Hydro-Economic Model for the Great Lakes Basin using a Multiregional Input-Output Optimization Approach

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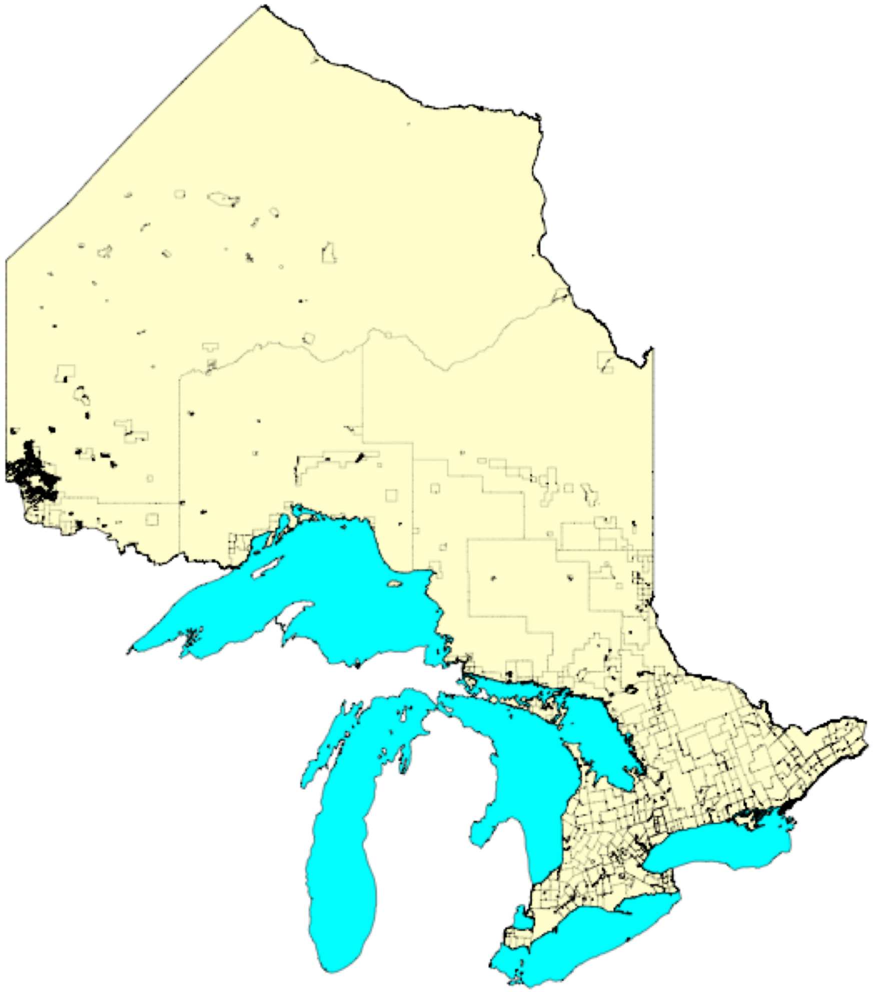
Outline

1. Canadian Great Lakes Basin
2. Climate change outlook
3. Problem statement
4. Methodology
5. Scenarios
6. Results
7. Conclusions
8. Next steps

1. Canadian Great Lakes Basin

- Canadian GLB located within Ontario.
- GLB contains **~20%** of **world's freshwater resources**[1].
- Covers 3% of Canada's area, home to **1/3 of its population**[2,3] (11.6 million).
- Province of Ontario **highest GDP share** (~38%)[4].
- One of **most diverse ecoregions** in North America.
- Greatest species diversity in Canada[5].



2. Climate change outlook

Despite GLB is rich in water resources, water of lakes considered **non-renewable**[6] and over the next decades is expected:

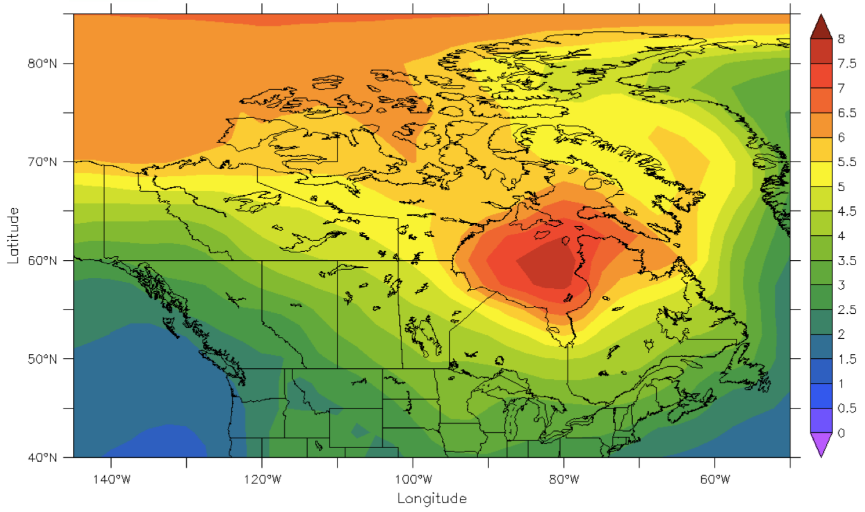


Image: Environmental and Climate Change, mean winter temp. change 2041-2070.
Source: https://www.ec.gc.ca/

- Air temp. increase 1.5-7° C[7], which increases evaporation and lead to **decline in water levels**[8].
- **Droughts** and **precipitation** to increase in frequency, duration and extent[9].
- Impact **recharge cycle** of groundwater impacted.
- Surface water temp. increase 0.9-6.7 °C, which will decrease vertical mixing leading to **more algae blooms**[10].

⟹ Impacts to **water availability conditions**.

3. Problem statement

GLB already a region with **severe water stress**[11] (WAI* ≥ 0.4) for August and more variability is expected.

$$WAI = \frac{water\ withdrawals}{renewable\ water\ availability}$$

- *What would be the economic impact of **localized water input reductions** due to weather events or policy interventions in the GLB?*

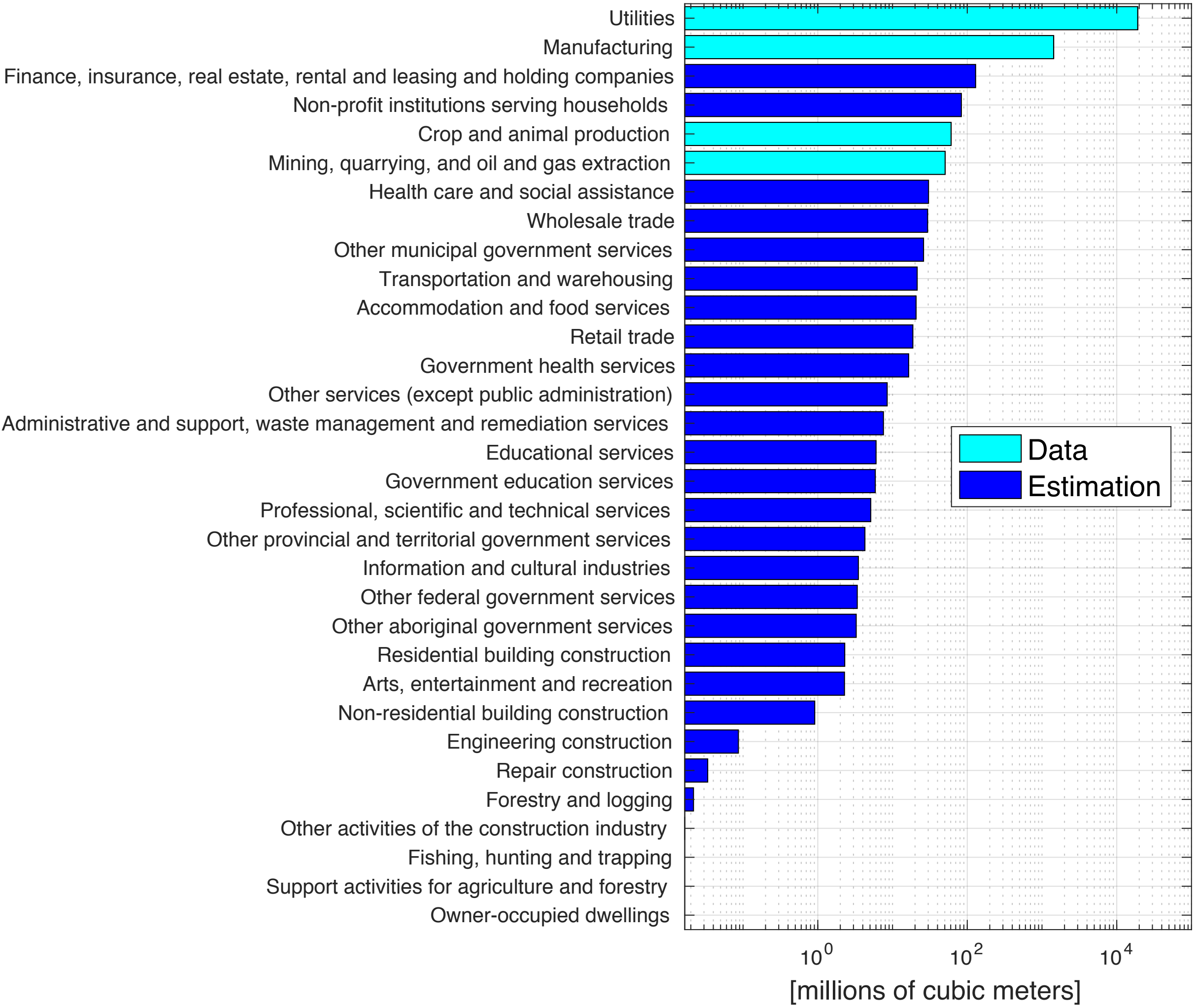
- *What if **food** and **energy security** are ensured?*

