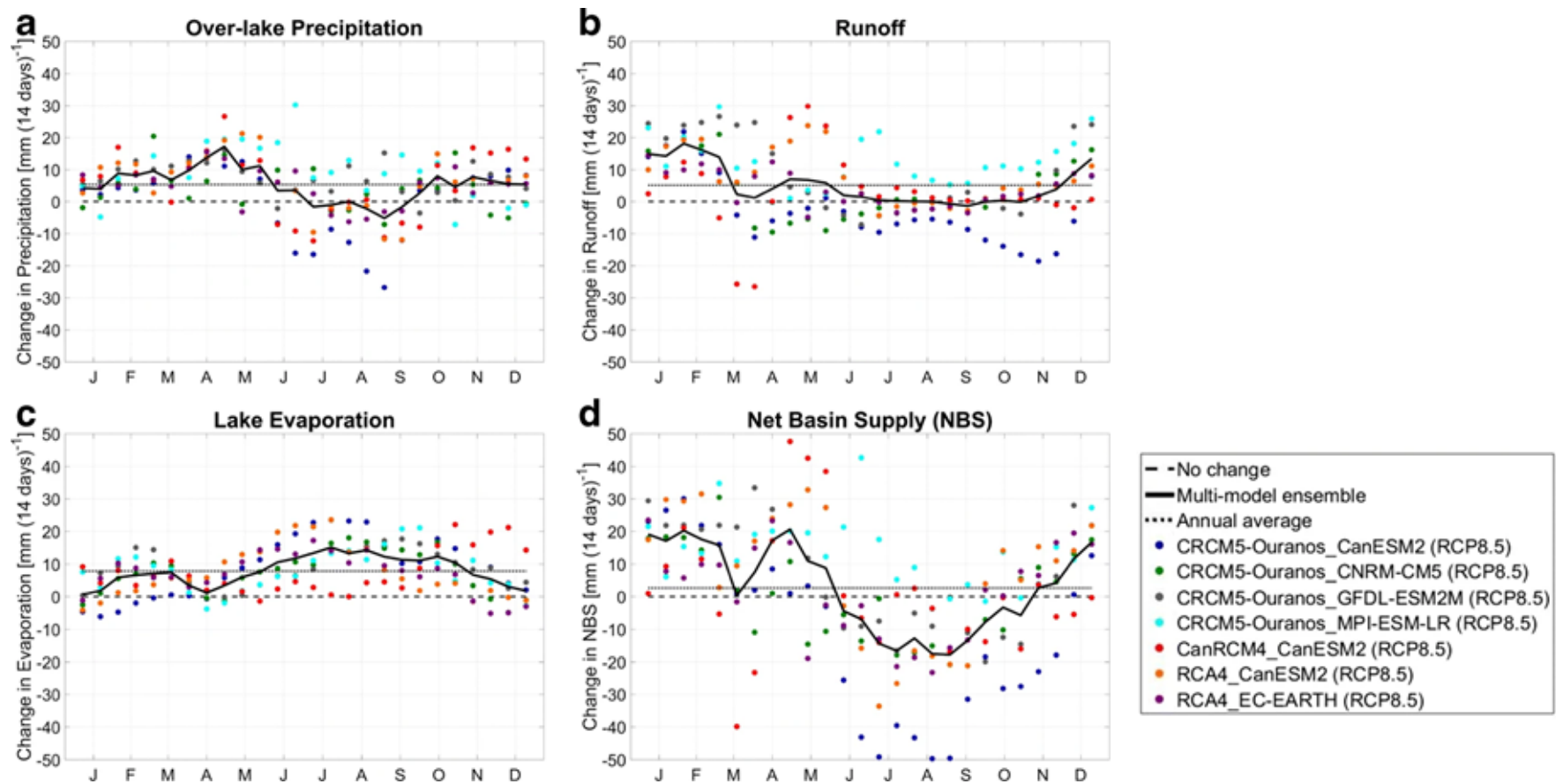
Edouard Mailhot^{1,2}  · Biljana Music^{1,3} · Daniel F. Nadeau⁴ · Anne Frigon³ · Richard Turcotte²

Received: 21 November 2018 / Accepted: 14 August 2019 / Published online: 19 October 2019

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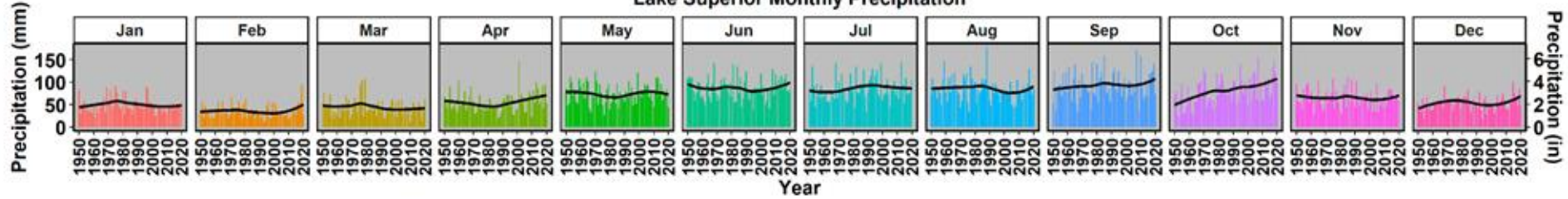
Validation of over-lake precipitation (a), land runoff expressed over the lakes (b), lake evaporation (c), and NBS (d) for the Great Lakes watershed over the 1970–2000 period using annual cycles of monthly means. The period for the reanalysis dataset is 1978–2000. The ensemble mean does not include HIRHAM5 Mailhot, E., Music, B., Nadeau, D.F. et al. Assessment of the Laurentian Great Lakes' hydrological conditions in a changing climate. *Climatic Change* 157, 243–259 (2019). <https://doi.org/10.1007/s10584-019-02530-6>



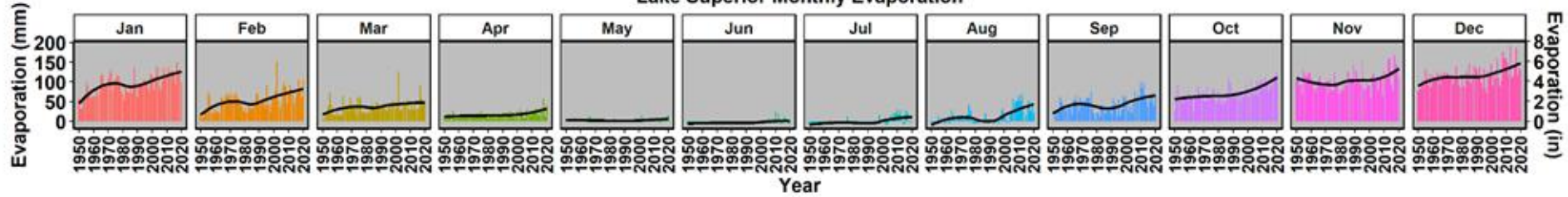
Trends in bi-weekly a over-lake precipitation, b land runoff expressed over the lakes, c lake evaporation, and d NBS for the Great Lakes over the 1953–2100 period based on Theil-Sen estimators from RCP8.5 simulations
 Mailhot, E., Music, B., Nadeau, D.F. et al. Assessment of the Laurentian Great Lakes' hydrological conditions in a changing climate. *Climatic Change* 157, 243–259 (2019). <https://doi.org/10.1007/s10584-019-02530-6>