Objective:

Develop a **multiregional model** to describe **direct and indirect economic impacts** of water disruptions considering climate change. Regions defined by drainage boundaries.

*Water availability index

4. Methodology



Allocation of water use to industries

Provincial data of some industries is available[13], for the remaining, national[14] values were:

- Water intake per dollar produced [m^3/$].
- Water intake per job [m^3/job].

Estimates differ overall less than 2%. Average was used.

4. Methodology

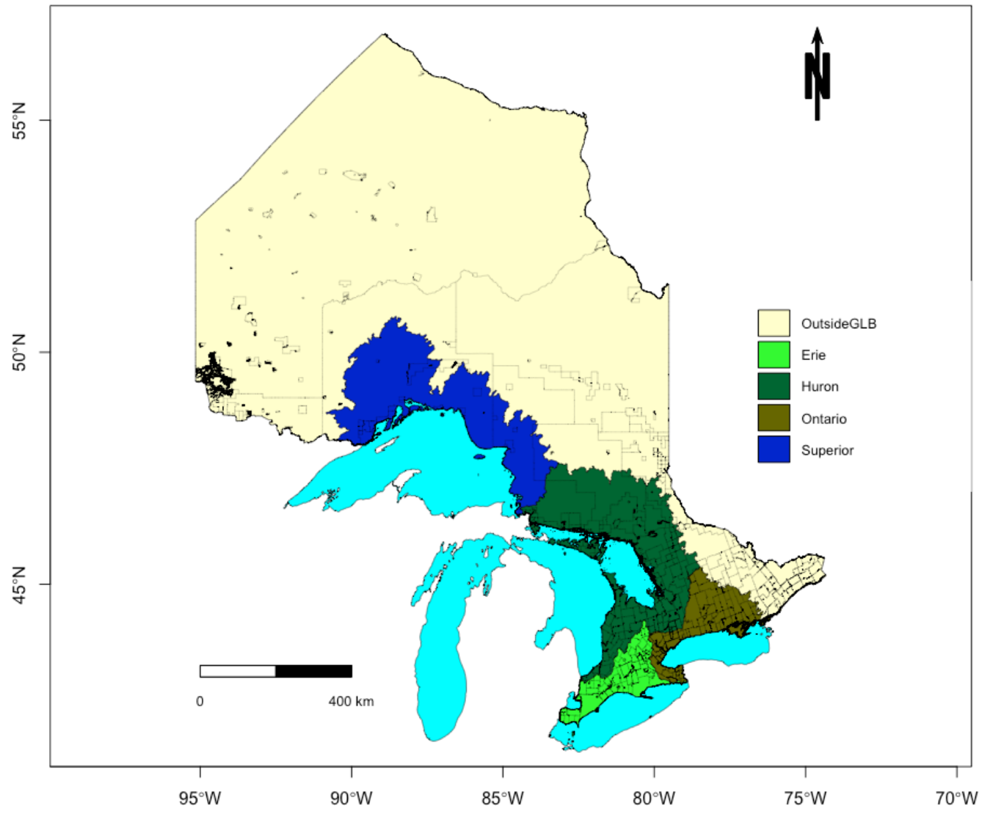
Allocation of gross output to regions

1. Employment to regions based on hydrological boundaries.

   Subdivisions = 575

   Average area = 1,700 km²

2. Initial gross output based on employment*.

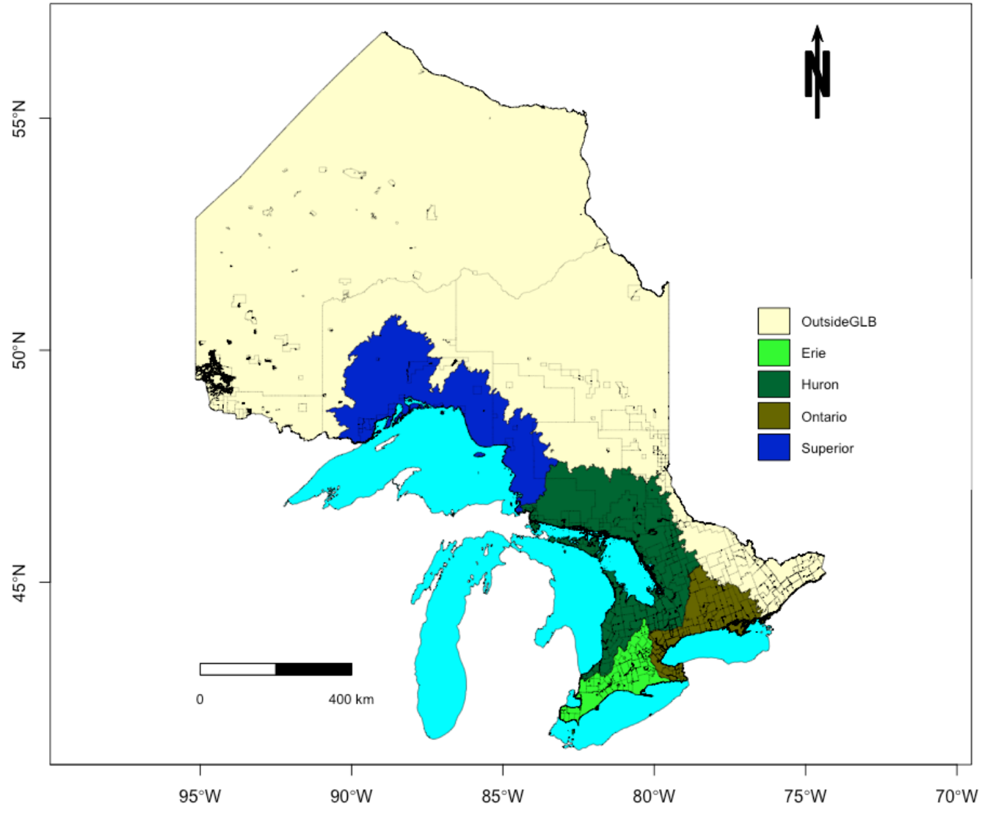


*Regression model created at provincial level to test linearity between jobs and output per industry, min $R^2 = 0.989$.

4. Methodology

Allocation of gross output to regions

3. Flegg Location Quotient (FLQ) was used to estimate interregional trade.
4. Final demand assigned based on population and initial output.
5. Optimization used to find multiregional IO table ensuring consistency and nonnegativity.



4. Methodology

Provincial model

$$Min\ z = (\boldsymbol{x} - \boldsymbol{x}_0)^T \boldsymbol{\Lambda}\, (\boldsymbol{x} - \boldsymbol{x}_0)$$

s.t

$$(\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} \leq \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}\boldsymbol{x} + \boldsymbol{f}_R + \boldsymbol{e}$$

$$\boldsymbol{x} \geq \hat{\boldsymbol{\alpha}}\, \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f}_{min}$$

$$\boldsymbol{\omega}^T\, \boldsymbol{x} \leq W_{Ind} - \Delta W$$

$$\boldsymbol{x} \geq \boldsymbol{0}$$

Proposed water-restricted input-output model

Minimize the weighted Euclidean distance between planned output and water-restricted output.

1. Portion of household consumption & gross capital formation depend on payments to labor and capital.
2. Allows for imports to substitute shortage in supply of commodities.
3. Ensures a minimum final consumption supply.
4. Resource restriction not exceeded (water).

5. Scenarios

- Assume climate change will extend current severe water stress (WAI) from one month to the summer.
- Scenarios focus of cost bringing down WAI from severe (≥ 0.4) to normal (≤ 0.2).
- Baseline 2015.

Scenario A

Select a region, apply total water **intake reductions** of **4-12%**.

Scenario B

Same as A, but ensuring **food** and **energy security**, i.e., agriculture, utilities, fishing, and mining must meet local final demand.

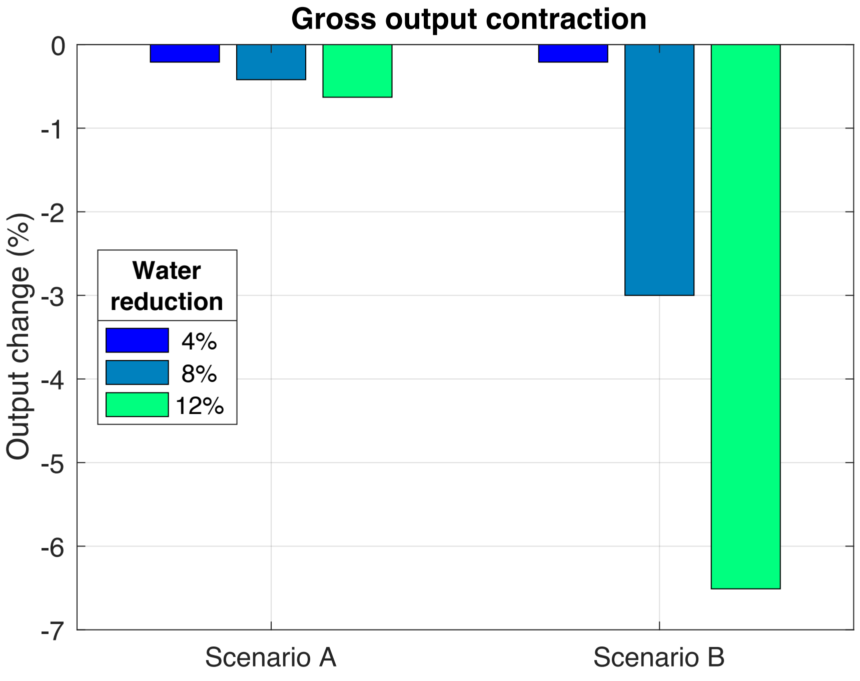
Scenario C

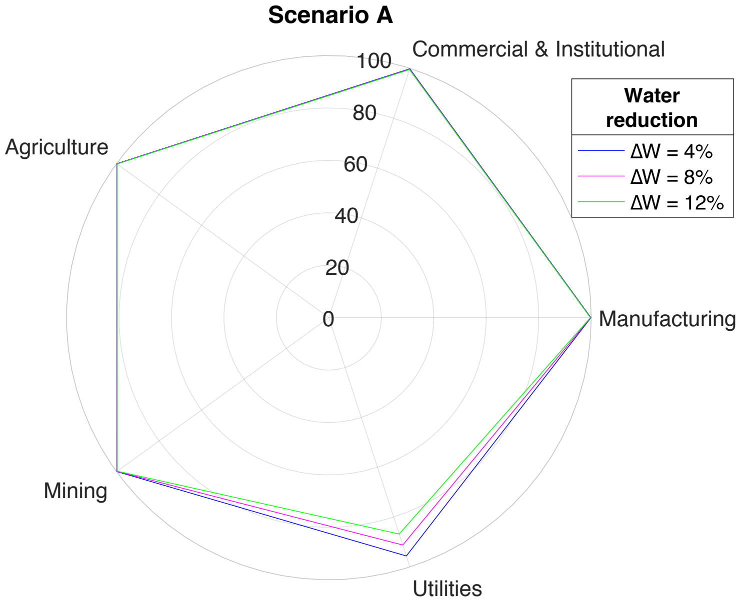
Same as B, but allowing **new trade** between to regions.

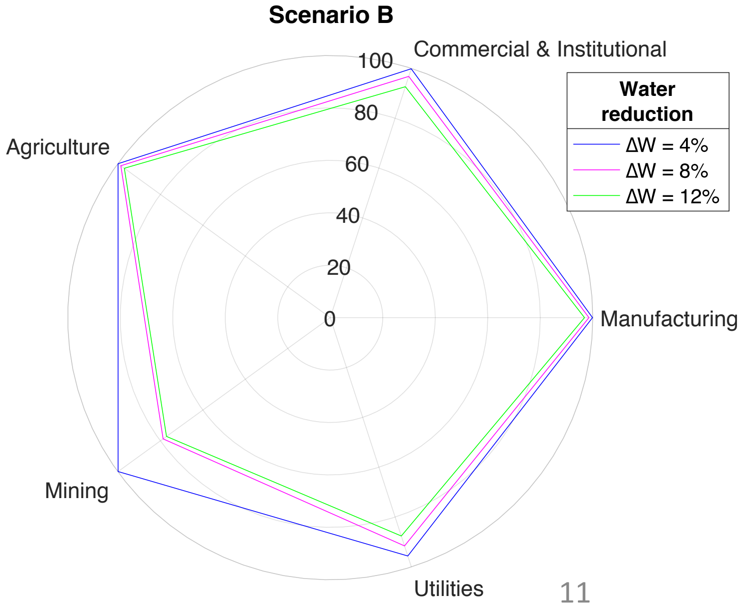
6. Results

Provincial model

	Scenario A				Scenario B			
Intake reduction	4%	8%	12%	Response	4%	8%	12%	Response
Δx (%)	-0.21	-0.42	-0.63	*linear*	-0.21	-3.00	-6.51	*nonlinear*
ΔGDP (%)	-0.23	-0.46	-0.7	*linear*	-0.23	-3.27	-7.04	*nonlinear*
ΔW [km^3]	-0.84	-1.68	-2.53		-0.84	-1.68	-2.53	







6. Results - MRIO

Multiregional model

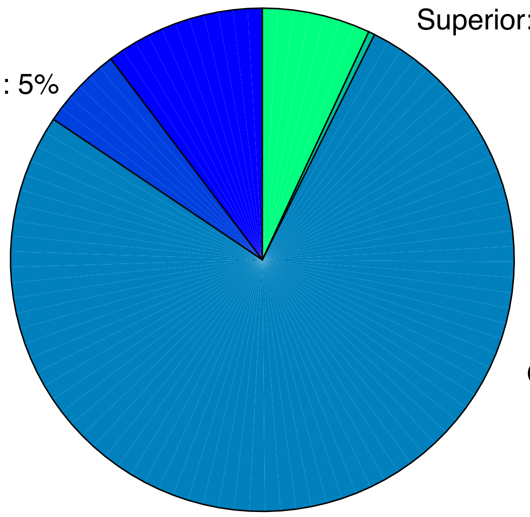
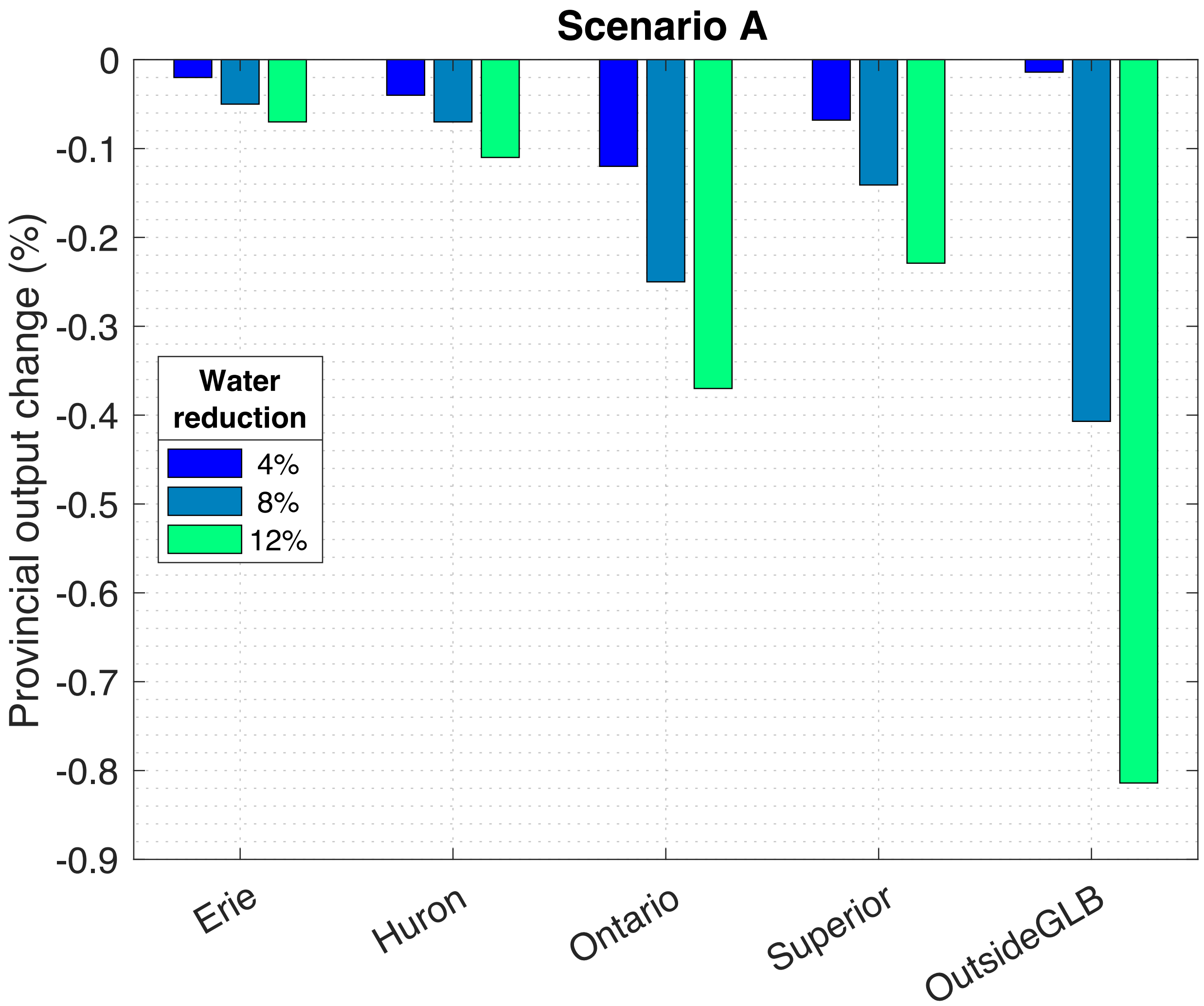