Lake Superior Monthly NBS Components

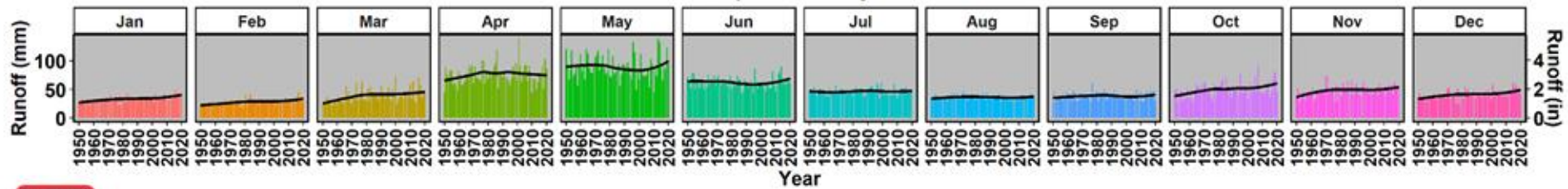
Lake Superior Monthly Precipitation



Lake Superior Monthly Evaporation

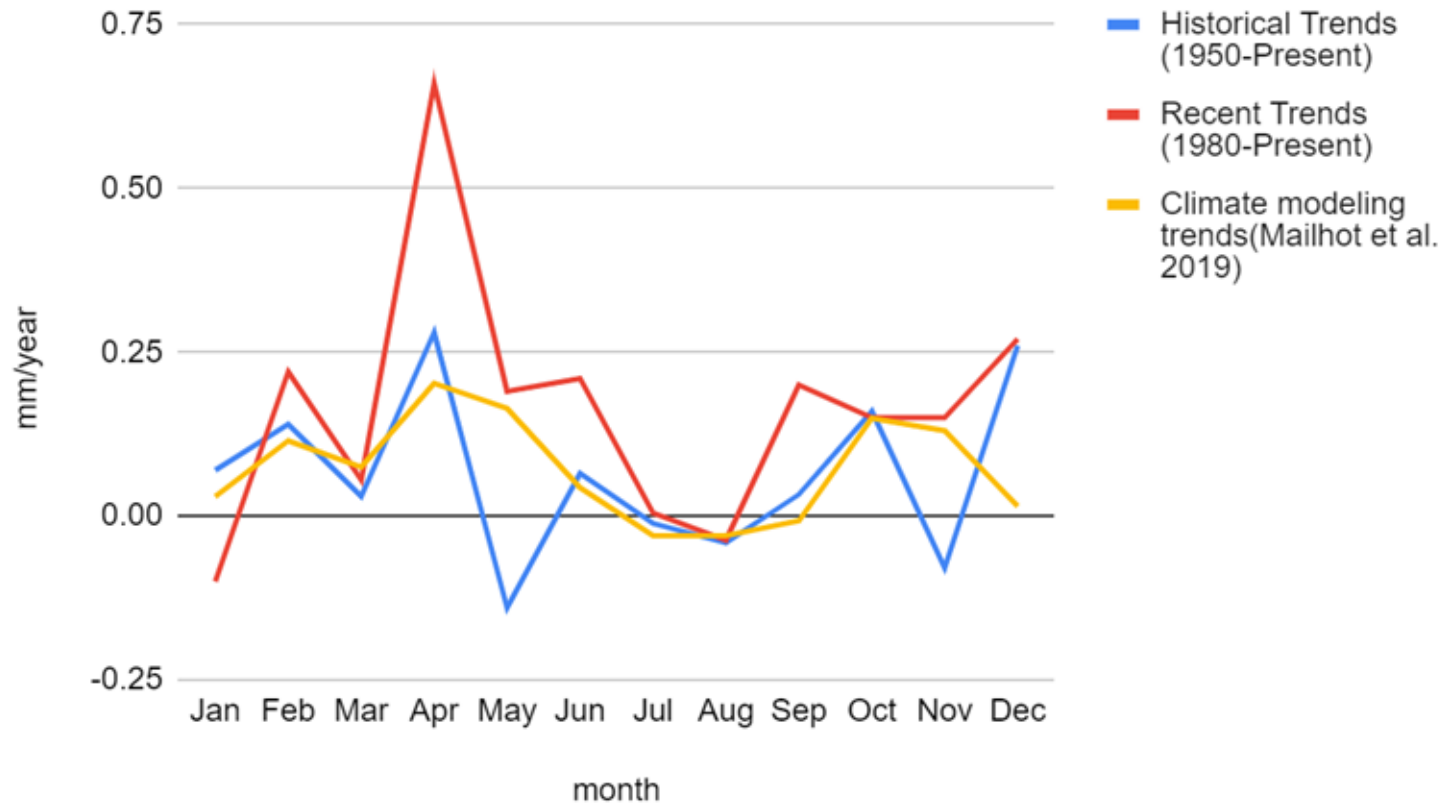


Lake Superior Monthly Runoff

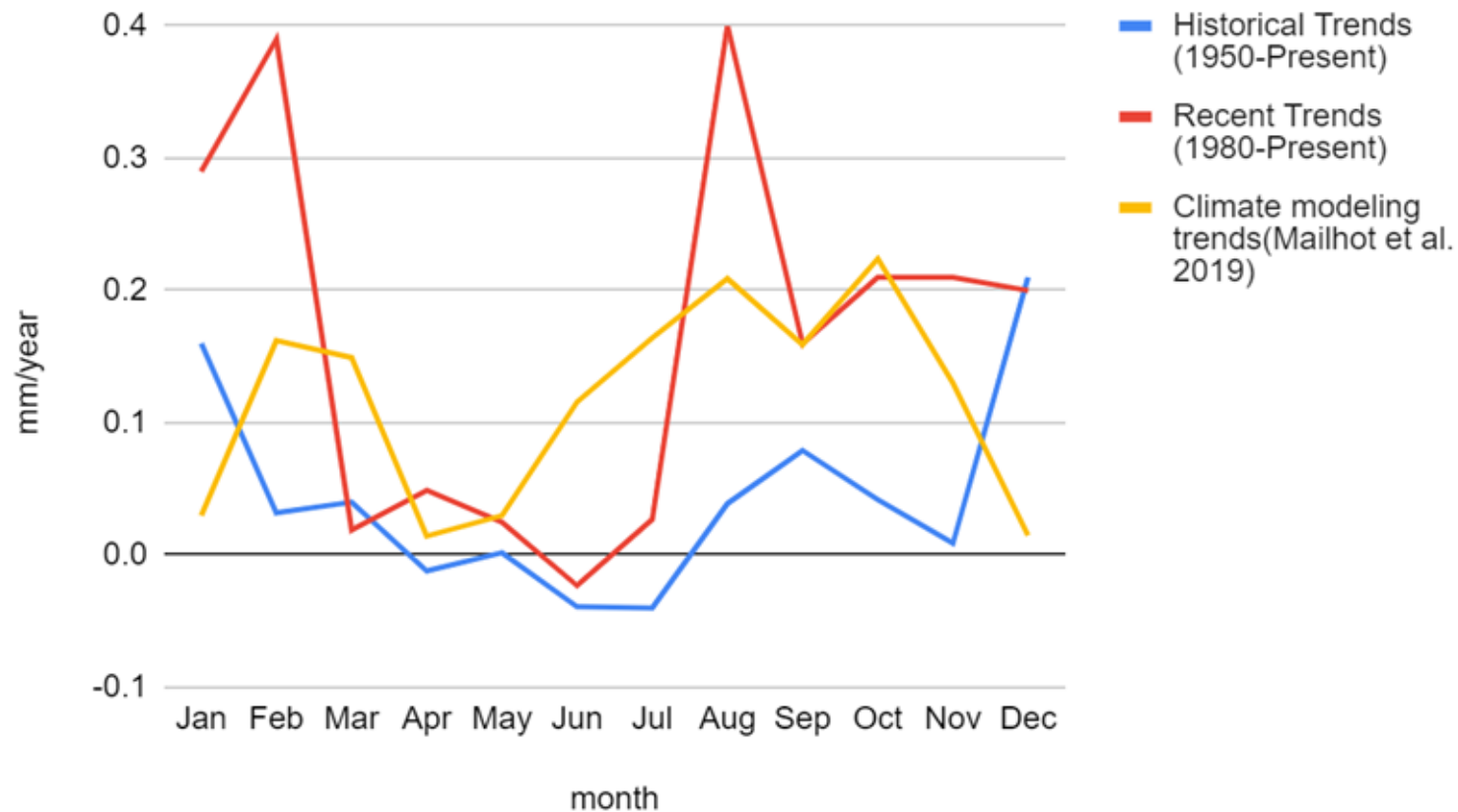


Detroit District, U.S. Army Corps of Engineers. Recent Great Lakes Basin Conditions. <https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Basin-Conditions/>