Table 3. Estimation of trade flows between sub-basins ($\times 10^6$ $)

Lake sub-basins		Destination: Erie	Huron	Ontario	Superior	Outside GLB	Exports	Total
Origin	Erie	123,660	5,230	22,580	1,380	5,410	40,420	198,680
	Huron	5,080	61,170	13,980	810	3,230	3,630	87,900
	Ontario	33,140	239,970	664,470	12,250	25,650	228,470	987,950
	Superior	510	300	1,330	3,530	320	820	6,810
	Outside GLB	4,700	2,850	26,070	730	59,290	3,270	96,910
	Imports	29,630	2,280	155,270	170	1,560	0	188,910
Total		196,720	95,800	883,700	18,870	95,460	276,610	1,885,620

Note: exports and imports include trade flows to and from other provinces and countries.

6. Results - MRIO



Scenario A
Water withdrawal reductions 4-12%.

Regions that trigger largest output contractions:
- Ontario (4%)
- OutsideGLB (8% and 12%)

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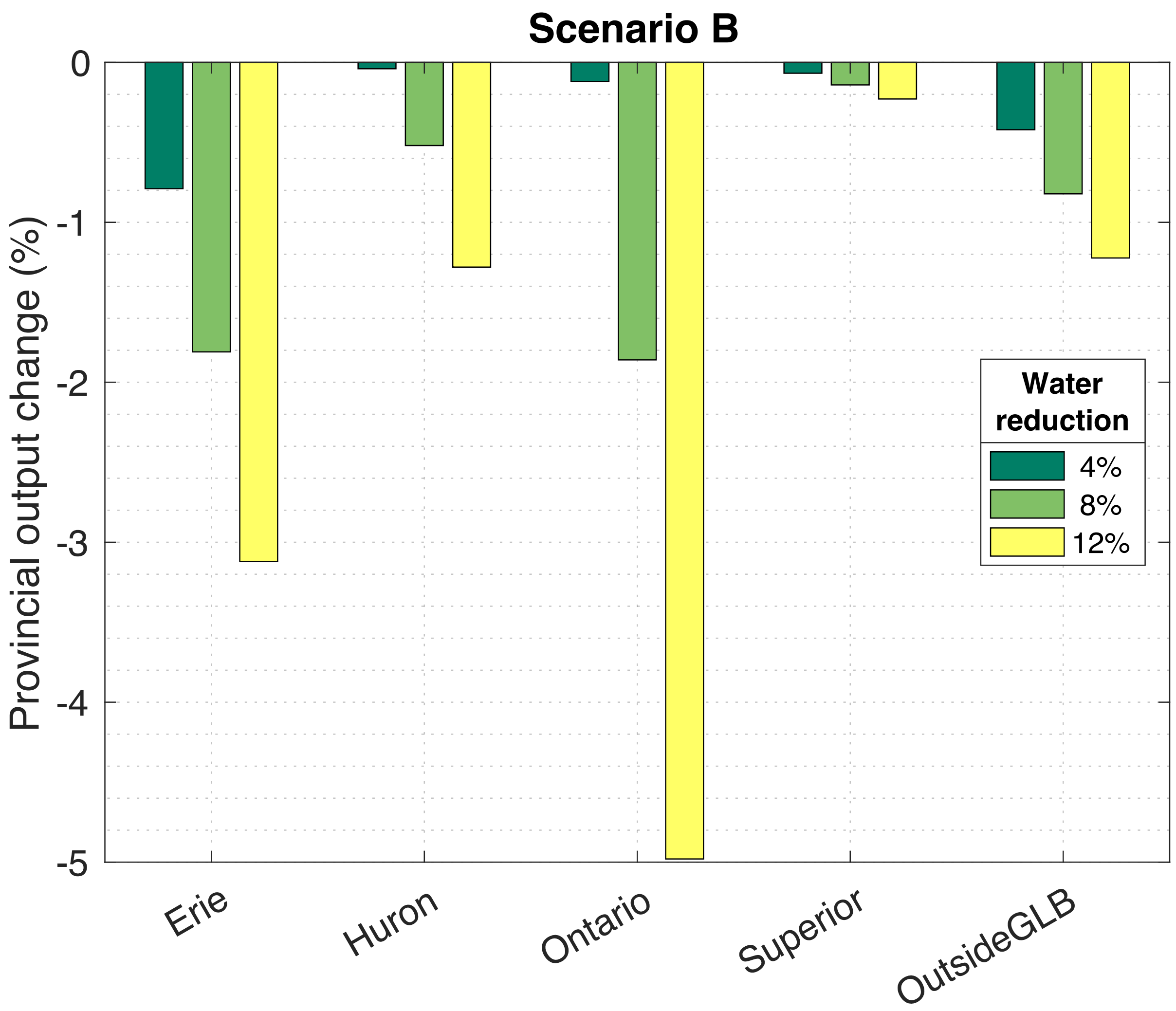
6. Results - MRIO



Scenario B

- Water withdrawal reductions 4-12%
- Food and energy security in the province.

Regions that trigger largest output contractions:

- Erie (4%)
- Ontario & Erie (8%)
- Ontario (12%)