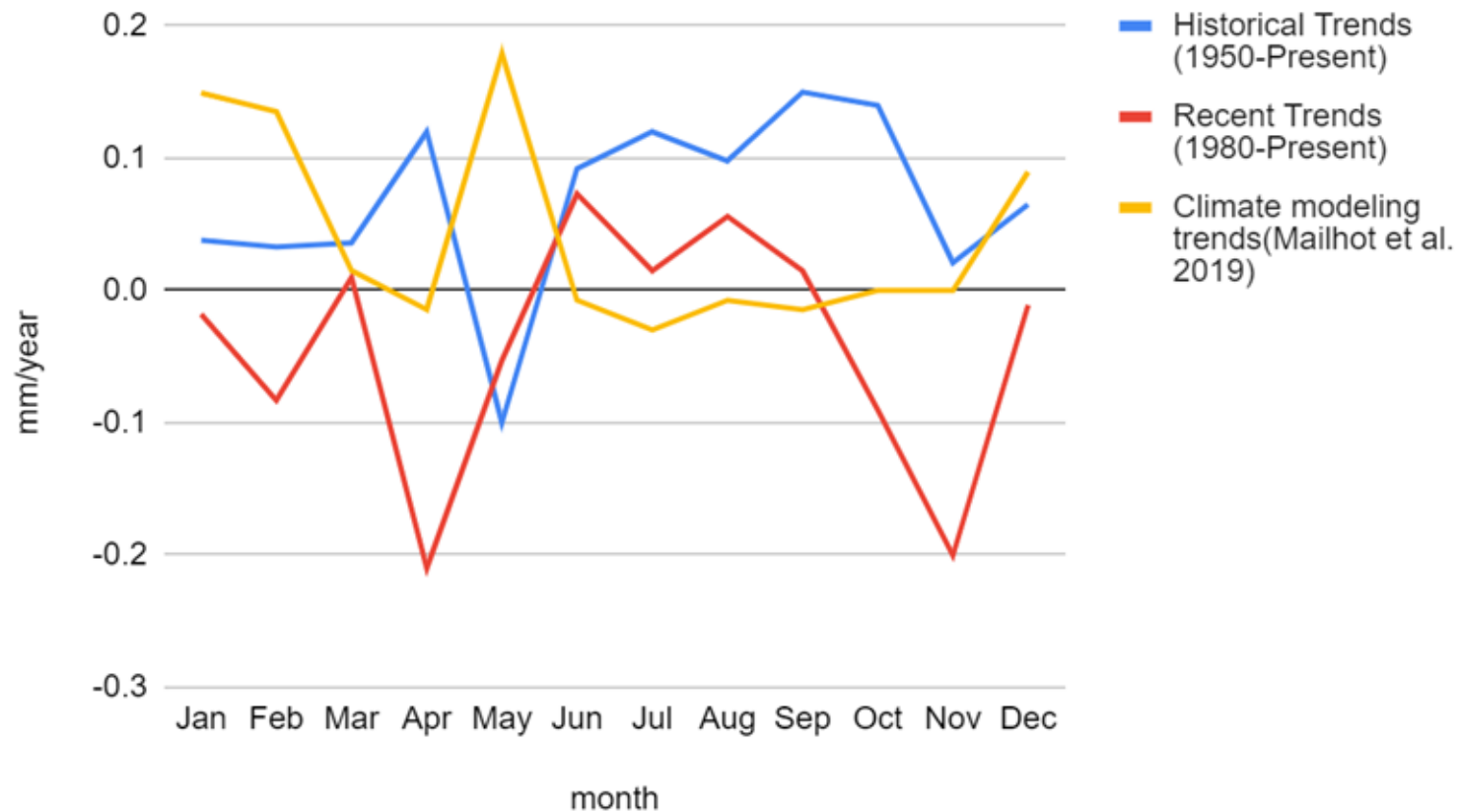
Lake Superior Precipitation Scenarios



Lake Superior Evaporation Scenarios



Lake Superior Runoff Scenarios



Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL090374

Key Points:

- An intensifying tug-of-war between precipitation and evaporation is dominating water level variability on Earth's largest lake system
- Competing forces are increasing or becoming more variable, setting the stage for oscillations between record high and record low levels

A Tug-of-War Within the Hydrologic Cycle of a Continental Freshwater Basin

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¹School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA, ²Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, USA, ³Faculty of Environment and Natural Resources, Nong Lam University, Ho Chi Minh City, Vietnam, ⁴Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, MI, USA

Outline

1. Introduction to the Great Lakes water balance
2. Reducing uncertainty in water balance
 - USGS Scientific Investigations Report 2004
 - Large Lake Statistical Water Balance Model (L2SWBM)
3. Climate change and the historical record
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 2. Reference period (1950-1979 vs 1980-2019)
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Conclusions

- Incorporating the L2SWBM into the CIA reduces uncertainty
- Climate change signals might exist in the historical record
- Precipitation and evaporation are likely to increase in the Great Lakes

Thank you!

GREAT LAKES
ST. LAWRENCE
GOVERNORS
& PREMIERS



Questions?

If you have further questions, please reach out to:

Dr. Drew Gronewold, University of Michigan: drewgron@umich.edu

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Supplementary Slides

The Large Lakes Statistical Water Balance Model (L2SWBM).

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

where: ΔH : change in lake storage over w months, i.e. from month j to month $j + w$ (mm);

P : over-lake precipitation (mm);

E : over-lake evaporation (mm);

R : lateral tributary lake inflow (mm);

I : inflow from upstream lake (m^3/s);

Q : outflow to downstream lake (m^3/s);

D : inter-basin diversions (to or from a specific lake) and consumptive uses (m^3/s);

ε : process error term representing water level changes not explained by the other components (mm) such as ground-water fluxes or glacial isostatic rebound⁵⁹.

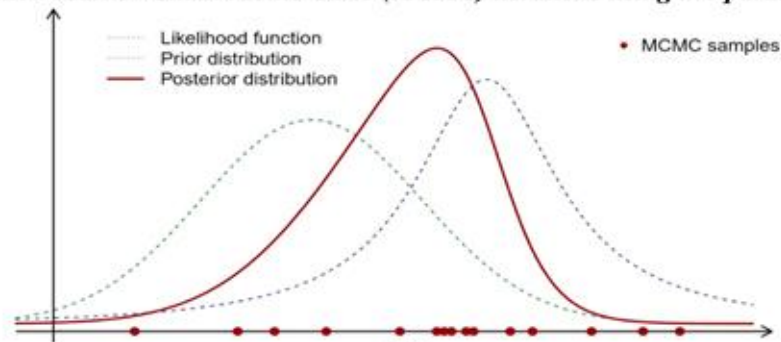
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Prior probability distributions were derived from legacy gauged-based datasets

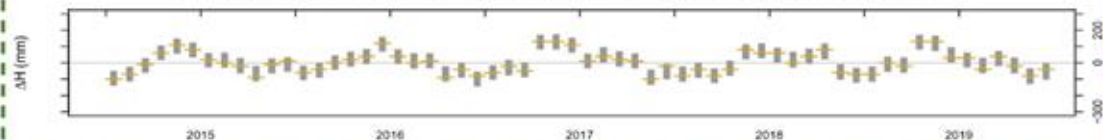
Likelihood functions were derived from multiple independent datasets

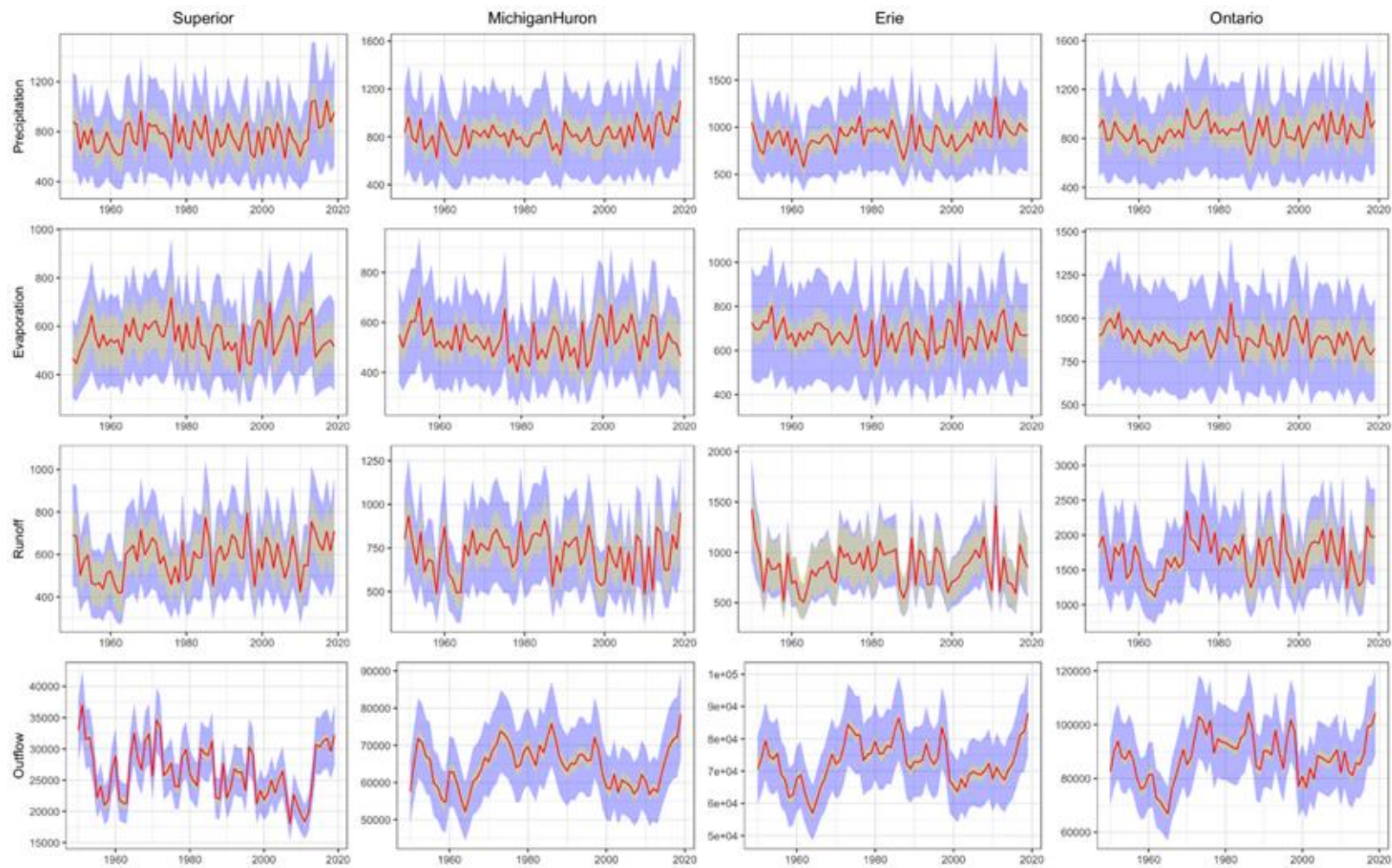
One-million Markov Chain Monte Carlo (MCMC) iterations using two parallel chains



$$\text{Constraint: } \Delta H_{j,w} = H_{j+w} - H_j = \sum_{l=j}^{j+w-1} (P_l - E_l + R_l + I_l - Q_l + D_l - \varepsilon_l)$$

Omitting the first half; thinning to 2000 iterations
(the 95% credible interval was used to represent the new estimates)





Lake Superior	Average magnitude	Average monthly estimate uncertainty			
		Low	High	Low (ft ³ /s)	High (ft ³ /s)
Component of water balance	ft ³ /s				
Connecting-channel inflow	N/A	N/A	N/A	N/A	N/A
Connecting-channel outflow	79,118	5%	15%	3,956	11,868
Change in storage	N/A	0.12 in (3 mm)	0.47 in (12 mm)	3,356	13,422
Over-lake precipitation	73,047	15%	45%	10,957	32,871
Runoff	55,619	15%	35%	8,343	19,467
Evaporation	54,233	10%	35%	5,423	18,982
Long Lac diversion	1,412	10%	30%	141	424
Ogoki diversion	4,035	10%	30%	404	1,211
Ground water	Unknown	100% of 850 ft ³ /s	100% of 3,500 ft ³ /s	850	3,500
Component NBS	70,398	11%	31%	7,567	21,848
Residual NBS	73,671	4%	12%	2,656	9,164

Uncertainty in the Great Lakes Water Balance



Scientific Investigations Report 2004-5100

U.S. Department of the Interior
U.S. Geological Survey

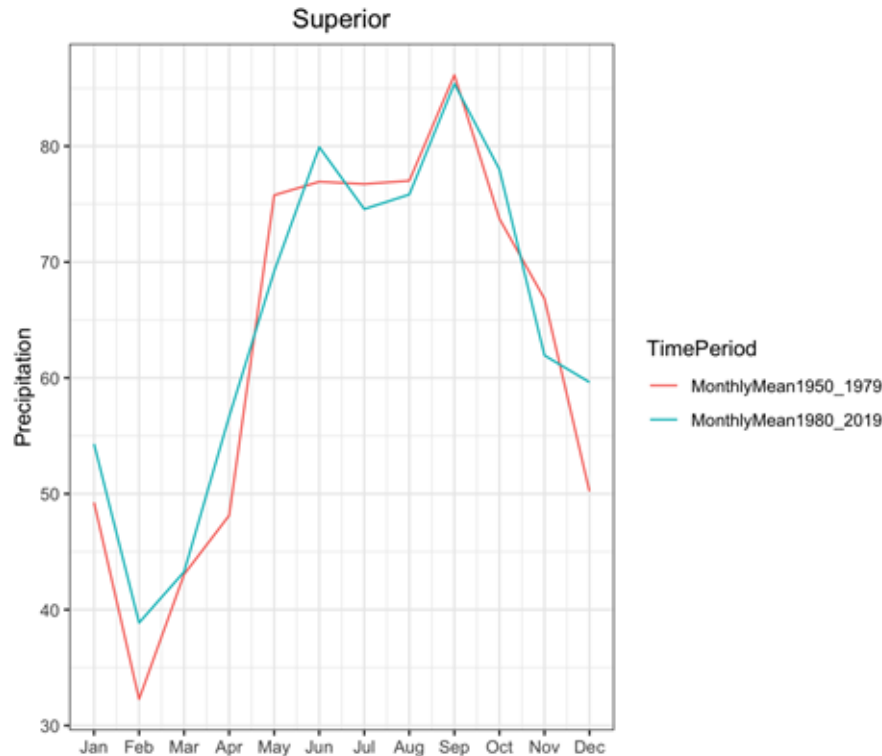
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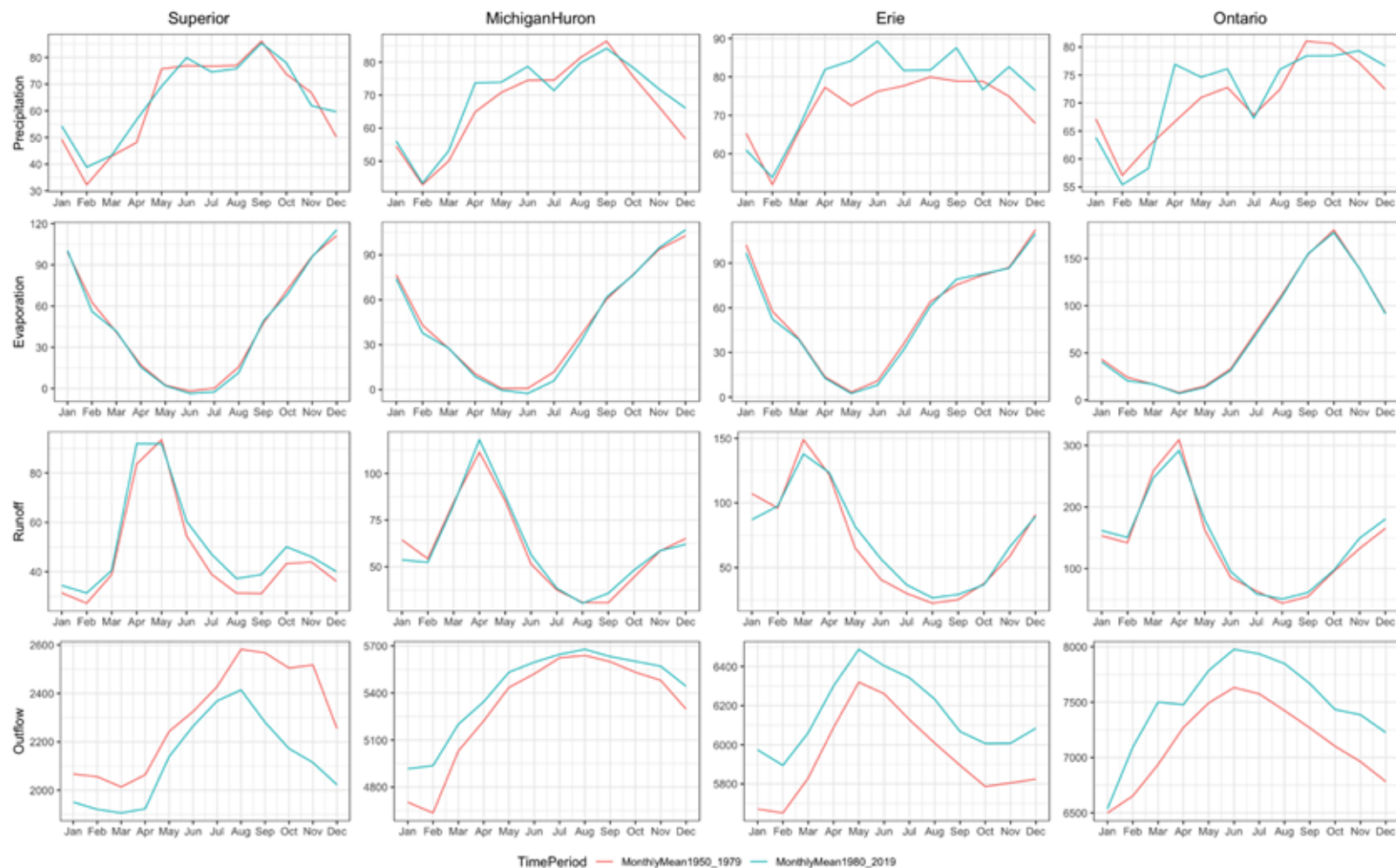
IPCC climate change definition

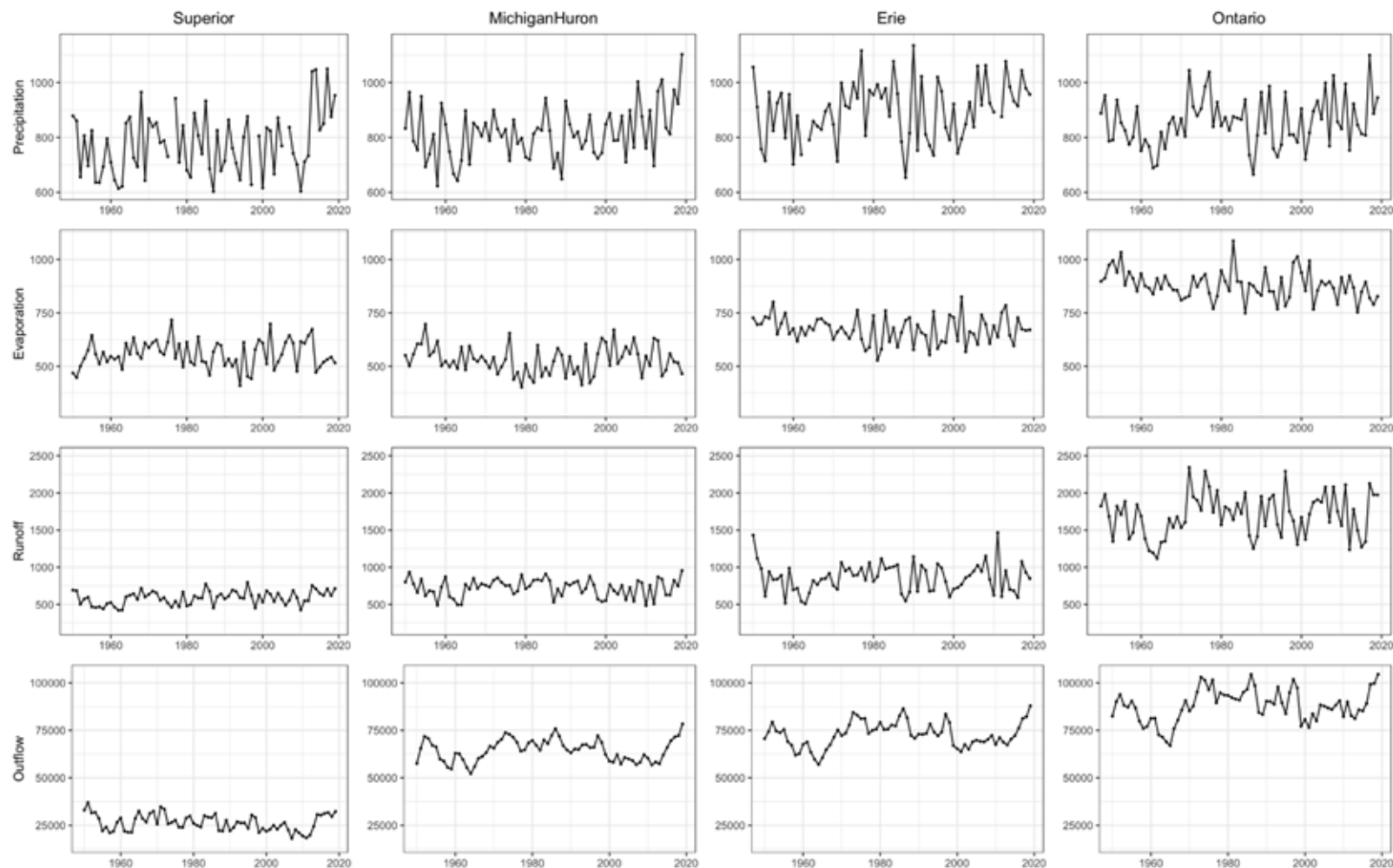
Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the **mean** and/or the **variability** of its properties and that persists for an **extended** period, typically decades or longer. Climate change may be due to **natural internal processes or external forcings** such as modulations of the solar cycles, volcanic eruptions and persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*.