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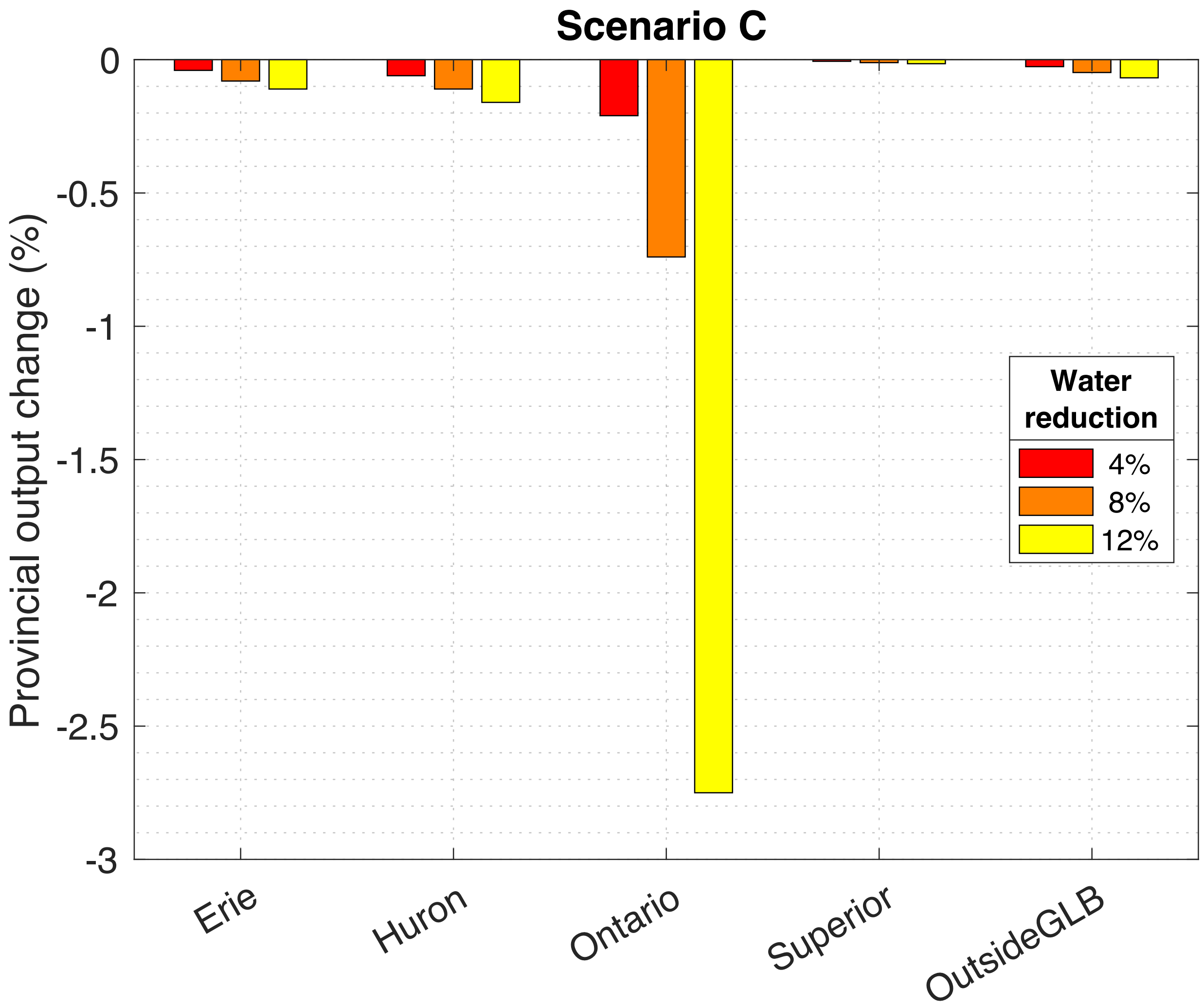

Scenario C

- Water withdrawal reductions 4-12%
- Food and energy security in the province.
- New unbounded trade is allowed.

Region that trigger largest output contractions:

- Ontario

7. Conclusions

Great Lakes Basin

1) GLB is able to cope reasonably well to 4% water intake reductions while ensuring food and energy security.
2) Higher water cutbacks trigger nonlinear output contractions and may threat the operations of certain industries.
3) Region integration significantly decreases the economic impacts of large (8%, 12%) water intake reductions.

Model

a) Captures nonlinear response due to bounding effect of decreased supply of commodities.
b) Expandable to include emission caps or other resource constraints.

8. Next steps

1) Include water quality restrictions (emissions caps: P and N).

2) Dynamic description coupled with lumped hydrological model.

3) Pan-Canadian model.

Thank you.

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4. Methodology

Input-Output table

- Input-Output (IO) tables are a representation of the economy in terms of supply and demand.
- Constructed from the System of National Accounts.
- Commodities expressed in monetary terms.
- Environmental-economic IO tables[12] include natural resources and emissions in physical units.

		Industry			Final demand	Total output	Water release (physical units)
		1	…	*n*			
Industry	*1*	$\boldsymbol{Z}$			$\boldsymbol{f}$	$\boldsymbol{x}$	$\boldsymbol{W}_R$
	…						
	n						
Imports		$\boldsymbol{i}^T$					
Value added		$\boldsymbol{v}^T$					
Total input		$\boldsymbol{x}^T$					
Water use (physical units)		$\boldsymbol{W}_{Ind}^T$					

IO table can be represented as the model:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f}$$

Supply

Intermediate and final demand

4. Methodology

Proposed water-restricted input-output model

Since regions are likely more integrated and may respond faster to each other needs; therefore

- Additional trade is allowed and penalized in the objective function.
- Allows localized water disruptions.

Multiregional model

$$Min\ z_M = \sum_{r=1}^{R} (\boldsymbol{x}^r - \boldsymbol{x}_0^r)^T \boldsymbol{\Lambda}^r \, (\boldsymbol{x}^r - \boldsymbol{x}_0^r) + \lambda_{new} \sum_{s}^{R} \sum_{r \neq s}^{R} \|\boldsymbol{t}^{sr}\|_2^2$$

s.t

$$\boldsymbol{x}^r + \sum_{s \neq r} \boldsymbol{t}^{sr} - \sum_{s \neq r} \boldsymbol{t}^{rs} - \sum_{s=1}^{R} \boldsymbol{A}^{rs} \boldsymbol{x}^s \leq \sum_{s=1}^{R} \boldsymbol{F}^{rs} \boldsymbol{x}^s + \sum_{s=1}^{R} \boldsymbol{f}_R^{rs} + \boldsymbol{G}^r \boldsymbol{x}^r + \boldsymbol{e}^r, \qquad \forall\, r$$

$$\boldsymbol{x}^r + \sum_{s \neq r} \boldsymbol{t}^{sr} - \sum_{s \neq r} \boldsymbol{t}^{rs} \geq \widehat{\boldsymbol{\alpha}^r} \left(\sum_{s=1}^{R} \boldsymbol{A}^{rs} \boldsymbol{x}^s \right) + \boldsymbol{f}_{min}^r, \qquad \forall\, r$$

$$\boldsymbol{\omega}^T \, \boldsymbol{x}^r \leq W_{Ind}^r - \Delta W^r, \qquad \forall\, r$$

$$\boldsymbol{t}^{sr} \leq \boldsymbol{c}^{rs}, \qquad \forall\, r \neq s$$

$$\boldsymbol{x}^r, \boldsymbol{t}^{rs} \geq \boldsymbol{0}, \qquad \forall\, r, s.$$

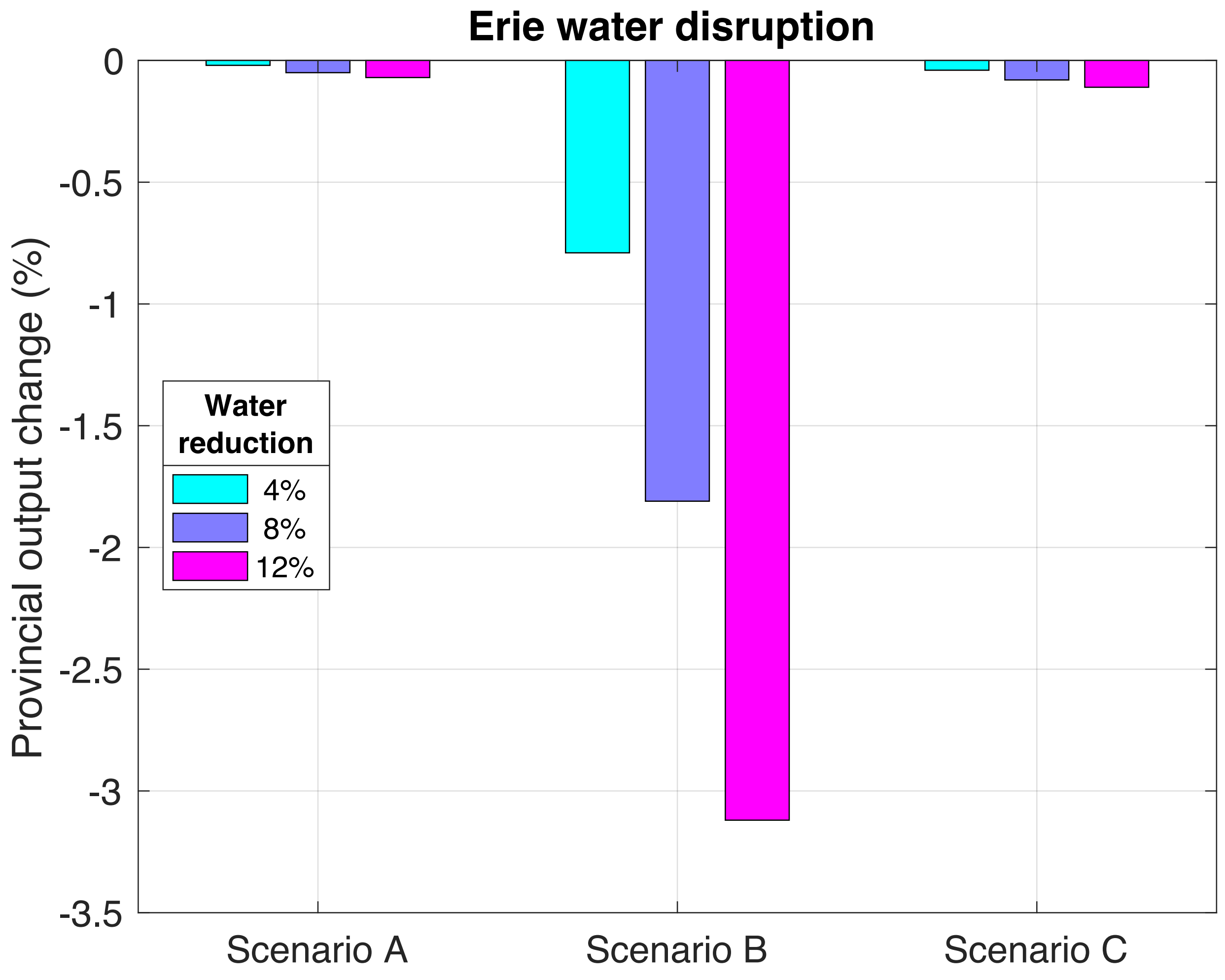
6. Results - MRIO

Disruptions in **Erie sub-basin**

Scenario A
- Econ. impacts linear.
- Reductions decreased by factor 0.05.