Note that the *Framework Convention on Climate Change (UNFCCC)*, in its Article 1, defines climate change as: ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.’ The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes. See also *Climate variability*, *Global warming*, *Ocean acidification (OA)* and *Detection and attribution*.

Method 2c: Monthly mean of a fixed reference period



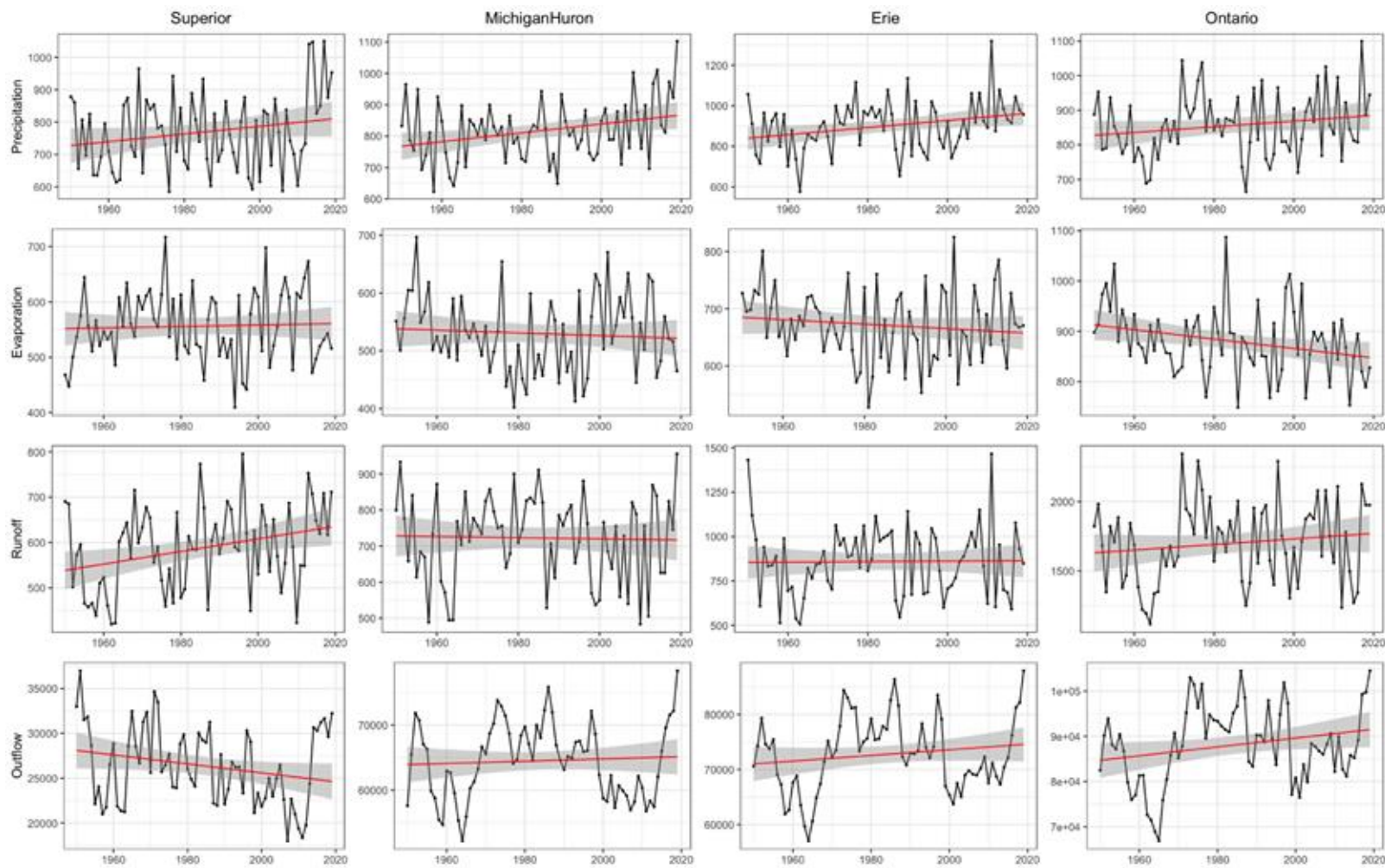


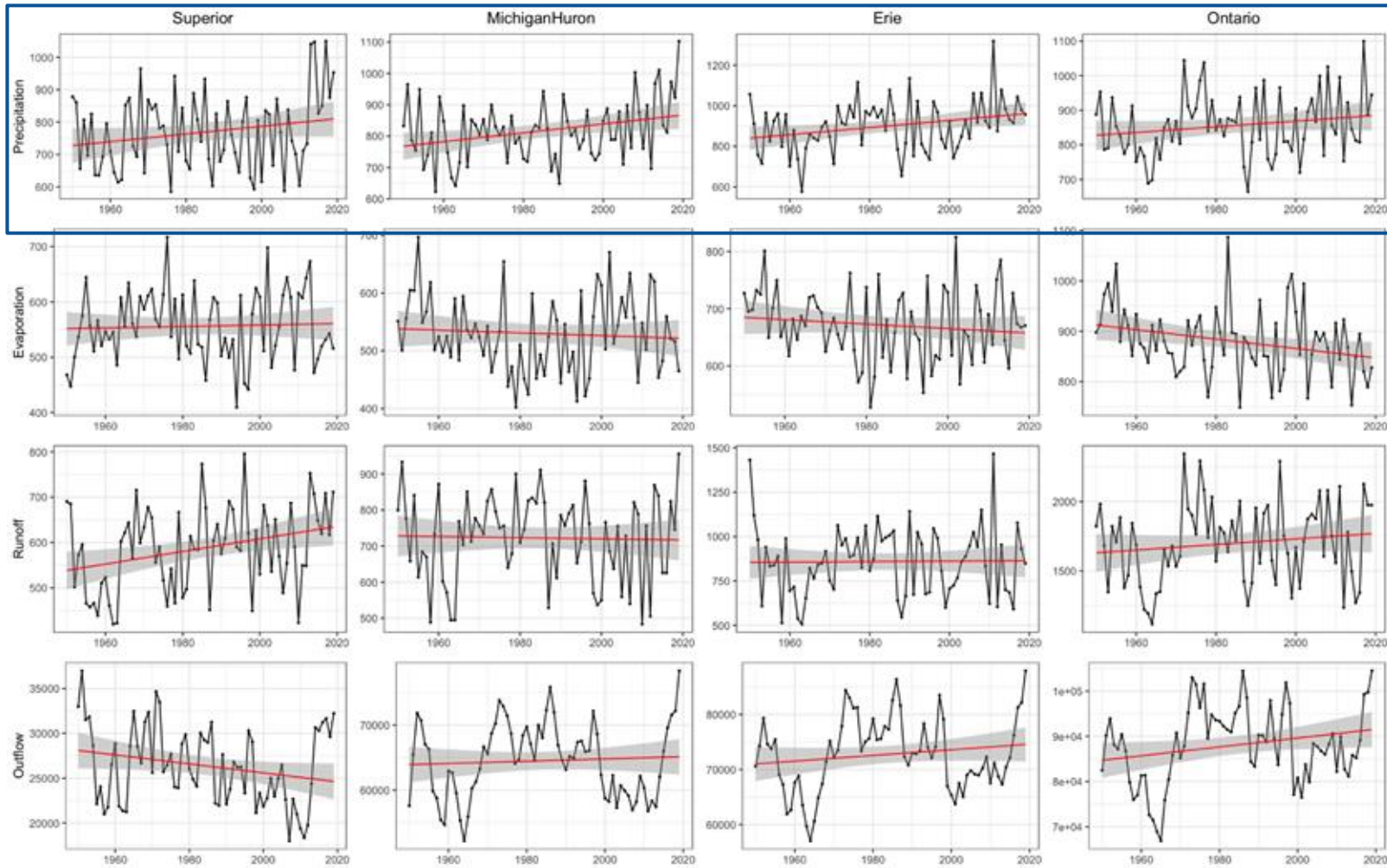


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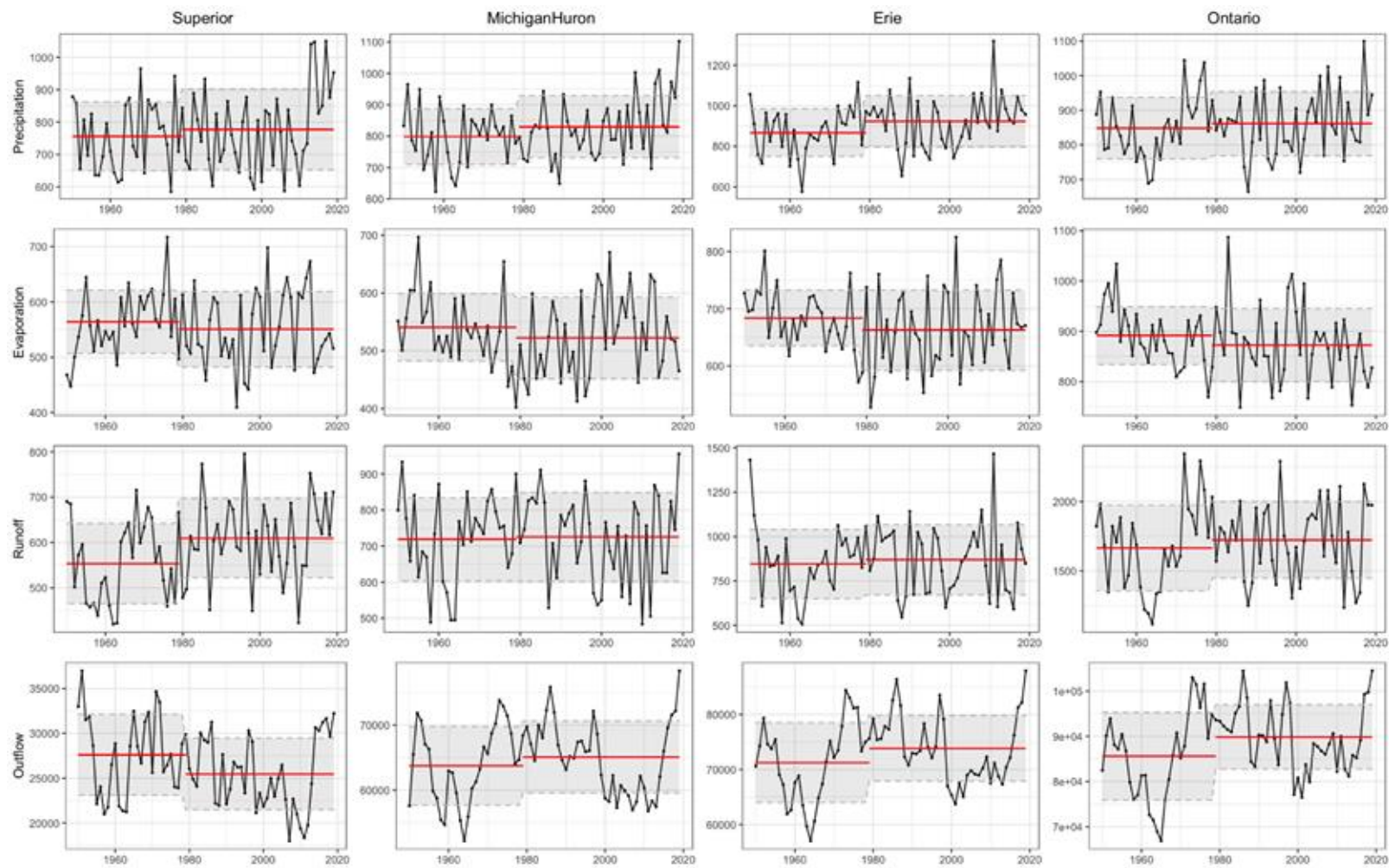