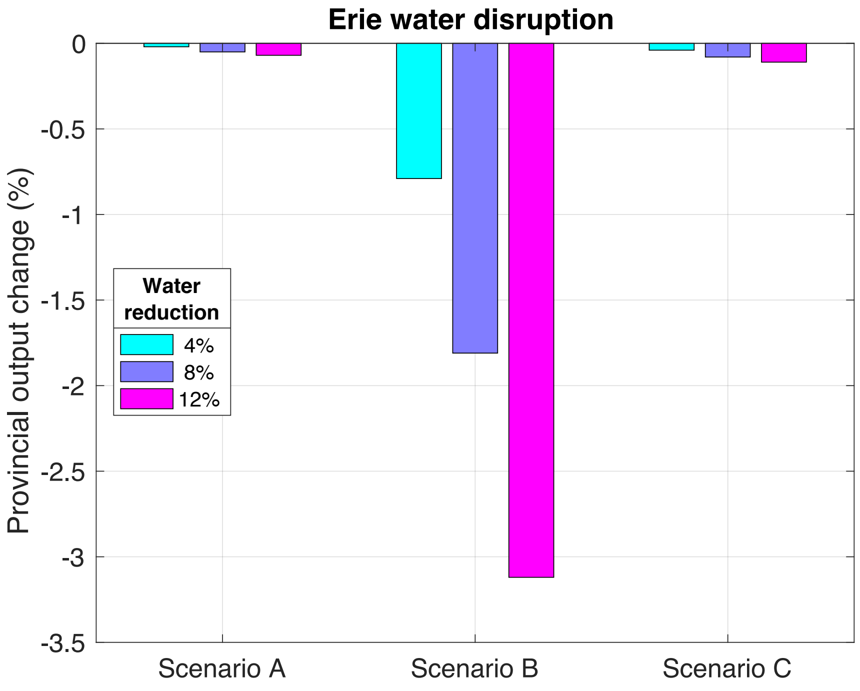
Scenario B
- Econ. impacts nonlinear.
- Reductions amplified by factor of 2.

Scenario C
- Eco. impacts less than linear.
- Reductions decreased by factor 0.1.

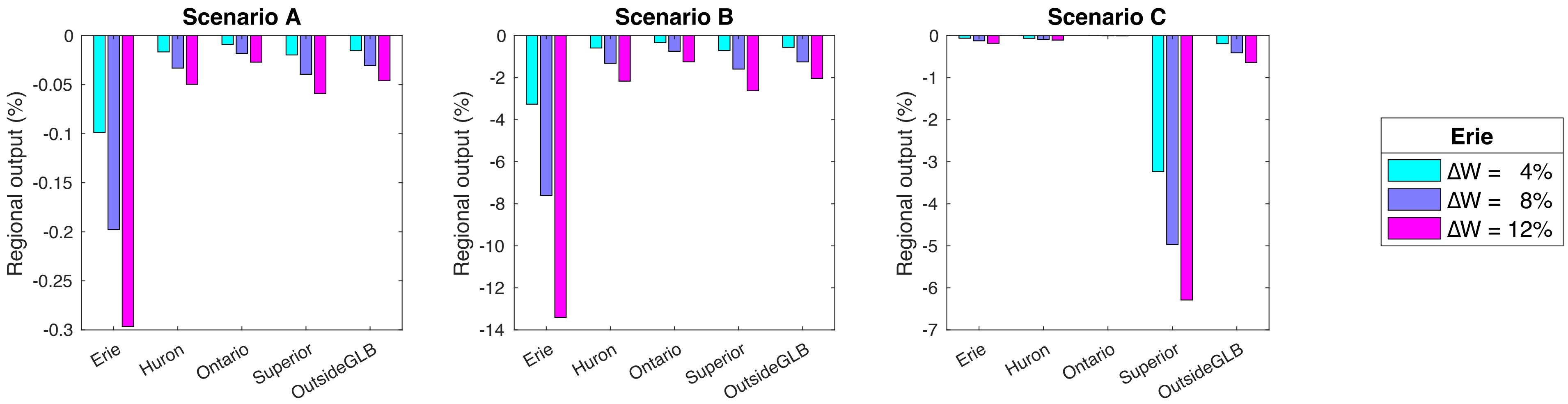


6. Results - MRIO

Disruptions in **Erie sub-basin**

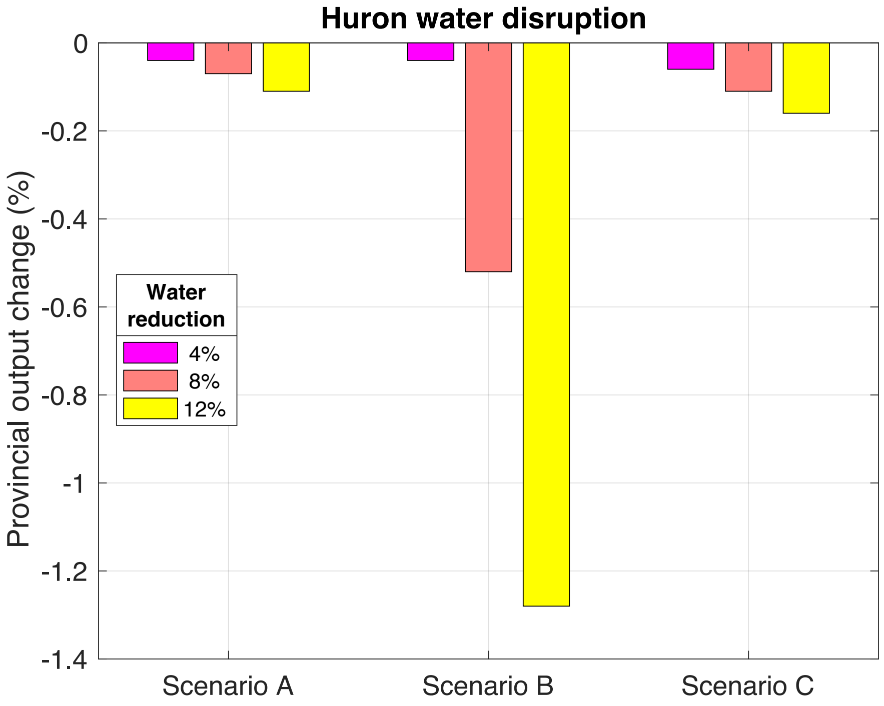


Spillovers:



6. Results - MRIO

Disruptions in **Huron sub-basin**



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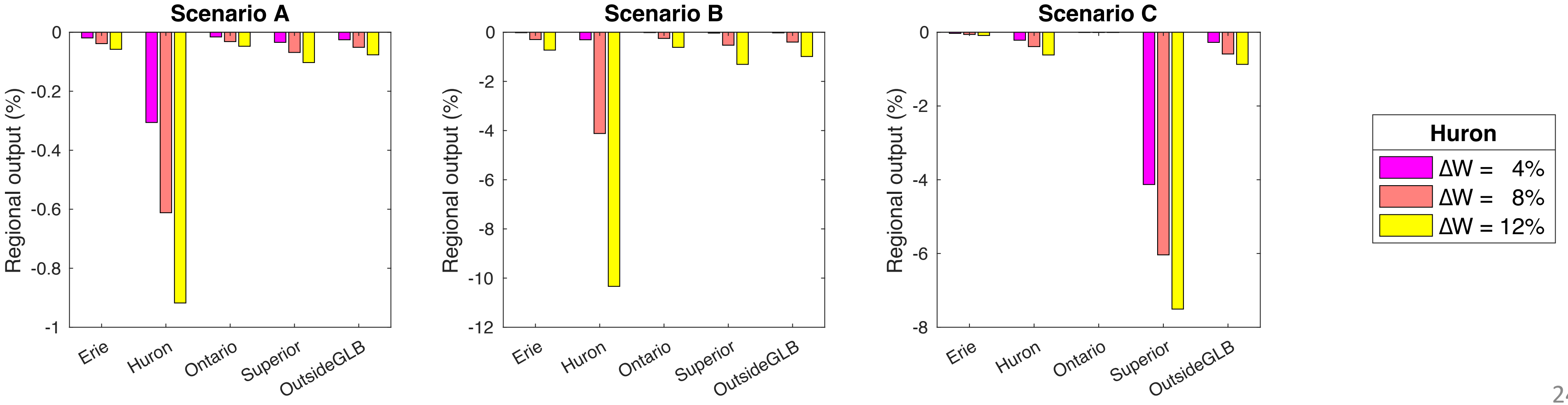
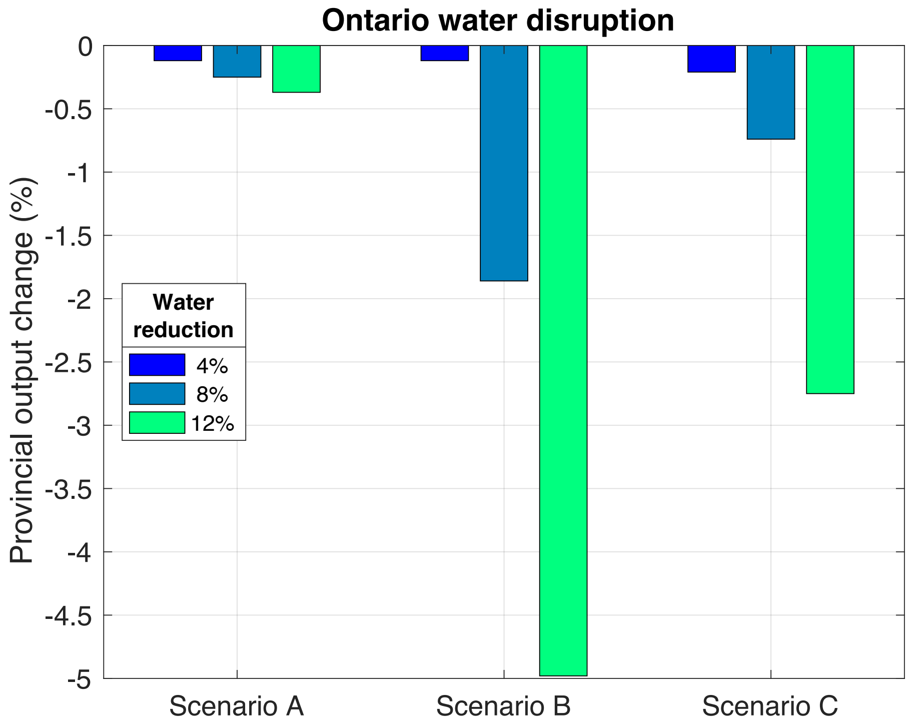


6. Results - MRIO

Disruptions in **Ontario sub-basin**



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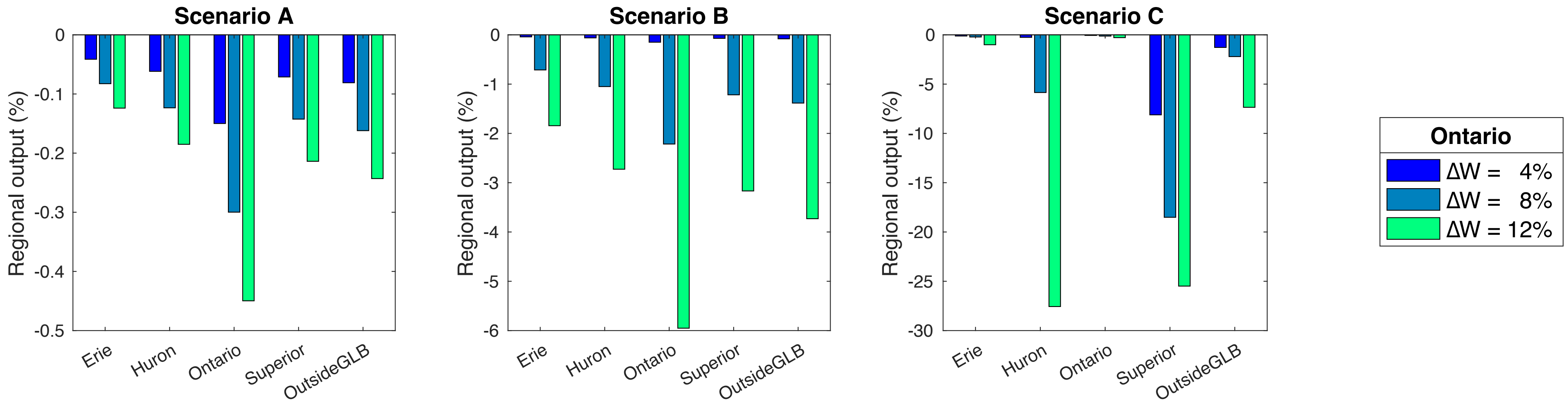
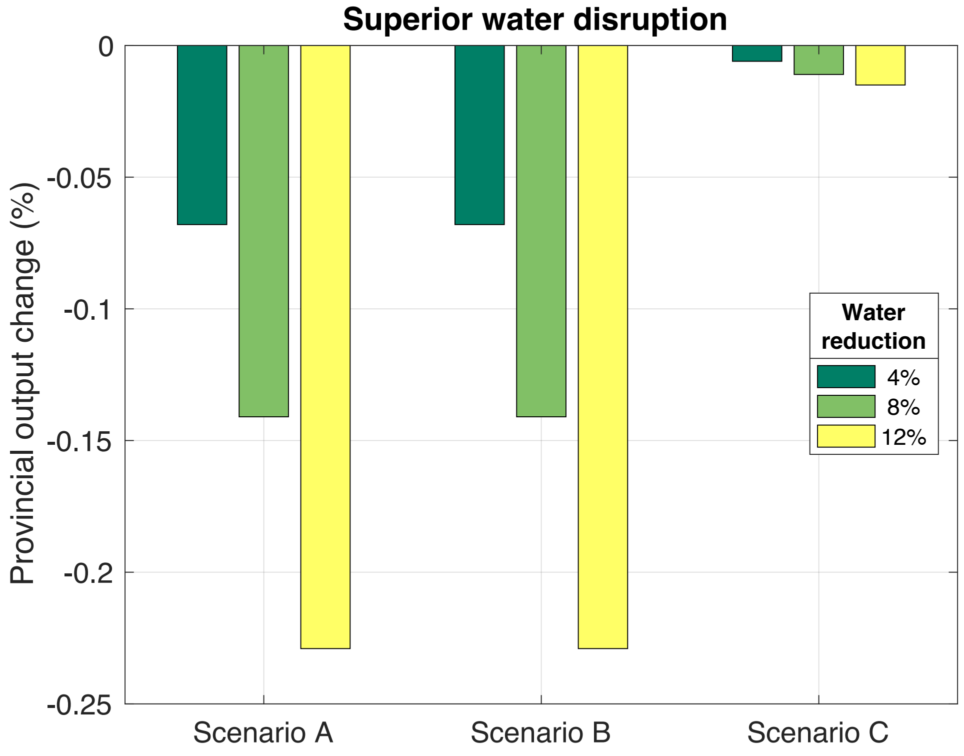