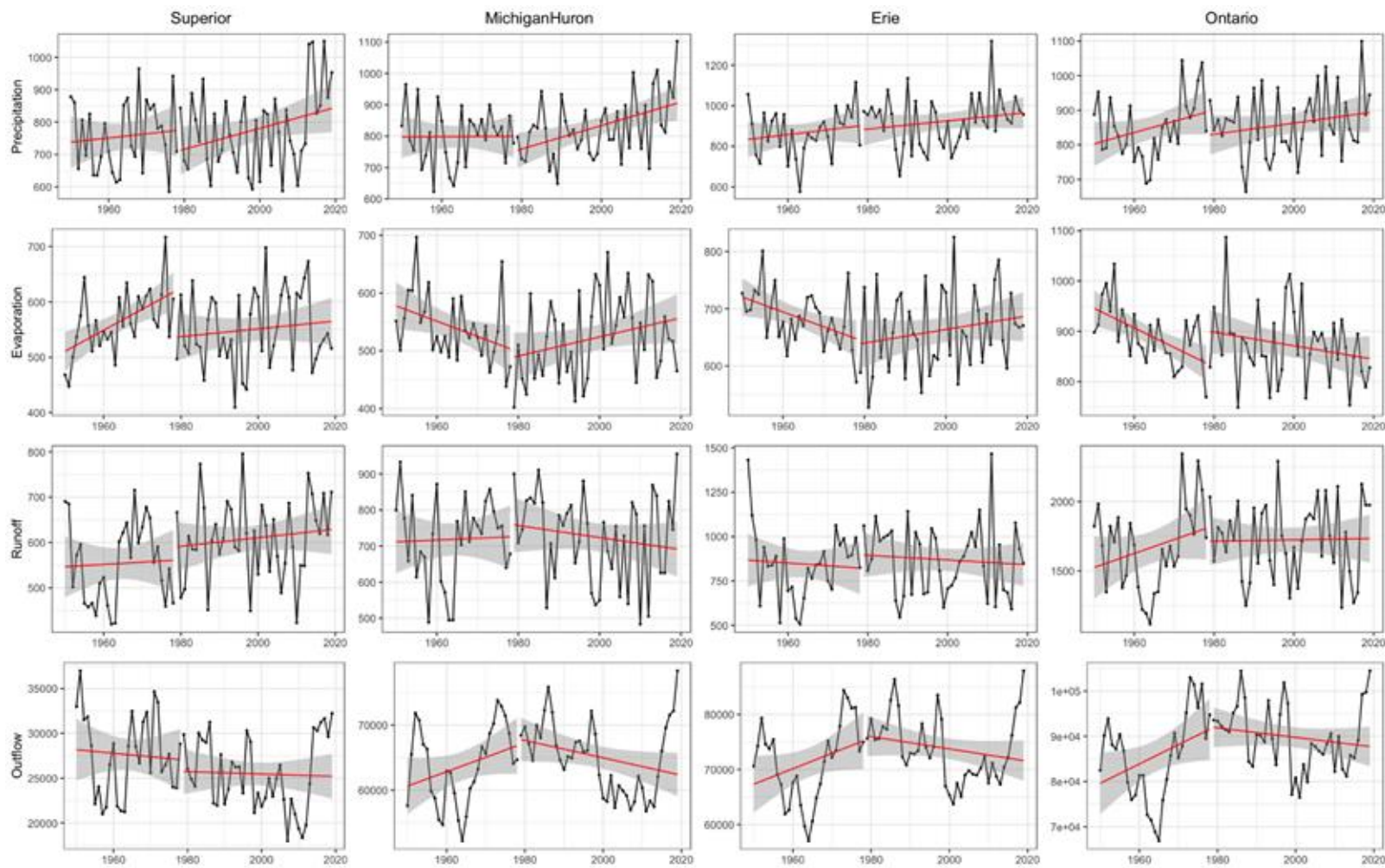


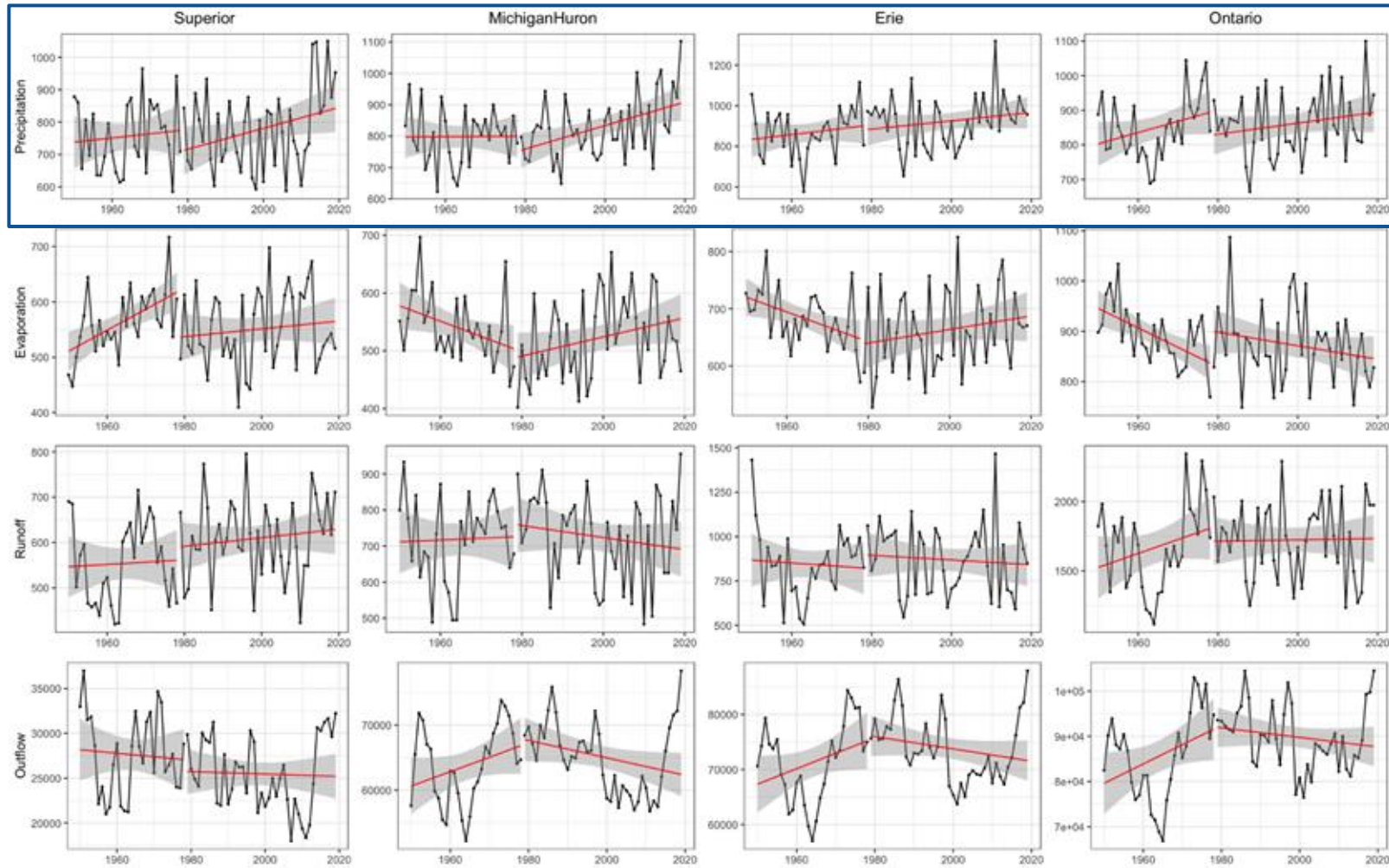
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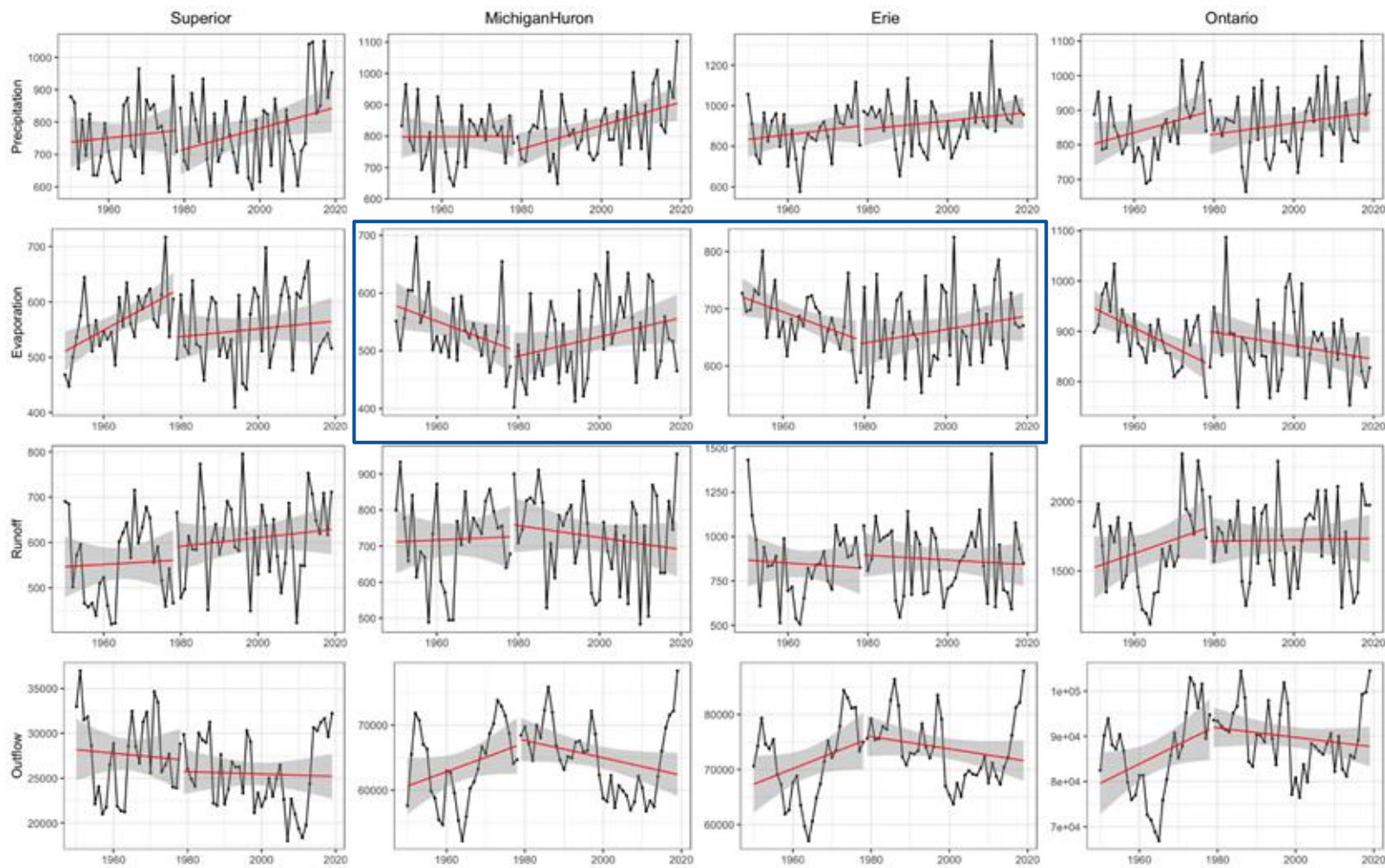
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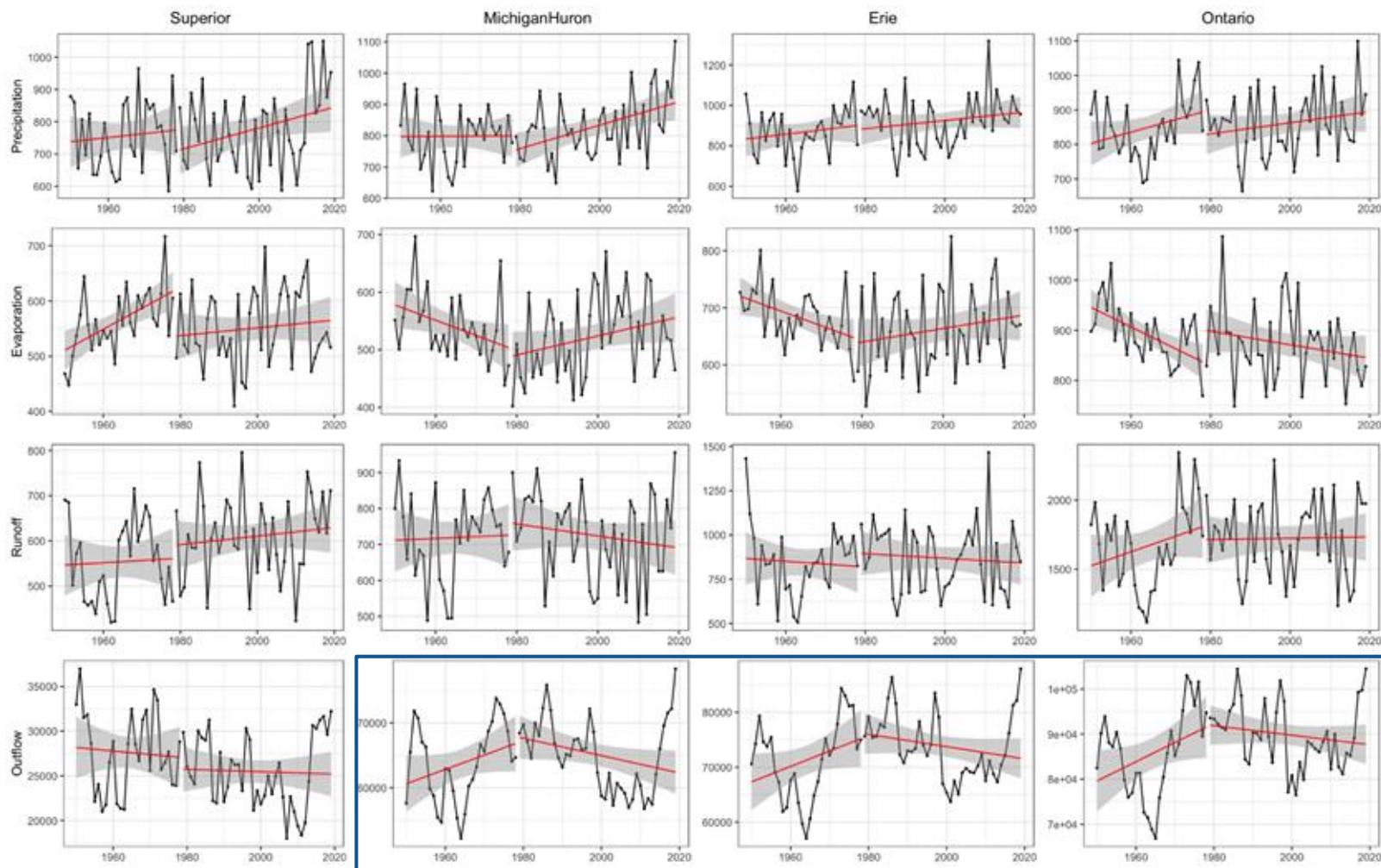








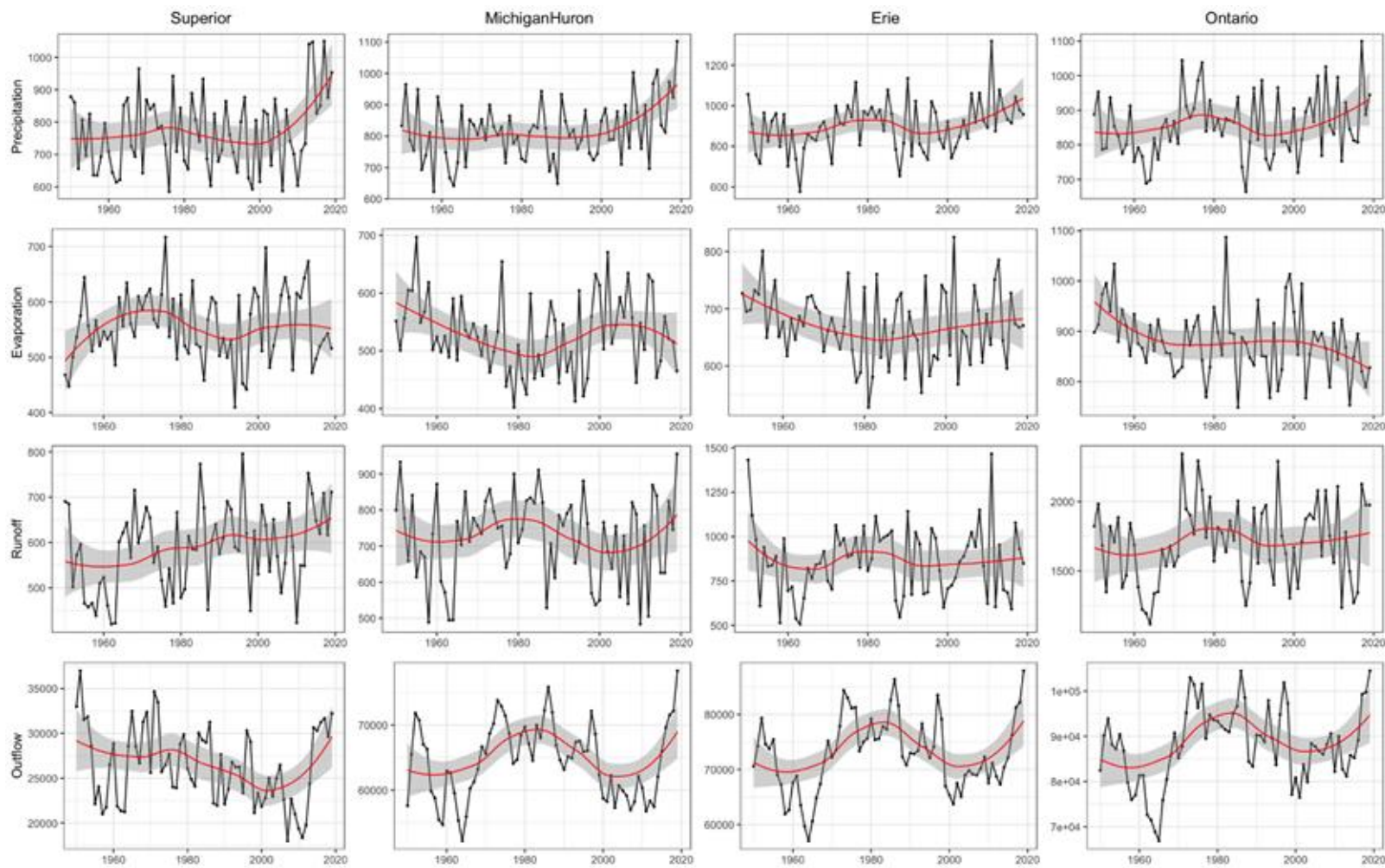




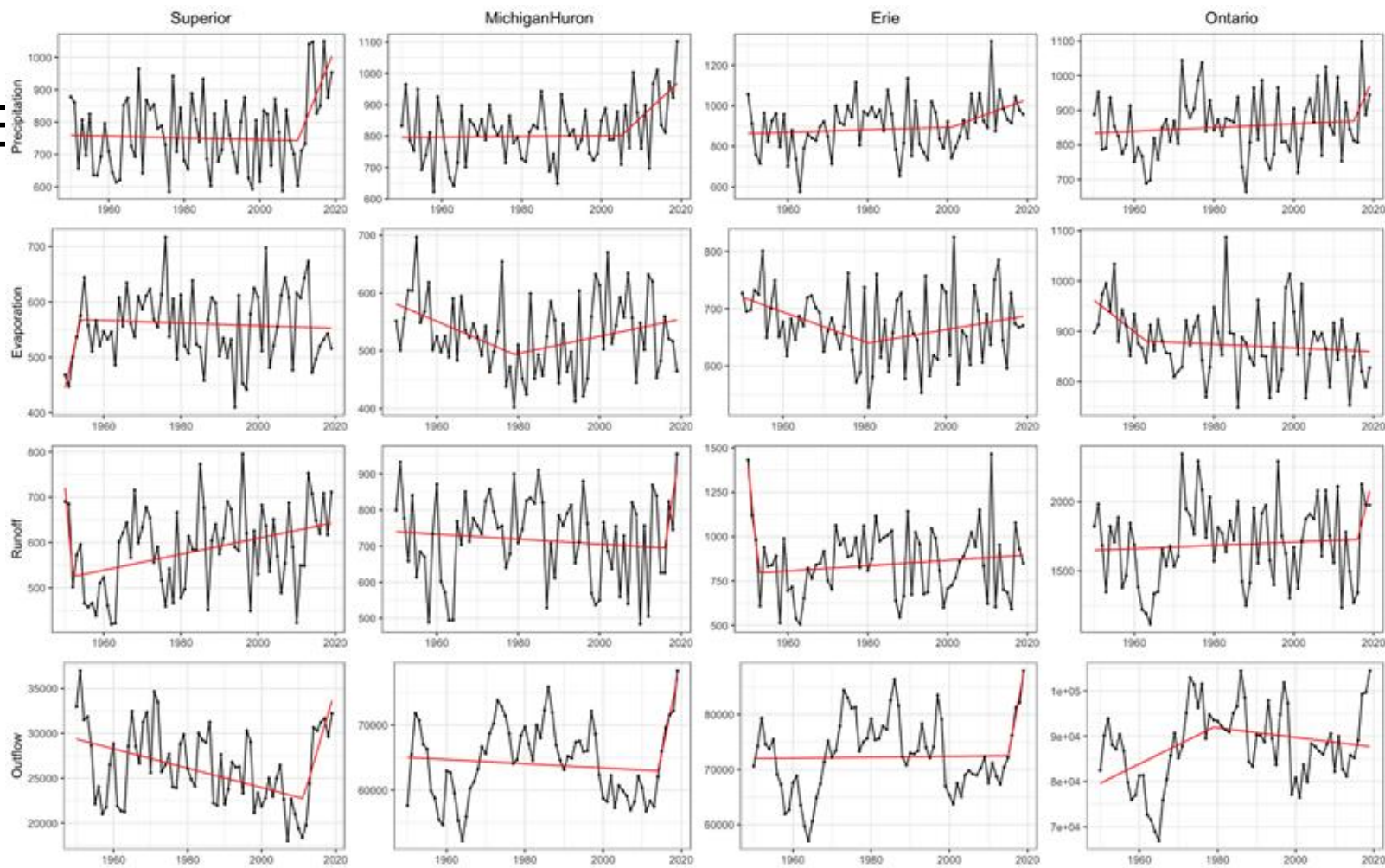
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