6. Results - MRIO

Disruptions in **Superior sub-basin**



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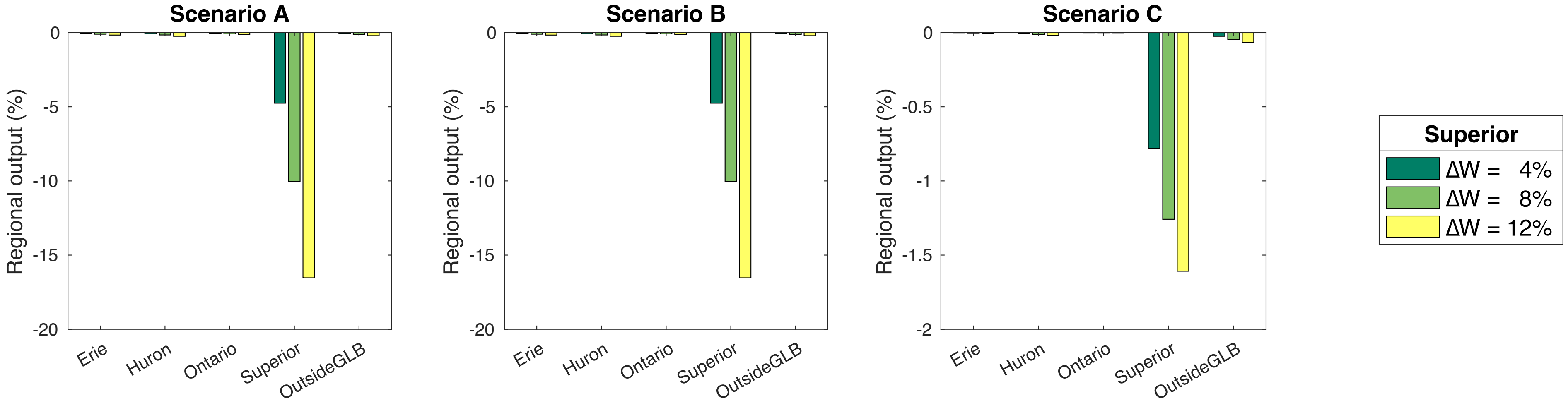
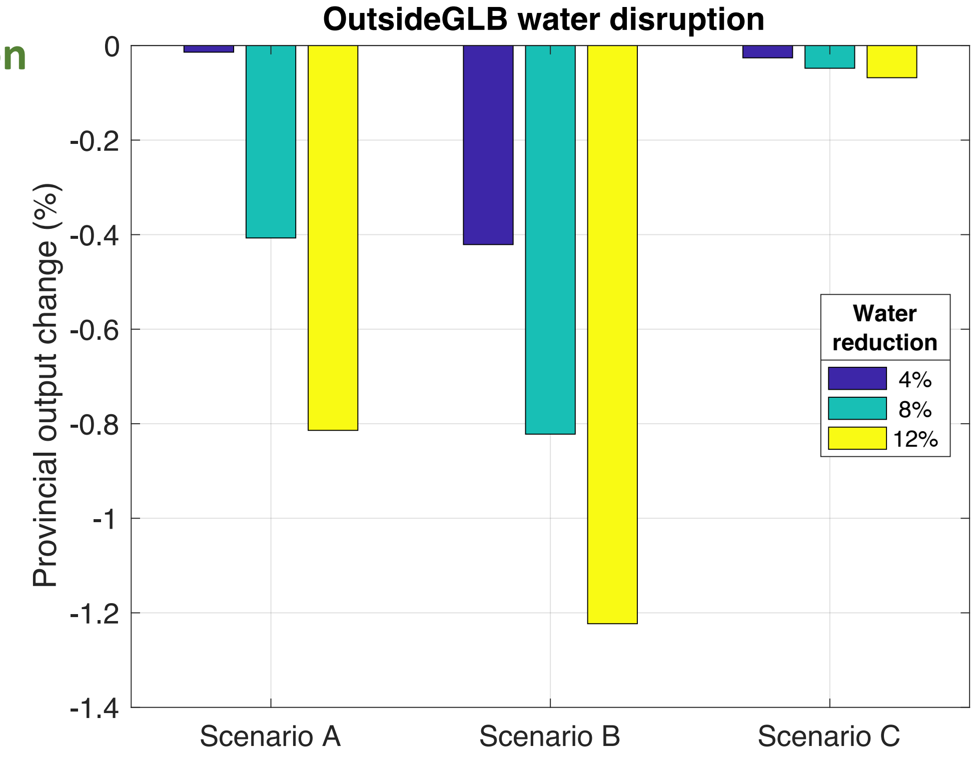


6. Results - MRIO

Disruptions in **OutsideGLB region**



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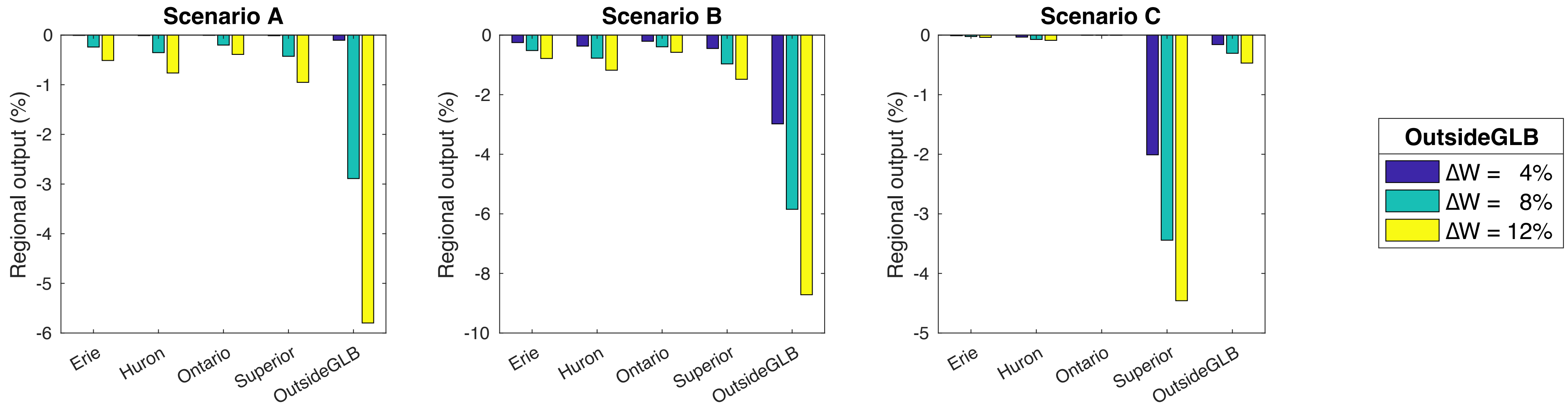


6. Results

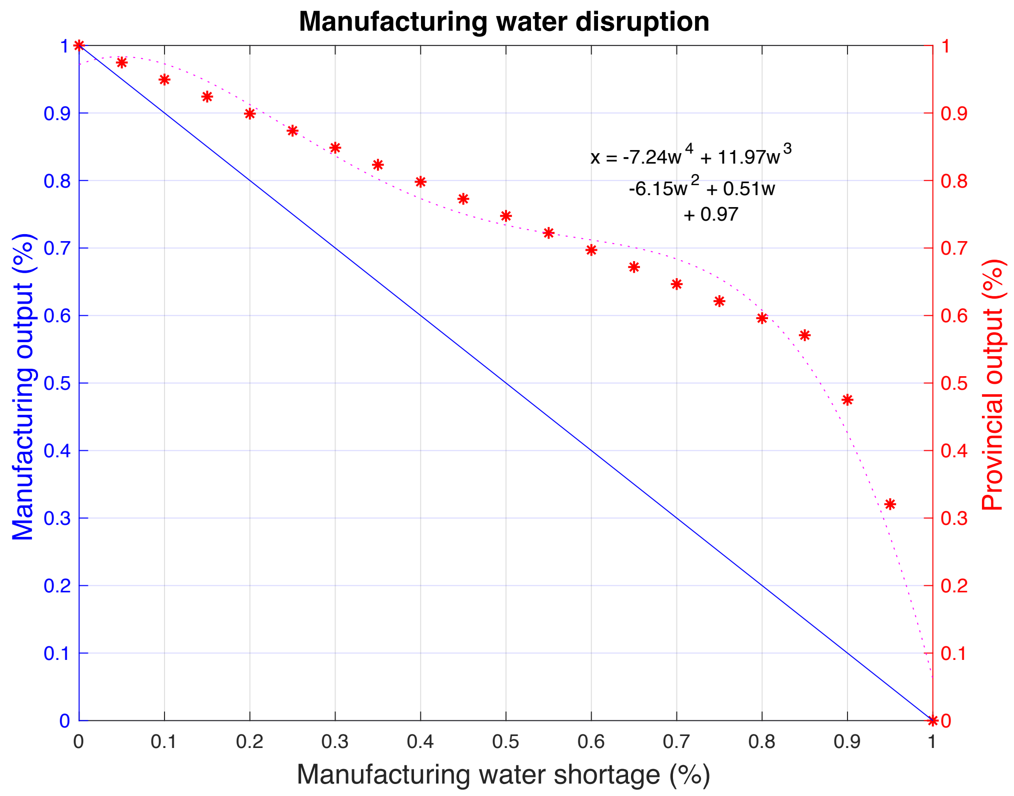
Industry-specific disruptions (Prov. model)

Four fundamental sectors were selected.

Water supply gradually reduced.

Economic impacts for water disruption ≤ 20%:

1. Manufacturing
2. Agriculture
3. Mining
4. Utilities



6. Results

Sector productivity: