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A multiregional input–output optimization model to assess impacts of water supply disruptions under climate change on the Great Lakes economy

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ABSTRACT

This paper presents a water-restricted multi-regional input–output model to evaluate the economic impacts of water supply reductions in the Canadian Great Lakes Basin (GLB), one of the largest freshwater reservoirs in the world. The proposed model, first of its kind applied to the GLB, aims to minimize the impact of water supply disruptions on the GLB-economy, measured by the loss of GDP. A new flexible economic optimization procedure is introduced, capable of imposing resource constraints and ensuring minimal supply levels for intermediate and final consumption at the same time. The model accounts for inter-regional trade between different lake regions. The impacts of two climate change scenarios on water security and the economy are investigated, with and without additional food and energy security restrictions. The proposed economic optimization model holds promise as a new tool for resource-restricted Input–Output analyses.

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Input–output model; nonlinear optimization; water scarcity; Great Lakes

1. Introduction

This study analyzes the direct and indirect impacts of possible future water use restrictions due to climate change on economic activities around the Great Lakes. The Great Lakes are located in North-America on the Canada-United States border and contain about 20% of the world's freshwater resources (Brinker et al., 2018; US EPA, 2020). The Great Lakes Basin (GLB) is composed of the lakes Superior, Michigan, Huron, Erie, and Ontario. However, Lake Michigan falls entirely within the US. The Canadian side of the Great Lakes is located in Canada's economic heart, Ontario, which is the most populated province where most of the country's GDP is generated (Statistics Canada, 2017a).

A wide variety of economic activities take place around the Great Lakes that depend on these lakes for their regular operations as a source and a sink. However, no study exists that attempts to systematically examine the economic values generated by these different lakes and the inter-regional trade flows between industries located around the Great Lakes.

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Such an analysis of economic connectivity and dependency across the lakes is of interest in view of the fact that water diversions across the lakes are prohibited based on the Great Lakes–St. Lawrence River Basin Sustainable Water Resources Agreement (Conference of Great Lakes and St. Lawrence Governors and Premiers, 2005). This implies that any future shocks to water availability in the GLB cannot be absorbed through water transfers, possibly impacting trade flows inside and outside the GLB.

Although the GLB is rich in freshwater resources, the water availability index (WAI) measuring the pressure imposed on water resources by human activities (OECD, 2015) indicates that it faces severe water stress during the summer when most of the water withdrawals take place and water supply is low (Environment and Climate Change Canada, 2019; Statistics Canada, 2017b). Climate change projections for the next decades estimate an increase in air temperature between 1.5–7 °C for the GLB, which will trigger more evaporation and lead to a decline in the water levels of the lakes (Brinker et al., 2018; Jensen et al., 2007; Kling et al., 2003; Lofgren et al., 2002; Mortsch et al., 2000). Therefore, more extreme weather events, such as droughts and heavy rainfall, are expected to increase in frequency, duration, and extent (Kling et al., 2003), affecting water availability. Surface water temperatures are furthermore expected to increase between 0.9–6.7 °C over the next decades, which will decrease vertical mixing in the water column. Combined with more severe precipitation and the subsequent runoff of nutrients, this will most likely produce more frequent harmful algae blooms (Brinker et al., 2018; Lofgren & Gronewold, 2012), also affecting water intake by surface water extracting industries and drinking water plants.

Additionally, the design and implementation of more sustainable water extraction policies is expected to further restrict current water use practices and increase policymaker demand for the estimation of the economic costs associated with these water intake restrictions. To this end, a multi-regional input–output model including water is developed for the GLB in this paper, in which each lake sub-basin is conceived as an economic region, accounting for inter-regional trade. This hydro-economic model allows for the estimation of the direct and indirect economic costs of water resource disruptions in different economic sectors across the sub-basins within the GLB.

2. Existing input–output modelling frameworks

Water is a primary input for industries and its scarcity or disruption may hinder regular operations and produce negative direct and indirect economic impacts. The quantification of economic impacts of sectoral, regional or national water disruptions requires the description and analysis of water use of industries, which is currently not included in the supply and use or input–output (IO) tables published by each nation. Recent economic-environmental accounting guidelines (UN, 2017) have started to explicitly include water as well as other environmental commodities into an environmentally-extended IO accounting framework (Kitzes, 2013). These tables can be used to quantify the cost of resource disruptions or the effect of sustainable resource extraction policies.

IO models have been used to study environmental pressures, emission intensities, or the quantification of ecological footprints of industries, commodities and final demand. Historically, studies of environmental repercussions of economic activities can be traced back to Leontief (1970), where undesirable by-products and remediation costs were included in the IO table, and Victor (1972) who proposed an IO table that included environmental commodities in a hybrid monetary-physical accounting framework.

In relation to water use, most of the IO studies have focused on calculating water pressure, water footprints, or virtual water trade flows. Studies related to water pressure or consumption typically aim at determining the direct and indirect water consumed by industries in order to satisfy final demand (Lenzen et al., 2013; Ridoutt et al., 2018; Velázquez, 2006). The estimation of water footprints is mainly concerned with determining the volumes of blue, green or grey water embodied in the commodities produced by each industry (Cazcarro et al., 2016b; Cazcarro et al., 2016a; Feng et al., 2011; Zhang et al., 2016). Studies concerning virtual water trade translate trade flows between nations to an equivalent water flow using the water embodied in the production of commodities. These studies are used to track the pressure that international trade imposes on regions with different water conditions, notably water scarce regions or areas prone to droughts (Antonelli et al., 2012; Liu et al., 2017; Mayer et al., 2016; White et al., 2015).

The use of IO models to study the economic effects of resource constraints, in particular water, has been limited. The reason is that IO models are generally incapable of directly dealing with resource constraints in view of the fact that the output is endogenously determined by the final demand, which is treated as exogenous. Mathematically, the gross output vector is the unique solution to a system of linear equations. Imposing a resource constraint on the system, water or otherwise, creates an additional hyperplane that may or may not contain the original solution point. If it does not contain the original solution, then the system becomes infeasible. If the equalities of the IO system were to be relaxed into inequalities, allowing for unmet final demand, then the restricted system has not a unique solution, but rather multiple solutions.

Different approaches have been proposed to deal with input or resource restrictions in IO models. The development of the supply-side model (Ghosh, 1958; Miller & Blair, 2009) aimed at describing primary input shocks. However in this model, it is not clear how to describe natural resource shocks since their use is generally not reflected in the value added accounts, which is needed to perform economic impact analysis. In addition, shocks to the supply-side model are based on the assumption that value added is exogenous. However, it can be argued that value added is dependent on gross output and thus endogenous. This feature leads to results where industries produce more (less) without increasing (decreasing) labor, capital, or changing technology (Oosterhaven, 1996, 2012).

Another well-known approach to deal with disrupted or degraded output is the inoperability IO model (Santos & Haimes, 2004) where the gross output is disrupted indirectly by means of degrading the final demand. This approach normalizes the gross output and final demand with respect to a 'planned' production and imposes a degraded proportion on final demand which is propagated to the output, obtaining the inoperability of each industry. This approach has been used, for example, to study the economic cost of imposing caps on greenhouse gas emissions (Lixon et al., 2008). However this model is incapable of dealing with direct output constraints and the output inoperability on each industry is limited by the share of its final consumption, which is problematic for industries with low final demand such as mining (Dietzenbacher & Miller, 2015; Oosterhaven, 2017).

A different approach is a mixed exogenous-endogenous IO model, proposed by Miller and Blair (2009). In this approach, a subset of industries is treated as exogenous and the remaining industries as endogenous. Exogenous industries are those who suffer direct disruptions due to environmental or policy constraints, and endogenous industries determine their output in terms of the disrupted industries. The use of hypothetical sector extraction or 'sector destruction' (Miller & Blair, 2009; Petkovich & Ching, 1978; Yoo & Yoo, 2009) has also been used to partition the economy into water sectors and non-water sectors and study the former as exogenous (Pérez Blanco & Thaler, 2014; Yoo & Yang, 1999). However, these approaches are able to impose resource restrictions only on a subset of industries which are treated as exogenous.

Optimization offers yet another solution. It allows to specify the economic system in terms of a set of equations that describe the sectoral interdependencies and a set of resource or input factor constraints that must be met while maximizing an economy's performance measure, such as GDP or gross output. For example, the 'rectangular choice of technology' model is a linear program that minimizes the cost of using different input factor technologies subject to consumption constraints and input factor availability (Duchin & Levine, 2011). In this model, sectors are allowed to choose from more than one production technology. This is achieved by representing sectors with as many variables as technological options they have available. Consequently, the matrix of technical coefficients becomes rectangular. Factor constraints are included to prevent that the factor endowment is exceeded. This model has been applied to study intake constraints by region and source of water (Duchin & López-Morales, 2012), repercussions of water shortages to power generation industries (Dilekli et al., 2018) or the generation, treatment, reuse and discharge of wastewater (López-Morales & Rodríguez-Tapia, 2019).

The model formulation in this paper is similar to the choice of technology model in that there is a set of restrictions ensuring intermediate and final consumption and resource input constraints that must be met. Although the present formulation does not implement technology choices, it allows sectors to leave final consumption unmet (e.g. international exports) as they cope with the imposed water restrictions. This is instrumented by specifying a minimal final consumption that must be met by each sector. Water disruptions are implemented by restricting water withdrawals in sectors that extract raw water directly from water bodies. At the same time, a water balance is included to equate the water volume extracted by drinking water plants or municipal water supply utilities to economic sectors and residential households. A multiregional IO model is developed to study spatially localized water disruptions in the GLB. Scenarios are created accounting for expected climate change, the impacts of which are analysed on the available water resources and economy at sub-basin and provincial level.

3. The water-restricted multiregional Input–Output model

3.1. Including water restrictions in the input–output model

A full description of the *Supply and Use tables* and the construction of demand-based IO models is given in Appendix A of the Supplementary Information. Table 1 shows the structure and meaning of the vectors in an IO table.

The present analysis focuses on water disruptions that may occur due to droughts, water quality changes that make water unusable for production purposes (e.g. irrigation, food processing), or the implementation of sustainable water management policies that place a limit on water withdrawals. Such disruptions are assumed to be exogenous and are specified

Table 1. Symmetrical Input–Output table with water use.

		Industry				Natural resources
		1 … I	Final consumption	Exports	Total output	Water discharge
Industry	1 … I	$\mathbf{Z}$	$\mathbf{f}$	$\mathbf{e}$	$\mathbf{x}$	$\mathbf{w}_{\mathrm{D}}$
	Imports	$\mathbf{m}^{\mathrm{T}}$	m_f	m_e		
	Value added	$\mathbf{v}^{\mathrm{T}}$				
	Total input	$\mathbf{x}^{\mathrm{T}}$				
Natural resources	Tap water use	$(\mathbf{w}^{\mathrm{tap}})^{\mathrm{T}}$				
	Raw water use	$(\mathbf{w}^{\mathrm{raw}})^{\mathrm{T}}$				

in terms of constraints to sectoral raw water withdrawals, which refer to the water extracted directly from water bodies. Not all sectors use raw water directly, but rather use water that has already been processed by a drinking water plant. This water is called tap water in this study. The water use of each sector is then the sum of raw water withdrawals and tap water use. In addition, there is an important distinction between water use and water consumption. The latter is the net water used by industries and is calculated as the difference between the water intake and discharge. This study is based on water use because this is the actual water input required by industries to operate and for which survey data are available (Statistics Canada, 2018a). Hence, any disruption or extraction cap would necessarily come specified in terms of water use.

Let $\mathbf{w}^{\mathrm{raw}} \in \mathbb{R}^I$ be the vector of raw water withdrawals by industries $i = 1, \ldots, I$ (in m^3) and $\boldsymbol{\omega}^{\mathrm{raw}} \in \mathbb{R}^I$ the vector of raw water coefficients (in $\mathrm{m}^3/\$$), which are assumed constant and obtained from $\boldsymbol{\omega}^{\mathrm{raw}} = \widehat{\mathbf{x}_0}^{-1}\mathbf{w}^{\mathrm{raw}}$, where $\mathbf{x}_0$ is the output in a specific reference or baseline year. The total raw water withdrawals by all industries is:

$$W^{\mathrm{raw}} = \sum_{i=1}^{I} w_i^{\mathrm{raw}} = (\mathbf{w}^{\mathrm{raw}})^{\mathrm{T}}\mathbf{1} = (\boldsymbol{\omega}^{\mathrm{raw}})^{\mathrm{T}}\mathbf{x}. \tag{1}$$

Drinking water plants (henceforth called the water sector 'WS') withdraw water directly from water bodies, process, and distribute it to households and industries. For this sector, the extracted water equates the distributed water as follows:

$$w_{\mathrm{WS}}^{\mathrm{raw}} = \sum_{i=1}^{I} w_i^{\mathrm{tap}} + w_{\mathrm{HH}}^{\mathrm{tap}} + w_{\mathrm{loss}}^{\mathrm{tap}} \tag{2}$$

Tap water use is also assumed to be proportional to the output of the sectors captured by the vector of coefficients $\boldsymbol{\omega}^{\mathrm{tap}} \in \mathbb{R}^I$ (in $\mathrm{m}^3/\$$) obtained from $\boldsymbol{\omega}^{\mathrm{tap}} = \widehat{\mathbf{x}_0}^{-1}\mathbf{w}^{\mathrm{tap}}$. Water losses due to leaking in the distribution system, $w_{\mathrm{loss}}^{\mathrm{tap}}$, are endogenized and treated as the tap water consumption of the water sector itself as follows: $w_{\mathrm{loss}}^{\mathrm{tap}} = \omega_{\mathrm{WS}}^{\mathrm{tap}} x_{\mathrm{WS}}$. In this manner, the losses are made dependent on the size of the operations of the water sector. Therefore, the balance equation for tap water is:

$$\omega_{\mathrm{WS}}^{\mathrm{raw}} x_{\mathrm{WS}} = \sum_{i} \omega_i^{\mathrm{tap}} x_i + w_{\mathrm{HH}}^{\mathrm{tap}}. \tag{3}$$

3.2. Modelling trade flows in the multiregional input–output model

Inter-regional input–output tables (IRIO) and multiregional input–output tables (MRIO) are extensions of IO tables that describe multiple interconnected regions as a single unit. They capture spillover effects of region-specific shocks and are not bounded by the assumption of having a single production structure. The construction of IRIO tables is generally based on survey methods, which may be expensive and require the generation of large amounts of data. If an IO table requires the collection of data to generate a matrix of size $m \times n$, an IRIO would require the generation of a matrix of size $R^2(m \times n)$ where R is the number of regions. The data collection hence has a quadratic growth with respect to regions. MRIO tables are a more operational option using non-survey methods or a mixture of survey and non-survey methods (Miller & Blair, 2009). The fundamental problem for MRIO models is the determination of inter-regional trade flows and the allocation of gross output to regions. Both these problems are addressed in the next section. A single IO table is decomposed into a consistent MRIO table containing intermediate and final demand estimates and regional gross output. The additional information required to disaggregate the single IO table is regional employment per industry, population, and distances between regions.

There are different methods available in the literature to estimate inter-regional trade flows. The cross-hauling adjusted regionalization method (CHARM) (Kronenberg, 2009; Többen & Kronenberg, 2015) aims at estimating gross exports and imports from and to a region under study. It requires an IO table where intermediate and final consumption includes domestic and foreign inputs, i.e. a type E table according to the classification of Kronenberg (2012), and knowledge of regional intermediate and final consumption and regional value added. Gross exports and imports refer to the additional amount of trade between two regions that is not captured by an account using only net exports. Another well-known approach is the use of location quotient (LQ) formulas (Bonfiglio & Chelli, 2008) to estimate trade flows from and to a region based on the relative size of the region and its sectors, which are assumed to determine its self-sufficiency and trade needs. LQ formulas are suited for IO tables where imports are recorded separately as a row vector and not included in the domestic consumption, i.e. type B tables (Kronenberg, 2012). Gravity models have also been used to estimate inter-regional trade flows (Sargento et al., 2012), using transportation data about origin, destination, distance travelled, volume, and value of shipments for each commodity group. Using a regression model, the inter-regional trade is estimated based on the size of the producer region, that of the consumer region, the distance between them, and other factors (Head & Mayer, 2014).

The approach taken in this study is to make use of a LQ formula to estimate the inter-industry inter-regional trade flows because the regional intermediate consumption matrices are not known and the IO table generated from the Canadian make and use tables is of type B, which makes it amenable for this method. The extended Flegg Location Quotient (FLQ) formula for multiple regions (Jahn, 2017) is used to produce intra- and inter-regional tables consistent with the provincial table. The FLQ is a well-known method to generate regional IO tables by estimating inter-industry commodity flows within the region under study (Flegg et al., 1995). Although it was originally designed to downscale national IO tables to single regions, the FLQ has also been applied to estimate MRIO tables (Canning & Wang, 2004; Jahn, 2017).

For the estimation of the final consumption trade flows, a functional form inspired by a simple naïve gravity model is used where the distance-decay exponent is taken from a gravity model regressed on actual shipment data across Canada (see Appendix B). These two steps (i.e. applying the extended FLQ and naïve gravity model) produce a set estimates which are input into an optimization model to obtain a consistent MRIO table. Due to space restrictions, this optimization procedure is presented in Appendix A of the Supplementary Information.

3.2.1. Inter-industry trade flows

In a first step, the initial regional gross output estimation is obtained using regional employment data per industry (ε_i^r):

$$x_i^r = \frac{\varepsilon_i^r}{\varepsilon_i} x_i, \quad \forall i, r \tag{4}$$

where ε_i^r is the employment of industry i in region r and ε_i is the provincial employment of industry i. The simple location quotient (SLQ) is computed per region using industry employment:

$$SLQ_i^r = \frac{\left(\frac{\varepsilon_i^r}{\varepsilon_{\text{tot}}^r}\right)}{\left(\frac{\varepsilon_i}{\varepsilon_{\text{tot}}}\right)}, \quad \forall i, r \tag{5}$$

where $\varepsilon_{\text{tot}}^r$ is the total employment of region r and ε_{tot} is the total provincial employment. The cross-industry location quotient (CILQ) is computed per region as follows:

$$CILQ_{ij}^r = \begin{cases} \frac{SLQ_i^r}{SLQ_j^r}, i \neq j \\ SLQ_i^r, i = j \end{cases} \quad \forall i, j, r. \tag{6}$$

The FLQ is computed next for each region:

$$FLQ_{ij}^r = \left[log_2 \left(1 + \frac{\varepsilon_{\text{tot}}^r}{\varepsilon_{\text{tot}}} \right) \right]^\delta CILQ_{ij}^r, \quad \forall i, j, r \tag{7}$$

where inter-regional trade is controlled by the parameter $\delta \in [0, 1]$ for which a larger (lower) value yields larger (lower) inter-regional trade and low (high) self-sufficiency.

After obtaining the FLQ per region, any entry higher than one is assigned to be one, so that:

$$FLQ_{ij}^r := \min\{FLQ_{ij}^r, 1\}, \quad \forall i, j, r. \tag{8}$$

Estimates of intra-regional trade (z_{ij}^{rr}) are obtained by multiplying the provincial trade flows by the corresponding FLQ value and the share of output in the region:

$$z_{ij}^{rr} = FLQ_{ij}^r \cdot z_{ij} \frac{x_j^r}{x_j}, \quad \forall i, j, r. \tag{9}$$

The intra-regional tables are subtracted from the matrix of intermediate transactions ($\mathbf{Z}$) to obtain the residual matrix ($\mathbf{R}$). A set of auxiliary matrices are created to estimate the inter-regional trade proportional to the size of the seller and the size of the buyer. Regional gross value added estimates are used as a measure of size. The auxiliary matrices are normalized to ensure each entry adds to unity. The residual matrix is calculated as:

$$R_{ij} = z_{ij} - \sum_{r=1}^{R} z_{ij}^{rr}, \quad \forall i, j. \tag{10}$$

Auxiliary matrices are created as:

$$H_{ij}^{rs} = v_i^r \cdot v_j^s, \quad \forall r \neq s. \tag{11}$$

The regional gross value added is computed as $\mathbf{v}^r = \widehat{\mathbf{v}^*}\mathbf{x}^r$, where $\widehat{\mathbf{v}^*}$ is a diagonal matrix containing the vector $\mathbf{v}^*$ of value added per dollar of gross output in the main diagonal, obtained from the provincial IO table. The total sum matrix used for normalization is computed as the sum of auxiliary matrices:

$$\mathbf{H} = \sum_{\forall r \neq s} \mathbf{H}^{rs}.$$

The normalization or rescaling of auxiliary matrices is made by an element-wise division:

$$H_{ij}^{rs} := \frac{H_{ij}^{rs}}{H_{ij}}, \quad \forall i, j, r \neq s. \tag{12}$$

Finally, inter-regional trade matrices are calculated by multiplying (element-wise) the normalized matrices representing the inter-regional trade by the residual matrix:

$$z_{ij}^{rs} = H_{ij}^{rs} \cdot R_{ij}, \quad \forall i, j, r \neq s. \tag{13}$$

This procedure produces consistent intra- and inter-regional estimates. To determine the value of the inter-regional trade parameter δ, Flegg and Tohmo (2013) proposed a formula which uses regional output shares and a survey-based propensity to import estimate. In the present study we adhere to the results found in Bonfiglio and Chelli (2008) where the performance of different LQ formulas are compared and a value $\delta = 0.3$ produced the best results for the FLQ method. However, a sensitivity analysis is performed on this parameter, the results of which are presented in section 5.

3.2.2. Regional allocation of final demand

In a second step, final use vectors (household consumption, domestic and international exports) and supply-side vectors (imports and gross value added) are assigned to regions. For household consumption (f_i^s), the allocation is based on the population share of the region: $f_i^s = \rho^s f_i$, where ρ^s is the fraction of the population living in region s and f_i is the provincial household consumption of industry i. For the remaining vectors, the allocation is based on the initial regional gross output estimation ($\mathbf{x}^r$) of equation (4): $e_i^r = e_i^* x_i^r$; $m_i^r = m_i^* x_i^r$; $v_i^r = v_i^* x_i^r$, where e_i^*, m_i^*, v_i^* are the coefficients of exports, imports, and gross value added per unit of gross output for industry i, respectively.

Trade flows to meet final demand between regions are based on household demand and are assumed proportional to the gross output of the sending region, household demand of the consuming region, and exponentially decaying with respect to average distance between both regions:

$$f_i^{rs} = k_s \frac{x_i^r f_i^s}{(d_{rs})^{k_\mathrm{d}}}, \quad \forall i, r, s \tag{14}$$

where f_i^{rs} is the household consumption in region s of commodities from industry i located in region r; k_s is a normalizing constant such that the total inter-regional consumption of a region from all sources is equal to its own consumption: $\sum_{r=1}^{R} f_i^{rs} = f_i^s, \forall i, s$; d_{rs} is the average distance between regions r and s in km; and k_d is the parameter that controls the trade decay as distance increases between regions. Its value is obtained from a naïve gravity model estimated using freight data across census metropolitan areas from 2011 to 2016 (Statistics Canada, 2019a). The results of this model are presented in Appendix B of the Supplementary Information. Distances d_{rs} are calculated here using the average distance from each region to each census sub-division (the province of Ontario consists of 575 sub-divisions) and from each census sub-division to each region, weighted by population.

3.3. Economic optimization of the water-restricted multiregional input–output model

The optimization model proposed here to study the disruption of water cutbacks on the economy is formulated in terms of a closed IO model, where changes to production trigger changes in labor and capital payments, which are then reflected in corresponding changes in final demand. Although the model is based on the demand side, it allows for input supply restrictions. It also allows for controlling the capacity of imported commodities to satisfy inter-industry demand. The objective function is expressed as the weighted Euclidean distance between the solution ($\mathbf{x}$) and the baseline output ($\mathbf{x}_0$). This specification is chosen because it implies that industries resist contractions with a growing force as they move further away from their original observed value. For numerical convenience, the objective function is formulated as the square of the distance.

The water-restricted model is:

$$\min_{\mathbf{x}} z = \Delta\mathbf{x}^\mathrm{T} \mathbf{\Lambda} \Delta\mathbf{x} \tag{15a}$$

s.t.

$$\mathbf{x} \leq \mathbf{A}\mathbf{x} + \mathbf{F}\mathbf{x} + \mathbf{f}_\mathrm{R} + \mathbf{e}_\mathrm{Nat} + \mathbf{e}_\mathrm{Int} \tag{15b}$$

$$\mathbf{x} \geq \hat{\boldsymbol{\alpha}}\mathbf{A}\mathbf{x} + \mathbf{f}_\mathrm{min} \tag{15c}$$

$$(\boldsymbol{\omega}^\mathrm{raw})^\mathrm{T}\mathbf{x} \leq W^\mathrm{raw} - \Delta W^\mathrm{raw} \tag{15d}$$

$$(\mathbf{E}\boldsymbol{\omega}^\mathrm{raw} - \boldsymbol{\omega}^\mathrm{tap})^\mathrm{T}\mathbf{x} \geq w_\mathrm{HH}^\mathrm{tap} \tag{15e}$$

where $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}_0$ and the matrix $\mathbf{\Lambda}$ is assumed to be symmetrical ($\mathbf{\Lambda} = \mathbf{\Lambda}^\mathrm{T}$) and positive definite, which allows for describing different types of disruptions. For example, if $\mathbf{\Lambda} = \mathbf{I}$, the model finds the minimal gross output disruption. Likewise, $\mathbf{\Lambda} = (\mathbf{I} - \mathbf{A})^\mathrm{T}(\mathbf{I} - \mathbf{A})$ finds the least disruption to final demand. In the present study, the objective function minimizes the GDP disruption, i.e. finds the water use allocation such that the baseline GDP is least changed:

$$Minz = \Delta\mathbf{v}^{\mathrm{T}}\Delta\mathbf{v} \tag{16}$$

by setting $\mathbf{\Lambda} = \widehat{\mathbf{v}^*} \cdot \widehat{\mathbf{v}^*}$. Here, the production approach to measure GDP is used as the sum of gross value added of all industries.

Equation (15.b) ensures that the industrial output does not exceed intermediate and final use purchases. We follow Bočkarjova et al. (2004) in establishing a relationship between payments to primary input factors ($\mathbf{v}$) and household consumption ($\mathbf{f}$), where a portion of these payments is spent on local commodities and is, therefore, responsible for a fraction of the final consumption. Household consumption is partitioned into:

$$\mathbf{f} = \mathbf{f}_{\mathrm{V}} + \mathbf{f}_{\mathrm{R}} \tag{17}$$

where $\mathbf{f}_{\mathrm{V}}$ is the endogenous consumption as a result of the payments to the primary input factors, most notably labor, and $\mathbf{f}_{\mathrm{R}}$ is the remaining household consumption. Let F be the sum of household consumption: $F = \mathbf{1}^{\mathrm{T}}\mathbf{f}$, V the sum of value added payments: $V = \mathbf{1}^{\mathrm{T}}\mathbf{v} = (\mathbf{v}^*)^{\mathrm{T}}\mathbf{x}$, where $\mathbf{v}^* \in \mathbb{R}^I$ is the vector of value added coefficients defined earlier, and k_{V} a factor that rescales consumption due to labor payments in terms of domestic demand: $k_{\mathrm{V}} = \min\{F, V\}/(F \cdot V)$. The endogenous consumption ($\mathbf{f}_{\mathrm{V}}$) and the remaining household consumption ($\mathbf{f}_{\mathrm{R}}$) can then be written as:

$$\mathbf{f}_{\mathrm{V}} = [k_{\mathrm{V}}\mathbf{f}(\mathbf{v}^{*\mathrm{T}})]\mathbf{x} = \mathbf{F}\mathbf{x} \tag{18}$$

$$\mathbf{f}_{\mathrm{R}} = (1 - V \cdot k_{\mathrm{V}})\mathbf{f}. \tag{19}$$

Appendix A of Supplementary Information shows how Equations (18–19) yield (17).

The inequality (15.c) ensures that output meets inter-industry purchases and guarantees a minimal supply for final consumption, for example to ensure food or energy security. The diagonal matrix $\hat{\boldsymbol{\alpha}}$ models the restrictiveness to substitute locally-produced inter-industry inputs by imported inputs. For instance, $\alpha_i = 1$ implies that inter-industry purchases of industry i commodities cannot be substituted by imported commodities during the period of analysis, whereas $\alpha_i = 0$ implies that commodities from industry i can be fully substituted by imported commodities. Appendix A of the Supplementary Information shows the derivation of this constraint. The minimal supply to final users is defined as $\mathbf{f}_{\min} = \hat{\mathbf{c}}(\mathbf{F}\mathbf{x} + \mathbf{f}_{\mathrm{R}} + \mathbf{e}_{\mathrm{Nat}})$, where $c_i \in [0, 1], \forall i$ sets the fraction of domestic final consumption that at least must be satisfied for sector i.

Inequality (15.d) ensures that raw water withdrawals do not exceed the available water, and (15.e) ensures that the intake of water by the water sector is at least sufficient to satisfy the tap water demand of industries and households. Matrix $\mathbf{E}$ is used to indicate the water sector parameter, and entries are defined as:

$$E_{ij} = \begin{cases} 1, & \text{if } i = j \text{ and } j \text{ is the water sector} \\ 0, & \text{otherwise.} \end{cases}$$

Applying this structure to multiple regions, the MRIO optimization model is:

$$\min_{\mathbf{x}^{\mathrm{MRIO}}} z^{\mathrm{MRIO}} = (\Delta\mathbf{x}^{\mathrm{MRIO}})^{\mathrm{T}}\mathbf{\Lambda}^{\mathrm{MRIO}}\Delta\mathbf{x}^{\mathrm{MRIO}} \tag{20a}$$

s.t.

$$\mathbf{x}^{\mathrm{MRIO}} \leq \mathbf{A}^{\mathrm{MRIO}}\mathbf{x}^{\mathrm{MRIO}} + \mathbf{F}^{\mathrm{MRIO}}\mathbf{x}^{\mathrm{MRIO}} + \mathbf{f}_{\mathrm{R}}^{\mathrm{MRIO}} + \mathbf{e}_{\mathrm{Nat}}^{\mathrm{MRIO}} + \mathbf{e}_{\mathrm{Int}}^{\mathrm{MRIO}} \tag{20b}$$

$$\mathbf{x}^{\mathrm{MRIO}} \geq \widehat{\boldsymbol{\alpha}^{\mathrm{MRIO}}}\mathbf{A}^{\mathrm{MRIO}}\mathbf{x}^{\mathrm{MRIO}} + \mathbf{f}_{\mathrm{min}}^{\mathrm{MRIO}} \tag{20c}$$

$$(\boldsymbol{\omega}_{\mathrm{GLB}}^{\mathrm{raw}})^{\mathrm{T}}\mathbf{x}^{\mathrm{GLB}} \leq W_{\mathrm{GLB}}^{\mathrm{raw}} - \Delta W_{\mathrm{GLB}}^{\mathrm{raw}} \tag{20d}$$

$$(\mathbf{E}\boldsymbol{\omega}_{\mathrm{GLB}}^{\mathrm{raw}} - \boldsymbol{\omega}_{\mathrm{GLB}}^{\mathrm{tap}})^{\mathrm{T}}\mathbf{x}^{\mathrm{GLB}} \geq w_{\mathrm{HH,GLB}}^{\mathrm{tap}}. \tag{20e}$$

4. Baseline and future water use restriction scenarios

The baseline scenario corresponds to the economic activities in the province of Ontario for the year 2015. The provincial IO table for that year is used to construct the multiregional IO optimization model, estimate the inter-regional trade flows, and calculate all the vector and matrix coefficients, including the water coefficients, which are furthermore region or lake specific. Water disruption scenarios are then created as a deviation from this baseline scenario to answer the question: 'What would be the direct and indirect economic impacts if water intake restrictions would be imposed on the economic activities in the GLB?'.

Although there exist projections of the likely climate change scenarios for the GLB (Lofgren et al., 2002; Mortsch et al., 2000), there is a high degree of uncertainty about how those projections can be downscaled and translated into more specific potential water disruptions at local level. The water availability index (WAI) is used here to guide the disruption scenarios. The WAI is defined as the ratio of water withdrawals to renewable water availability (OECD, 2015; Pfister et al., 2009), where water yield is typically used as an estimate for the renewable water availability (Statistics Canada, 2017b). The GLB is a region with severe water stress during the month of August, which is the last month of summer where most of the water withdrawals take place and water supply is low (Environment and Climate Change Canada, 2019; Statistics Canada, 2017b) as shown in Appendix B of the Supplementary Information. The WAI in the GLB is larger than 0.4 in that month, which indicates severe water stress.

Two future water use restriction scenarios were created, inspired by expected climate change and a sustainable water policy intervention. Scenario A assumes climate change would increase the current severe water pressure in the GLB from one month (August) to a whole season (summer). This scenario is used to estimate the economic costs of bringing the WAI from severe (0.4) to normal pressure (0.2) during the four summer months, which is equivalent to an industrial water use reduction in the GLB ranging from 4% to 12%.[1] Scenario B is the same as scenario A, but here food and energy security are ensured by imposing the restriction that the food and energy industries must satisfy existing household consumption levels for the province as a whole as well as for exports to other Canadian provinces. Note that in order to obtain a more comprehensive and detailed picture of the provincial and regional responses, raw water reductions were implemented following 0.5% raw water decreases from zero up to 12% for both scenarios.

[1] A reduction of monthly industrial water intake by half to reduce the WAI from 0.4 to 0.2 gives a change in W^{raw} as follows: $\Delta W^{\mathrm{raw}} = (1/2)(1/12)W^{\mathrm{raw}} \approx 0.04W^{\mathrm{raw}}$.

5. Results

5.1. Data used for the creation of the multiregional input–output model

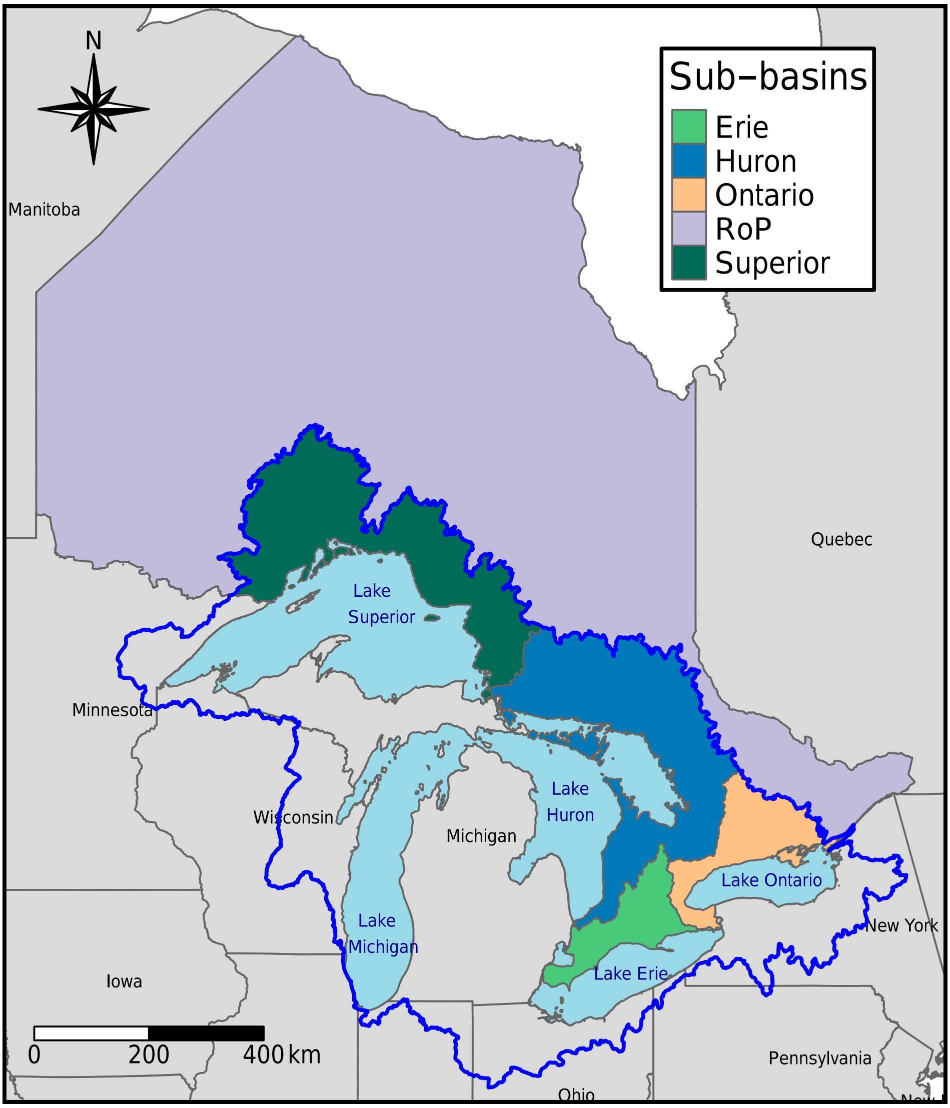
Supply and *Use* tables at the province level for 2015 were used (Statistics Canada, 2017a). The 'link' aggregation level was chosen, consisting of 191 industries and 450 commodities, to extract the water sector (called 'water, sewage and other systems') from the utilities sector, while the other industries were aggregated at the 'summary' level, yielding a total of 33 industries. Employment data were taken from the 2016 census (Statistics Canada, 2017c), which uses the North American Industry Classification System (NAICS), whereas the *Supply* and *Use* tables use the Input–Output Industry Codes (IOIC). A concordance table was therefore used to express employment data using IOIC instead of NAICS (Statistics Canada, 2018b). To justify the initial regional gross output allocation of Equation (4), proportionality between gross output and employment was tested using linear regression analysis on provincial data and estimating a model for each industry. It was found that employment is a good linear predictor of gross output in all industries. The minimal coefficient of determination (R^2) is 0.94.

Raw water withdrawals by sub-basin for agriculture (irrigation and livestock), power generation, manufacturing, and mining were taken from the Great Lakes regional water use database (Great Lakes Commission, 2019). Tap water use (municipal supply) for these sectors was taken from the agricultural water survey (Statistics Canada, 2017d) and the industrial water survey (Statistics Canada, 2018a). Raw water withdrawals for the water sector were equated to the total tap water use in each sub-basin, which includes industries, households and system losses. Residential household consumption was allocated to sub-basins proportional to the population served and system losses proportional to the volume supplied (Statistics Canada, 2019b).

For the remaining 28 industries, referred to as commercial and institutional sectors, it was assumed that they satisfy their water needs using tap water. Since there are no provincial data available for water use for these 28 sectors, only national data (Statistics Canada, 2017e), the provincial tap water use was estimated using two approaches. First, assuming the same productivity of gross output produced per cubic meter of water consumed ($/m^3) at the provincial level as for the national data. Secondly, assuming the same productivity of jobs per cubic meter consumed (job/m^3) at the provincial level as for the national level. Both approaches yield similar water intake estimates that differ overall less than 2%. The average of both estimates was used to determine the tap water use for each of these 28 remaining sectors, and the same productivity of tap water use for these sectors was assumed across sub-basins. Provincial water use per industry is shown in Figure 2 and Figure 3 shows the direct water use intensities by sub-basin.

Overall, water use for Ontario is about 23 km^3 per year from surface and groundwater sources, of which household consumption and system losses constitute about 1 km^3. Hence, most water use is for industrial purposes. The Gini index was computed to measure the concentration of water use among industries and regions, giving a value of 0.97, which reflects high water usage in only a few industries (See Appendix B of the Supplementary Information). The most intensive water user (power generation) accounts for 86% of the total water withdrawn in the province, followed by the water sector (7%) and manufacturing (6%). Agriculture (crop and animal production) is the fourth largest water user

Figure 1. Map of the Great Lakes Basin, the blue line shows its hydrological boundary, the colored areas the Canadian sub-basins and the rest of the province (RoP).



in the province (130 million m^3/year), but accounts only for 0.6% of the total provincial withdrawals.

5.2. Baseline scenario

The water-restricted MRIO model was used to assess the economic impacts of water intake reductions in the GLB in view of the fact that this study is most interested in modelling the economic impacts of localized disruptions rather than provincial-wide reductions. The spatial disaggregation follows the hydrological boundaries of the Great Lakes, resulting in five regions: 'Superior', 'Huron', 'Erie', 'Ontario', and 'RoP' (Rest of the province). The

Figure 2. Provincial water use, 2015.

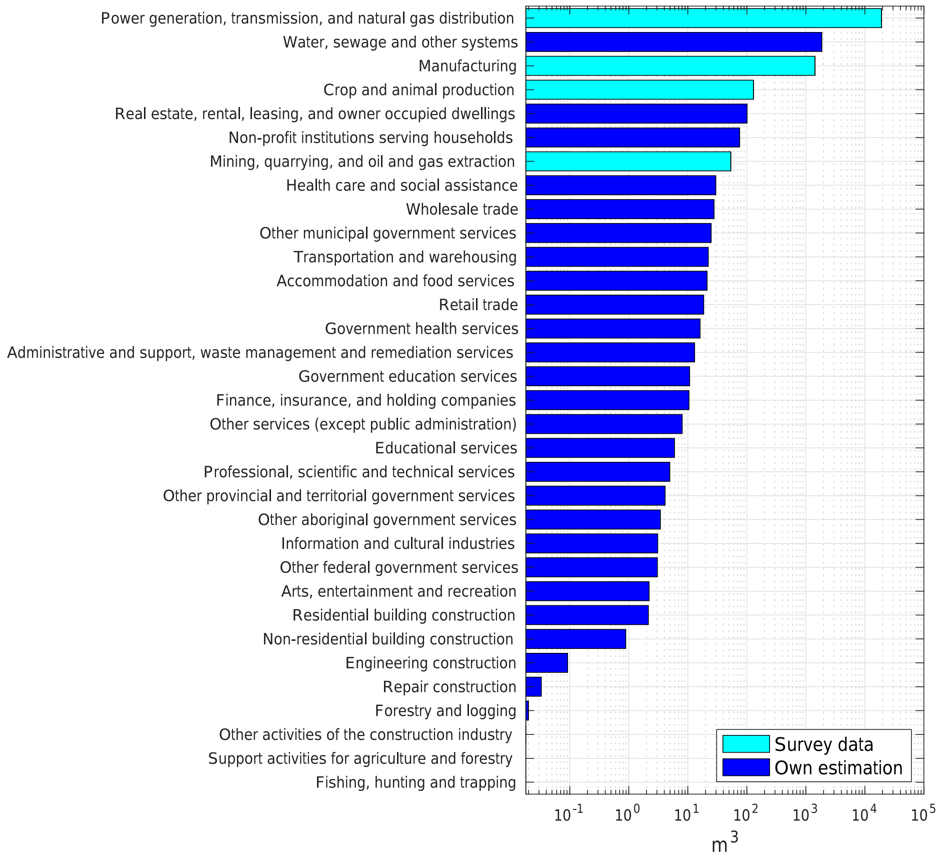
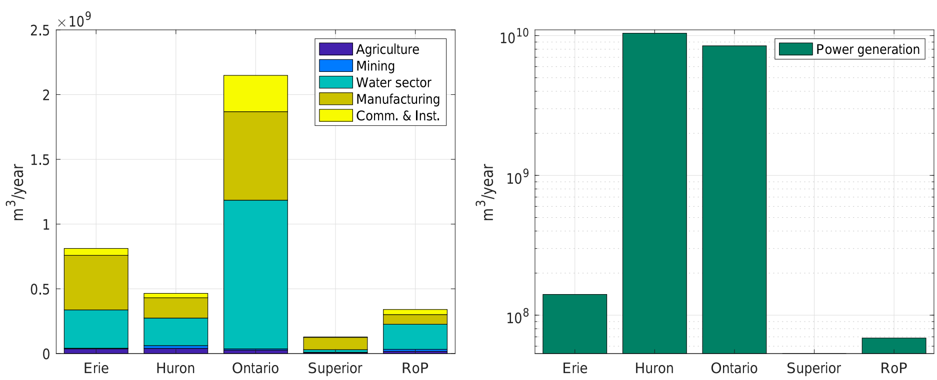
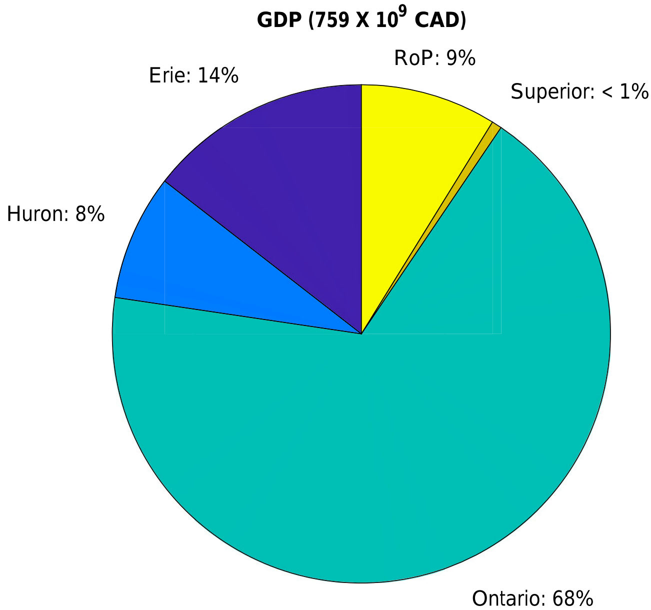


Figure 3. Direct water use intensities by sub-basin and the rest of the province (RoP), 2015.



Note: Compared to the other main water users, power generation water use is an order of magnitude higher and therefore presented separately. Comm. & Inst. refers to the remaining 28 commercial and institutional sectors in the economy.

Figure 4. GDP shares by sub-basin and the rest of the province (RoP), 2015.

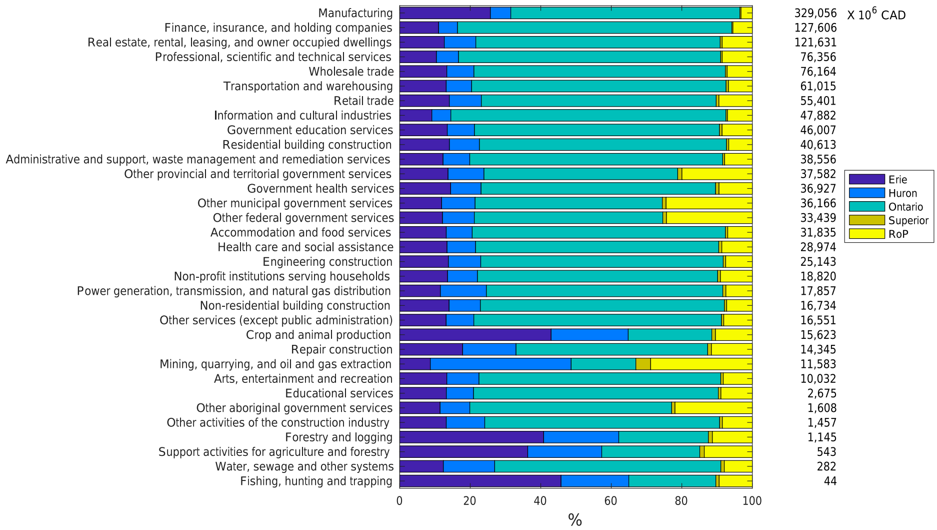


allocation of employment and population to sub-basins was based on the area of the official census subdivisions (CSD) that falls inside the hydrological boundaries of each sub-basin, following similar procedures elsewhere (Brouwer et al., 2008; Brouwer et al., 2005).

Based on this spatial disaggregation procedure of economic activities to sub-basins, the Lake Ontario sub-basin is, not surprisingly since it includes the densely populated Greater Toronto Area, found to be the region with the highest GDP contribution (68%). It has the largest output share in the manufacturing sector, utilities (power generation and water sector), construction, and most of the commercial and institutional industries (Figure 4 and 5), thus making this region the overall economic motor of the province. It is followed by the Lake Erie sub-basin (14% of provincial GDP), which is dominant in agriculture-related industries, making this region the food supplier of the province. The RoP region produces 9% of the provincial GDP and consists mainly of government-related service industries, and makes a substantial contribution to the mining sector. The Lake Huron sub-basin produces 8% of the provincial GDP and contributes largely to mining, quarrying and oil and gas extraction. Finally, Lake Superior produces less than 1% of the provincial GDP, with its largest industries being manufacturing, finance and mining.

The calculation of the inter-regional trade flows showed that most regions are net exporters, making the GLB a net exporter of commodities to other provinces and outside of Canada (see Table 2). Lake Ontario is by far the largest exporter (60%) but it is also the largest importer (62%). The major exporters and importers to domestic and international markets correspond to the regions with the highest output. Trade flows show that most trade is intra-regional (shaded values in Table 2), as opposed to inter-regional trade, yielding shares of 58% and 42% respectively.

Figure 5. Sectoral output shares by region, on the right-hand side the total provincial gross output is shown, 2015.



The MRIO table was also computed under different interregional trade configurations by changing the parameters δ in Equation (7) and k_d in equation (14) that control the amount of inter-regional trade flows. These results are presented later in section 5.4. The minimum and maximum of these results, along with the baseline values, are presented in Table 2. In all cases, the total summation of the trade flows consistently adds up to the provincial gross output plus imports to the province.

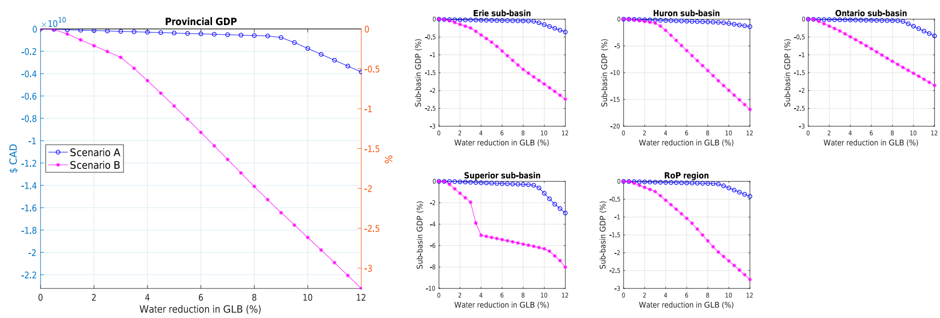
5.3. Water disruption scenarios

The results for the first water disruption scenario A show piecewise linear contractions for provincial GDP, with a drastic change in the slope of the total economic cost curve when the water supply reduction reaches 9% (see Figure 6). These results also show up for the GDP contractions at sub-basin level. Lake Erie, Ontario and the RoP experience similar relative contractions, whereas these relative contractions are a factor two and seven larger for the sub-basins of Lake Huron and Superior, respectively. The change of slope in the loss of GDP is caused by the decrease in the supply of intermediate inputs in the economy due to the reduction in water availability, which forces other sectors to shrink. Nonetheless, the economic costs of a 12% water supply reduction in the GLB results in a 0.5% contraction in provincial GDP only, which shows that the search for an optimal allocation of water cutbacks pays off and can reduce the economic impacts substantially. The sub-basin Lake Superior shows the largest relative decrease in GDP under this scenario. This is due to the fact that in the optimization water cutbacks are allocated to regions and sectors that generate relatively speaking the lowest net economic benefits, such as power generation in Lake Huron. Note that these results do not imply or reflect the transfer of water between regions, but the relative cutback in production, consumption and trade flows between regions as a result of the imposed water use restrictions across the GLB in our model.

Table 2. Estimation of trade flows between sub-basins ($\times 10^6$ CAD).

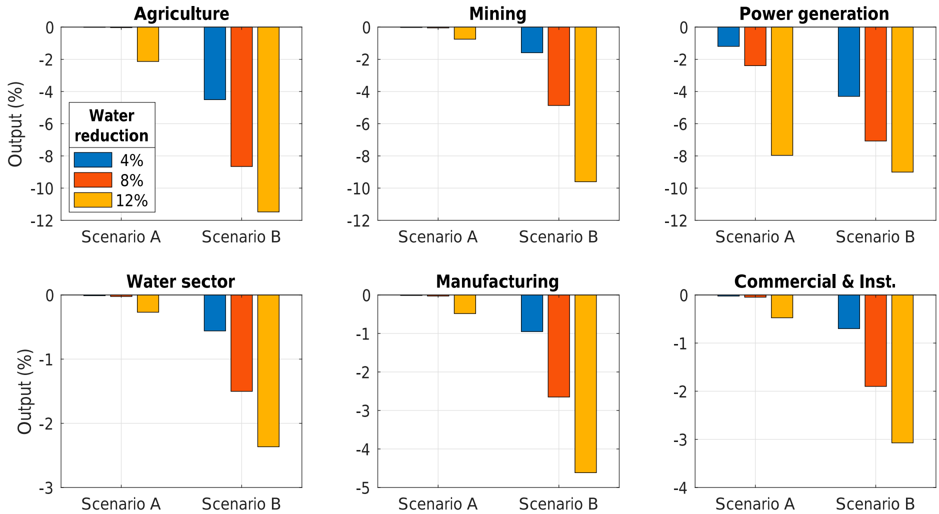
Lake sub-basins / regions			Destination: Erie	Huron	Ontario	Sup.	RoP	Exp. RoC	Exp. Row	Total
Origin	Erie	Value	**85,119**	5,241	75,408	463	5,396	12,037	38,094	221,757
		Min	27,345	2,099	9,281	222	2,317	9,002	35,964	209,536
		Max	156,297	10,893	122,613	958	10,247	14,190	41,081	224,564
	Huron	Value	9,849	**30,795**	52,624	311	4,560	5,081	5,246	108,467
		Min	4,940	8,573	8,030	153	1,898	4,057	4,364	105,888
		Max	17,852	64,875	76,950	1,911	14,781	17,540	14,890	119,387
	Ontario	Value	52,246	15,225	**640,054**	1,366	17,452	80,940	122,731	930,013
		Min	9,882	6,236	500,230	674	7,315	72,302	113,980	901,661
		Max	101,296	40,824	707,381	2,776	50,220	87,242	129,279	943,620
	Sup.	Value	735	439	2,002	**1,525**	569	1,338	1,851	8,458
		Min	267	150	669	97	162	683	624	8,373
		Max	1,288	832	4,301	8,429	974	1,928	2,292	11,300
	RoP	Value	9,082	4,131	45,148	511	**39,393**	5,778	6,916	110,958
		Min	2,088	1,241	5,703	132	9,052	1,879	2,761	107,878
		Max	14,858	9,728	96,050	1,330	95,623	7,377	8,940	130,671
	Imp. RoC	Value	4,448	549	50,191	23	546	–	–	55,756
		Min	2,642	363	47,106	21	195	–	–	55,756
		Max	5,810	652	52,494	42	2,183	–	–	55,756
	Imp. RoW	Value	19,001	898	115,114	2	1,033	–	–	136,047
		Min	17,190	640	110,495	0	375	–	–	136,047
		Max	20,370	1,203	117,800	10	4,048	–	–	136,047
Total		Value	180,479	57,277	980,540	4,201	68,948	105,173	174,837	**1,571,455**
		Min	170,162	56,092	897,498	3,875	68,948	105,173	174,837	
		Max	195,535	76,684	983,597	11,380	120,154	105,173	174,837	

Figure 6. Provincial and regional GDP contractions for scenario A and B.



The results for scenario B, where food and energy security are guaranteed for domestic (Canadian) final consumers, also show an approximately piecewise linear response in GDP to water reductions. However, under this future scenario, the magnitude of the economic costs in terms of loss of GDP is considerably larger than under the first scenario A. The contraction in provincial GDP under scenario B has a change in its slope when around 3% of the baseline water supply is reduced in the GLB, and reaches a maximum cost of 3.3% loss of GDP when 12% of the available water is reduced, which is about seven times the cost under scenario A for the same level of water reduction. This result reflects the additional cost of the introduced rigidness in re-allocating production and consumption across sectors in the different sub-basins. Maintaining the same (baseline) level of self-sufficiency in

Figure 7. Provincial sectoral output contractions under scenario A and B.



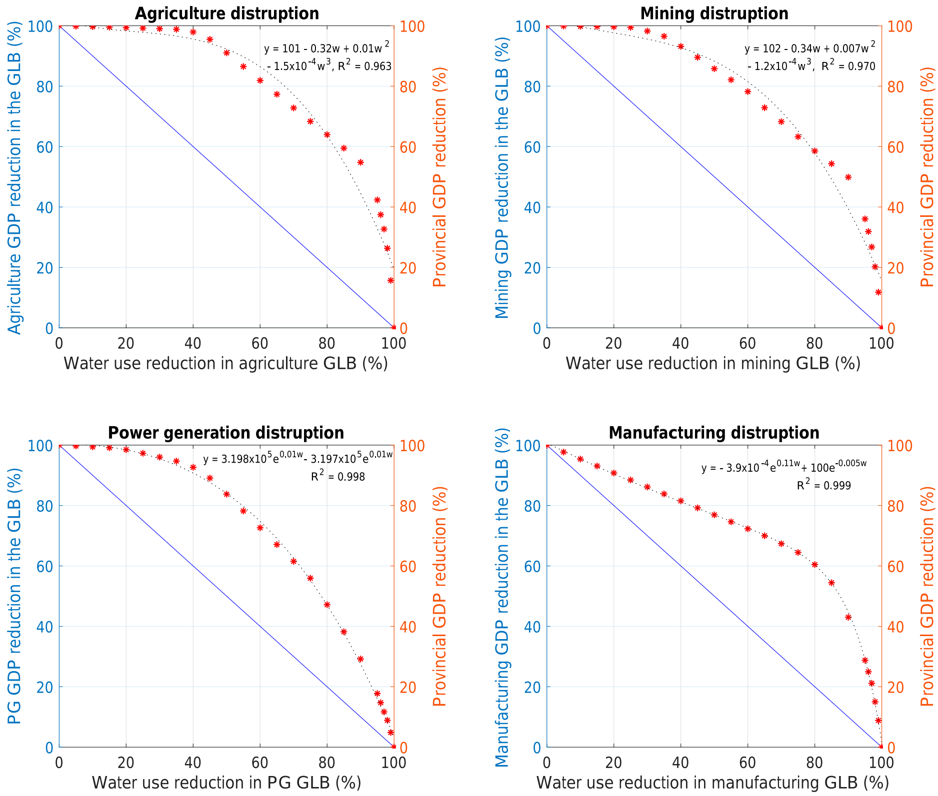
food and energy makes the economy more sensitive to water cutbacks as domestic sectors are forced to satisfy domestic final consumption first. As a result, the substitution of local for imported commodities is limited.

As under scenario A, the sub-basins of Lake Erie and Ontario and the RoP experience a similar relative contraction in GDP, following an approximately linear decline. The sub-basin Lake Huron experiences a much steeper contraction in GDP because the largest water user, power generation, is mainly located in this sub-basin with a relatively low economic value for water use. The GDP contractions in Lake Superior display a somewhat more unpredictable behavior and change their relative size (as reflected in the slope of the cost curve) depending on the size of the water reduction. These contractions can be characterized as piecewise linear from a zero to 10% water reduction and quadratic when the reduction in water availability is reduced further.

Examining the impacts of the two scenarios on specific sectors, power generation (up to 8%) and agriculture (up to 2%) are the most affected sectors under scenario A in terms of output contraction (Figure 7). Under scenario B, the largest sectoral output contractions are found in agriculture (almost 12%), mining and gas extraction (almost 10%), power generation (up to 9%), manufacturing (up to 5%), the other commercial and institutional sectors (up to 3%), and finally the water sector (up to 2.5%).

Additional tests were performed to assess the response of provincial GDP to sector-specific water reductions in the GLB. For these tests, four major water use sectors were selected: agriculture, mining, power generation and manufacturing. Raw water reductions were applied uniformly to these sectors across the four sub-basins from zero to 100% of its current (baseline) raw water use. Substitution of local intermediate inputs by imports was not allowed and no minimal final consumption was imposed, in view of the fact that the main purpose of this exercise is to study how the economy endogenously absorbs the imposed water cutbacks. The results are presented in Figure 8.

Figure 8. Industry-wise water disruptions for sectors located in the Canadian Great Lakes Basin.

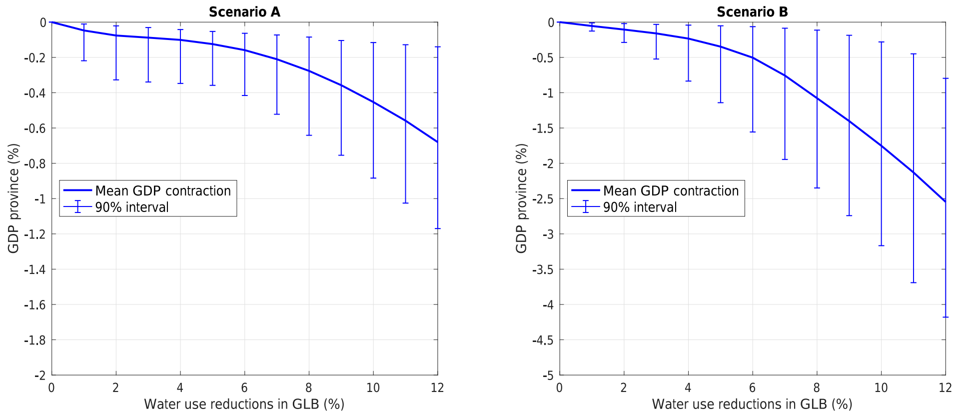


Overall, the results show increasing marginal costs as water reductions are increased. Sharp slope changes in provincial GDP occur at 40% and 90% reductions of total agricultural water use, and 30% and 90% reductions in mining water use. Water use reductions in power generation produce exponential marginal cost. Manufacturing faces the largest provincial GDP contractions for water reductions up to 60% and has a change in the slope of its cost curve when 80% of its water use is reduced. In these four sectors, the economy collapses when raw water use is completely cut down. This feature is partly a consequence of the assumption that no intermediate input substitution will take place, thus limiting industrial output. However, it also highlights the importance these sectors have for the province as a whole and illustrates that the current economic structure cannot be sustained without any of these sectors.

5.4. Sensitivity analysis

A major source of uncertainty in this study relates to the estimation of trade flows between the regions in the MRIO table. Larger trade flows between any two regions imply higher interdependency and may change the spillover effects should a region be disrupted in terms of water supply. The present study uses the extended FLQ to estimate the inter-industry inter-regional trade flows, which are controlled by the δ parameter in Equation (7). Lower values for this parameter are associated with low inter-regional trade flows and values close

Figure 9. Mean and 90% confidence interval of provincial GDP contraction for scenario A and B under different interregional trade configurations.



to one are associated with large trade flows. For the allocation of final consumption across regions, the parameter k_d in Equation (14) controls the decay in the allocation of gross output to final demand as the distance between regions grows. A large value penalizes the trade flow, while a value of zero would eliminate the distance effect.

Therefore, the MRIO table and the two scenarios applied in this paper were re-estimated for trade parameters ranging over the joint domain given by $\delta \in [0, 1]$ and $k_d \in [0, 5.4]$. This represents the entire domain for δ, while for k_d the explored domain goes from its minimum value of zero up to a value that is one order of magnitude higher than its estimated value by the naïve gravity model (see Appendix B of the Supplementary Information). Each parameter was gradually increased 1/10th the size of its range, yielding 11 points on each and a total of 121 trade configurations for each scenario. To ease the computational effort of this sensitivity analysis, water reductions were implemented following 2% instead of 0.5% reductions on both scenarios. This analysis provided a set of MRIO tables with different trade configurations over which scenarios A and B were implemented. The aggregated minimum and maximum values are presented in Table 2 below the corresponding baseline MRIO values.

Figure 9 shows the range of GDP contractions produced by the different trade configurations. For scenario A, most contractions under the different trade configurations follow a similar pattern of behavior consistent with that of the initially estimated scenario A. Although the initial costs are lower than the mean cost of the alternative configurations, they fall within the cost range produced by 90% of all cost curves of the alternative configurations. This range grows with water reductions up to a size of 1% difference in GDP loss for the maximum water reduction of 12%. For scenario B, the initial scenario produced higher costs than the mean cost of the alternative configurations but within the cost range produced by 90% of the cost curves. Here again, the pattern of responses is similar to that of the initial scenario B, and the cost range widens as water reductions are increased up to a range of 3% difference in GDP loss for the largest water reduction of 12%. Overall, these results show that the economic costs at provincial level are sensitive to the mutual interrelation of its regions as illustrated by their trade flows. However, this sensitivity is bounded by the size of the water reduction.

6. Discussion

The GLB was estimated to be responsible for 91% of the gross output generated in Ontario, which is equivalent to about 35% of the gross output of Canada as a whole. Although there are only a limited number of major industries directly dependent on the available freshwater resources, these industries were shown to play a key role in the economic structure of the region. With a loss in GDP of less than 0.1%, the province of Ontario seems to be able to cope well with water reductions in the GLB of up to 9%, only if an optimal water allocation plan is implemented. Such a plan would involve the reduction of water supply to certain sectors, most notably power generation. Higher future water reduction levels are expected to result in increasing marginal losses in provincial and regional GDP. Trying to maintain water, food and energy security under these circumstances, as illustrated in scenario B, imposes a considerably higher cost on the regional economy to address these water disruptions. Under this scenario, agricultural output is most affected, resulting in an important reduction of international exports from this sector. Under the most constrained conditions as reflected in scenario B, water withdrawal reductions of 4, 8 and 12% in the GLB result in a loss of provincial GDP of up to 0.7, 2.0, and 3.3% respectively.

The climate change scenarios hence reveal that the economic costs per volume of reduced water can vary greatly depending on the magnitude of the water disruption, reflecting non-linearities in the economic response, and whether or not minimal amounts of commodities for final demand are to be guaranteed. Roughly speaking, large water users with a relatively low GDP contribution per volume of water use and with relatively low inter-industry dependencies are most affected. Examples include power generation and agriculture. Manufacturing, commercial and institutional industries have a much higher marginal contribution to GDP per dollar of water used. The sensitivity analysis performed on the trade flow parameters shows that the degree of interdependency between regions gives a range of economic losses that becomes more pronounced as water restrictions become more binding.

In terms of methodology, the use of IO tables is widespread, making this a highly reproducible modeling framework. This also applies to the economic optimization procedure, and the introduced constraints related to water, food and energy security. The flexible economic optimization procedure presented here allows the introduction of site-specific constraints, such as water rights or priorities in water allocation, extending its domain of application to regions with different institutional-economic water allocation conditions and agreements. The challenge in developing a MRIO model is found in the availability of sufficient spatially detailed data to disaggregate the IO data to the relevant geographical units, in this case the hydrological boundaries delineating the GLB, and the modelling of the trade flows between regions. It is especially the latter that poses challenges and requires additional spatially explicit data and assumptions since such trade data are typically only available at specific administrative levels at which the IO tables are created (provincial or national level). This spatial disaggregation makes the MRIO model at the same time location and context specific, hampering its transferability to other locations or sites. An interesting future challenge is to also include the US-side of the GLB in the modelling framework. Four of the five Great Lakes are shared with the US, while Lake Michigan is entirely located in the USA. Each of these lakes are expected to have their own site-specific characteristics, which will have to be represented in the regions making up the MRIO table. In addition, transboundary trade flows will have to be incorporated between the lakes shared by the two countries.

7. Conclusions

This study introduced a new approach to impose resource or input factor constraints into an input–output (IO) modelling framework through the use of an economic optimization procedure. The proposed new model was used to study the effects of potential future water supply disruptions on the economy of the Canadian Great Lakes, one of the largest freshwater resources in the world. A multi-regional input–output (MRIO) model was developed where each lake sub-basin is treated as a single economic unit. Scenarios of water supply cutbacks, based on future climate change, were explored to determine their potential impacts on the regional and provincial economy.

The novelty of the economic optimization framework presented here is found in the fact that besides being able to impose primary and secondary input supply constraints, the economic optimization procedure also allows for the specification of a minimal supply of industrial commodities to meet final consumption, for example to simultaneously ensure food and energy security. An unexplored feature of the model is its capacity to formulate different objective functions that also drive the allocation of available resources, e.g. minimize unemployment or lack of supply to meet final consumption. The model is furthermore able to capture non-linear direct and indirect effects, which arise due to the increasingly bounding effect of water availability on the economy as industrial commodities from the disrupted water-based industries become increasingly scarce. These features offer an advantage over traditional IO impact analyses and expand the type of studies capable to be addressed by the IO framework, in particular in the field of environmental studies or the assessment of sustainable water management policies.

The practical value of the developed MRIO model is found in its possible application in water policy and decision-making related to the Great Lakes. This is to our knowledge the first attempt to assess the role of water in the broader economy of the Great Lakes Basin and Ontario as a whole. Until now, no comprehensive economic model was available that allowed policymakers to estimate the economic impacts of changes in water flow levels, and subsequently water supply. The findings of this study are therefore considered of great value to provincial authorities such as Ontario’s Ministry of the Environment, Conservation and Parks, responsible for the implementation of Ontario’s Great Lakes Strategy. Changing water levels and the impacts of climate change on these water levels are identified in this Strategy as major challenges facing the Great Lakes today. The MRIO model can assist in designing sustainable water extraction policies or contingency plans for the Great Lakes in order to deal with potential future water scarcity threats due to climate change. As highlighted in the results, such policies and plans should consider the economic spillovers to other regions and sectors and the potential impact on water, food and energy security in the region, province and country as a whole given the national significance of the Ontario economy.

The MRIO model can also support the International Joint Committee (IJC), one of the oldest transboundary water management authorities in the world, in its decision-making regarding water levels in the Great Lakes Basin. Water levels in the Great Lakes are controlled and managed by the IJC, for example for the purpose of hydropower generation and commercial shipping. Understanding how changes in water levels and hence water availability influence these economic activities and the economic values they generate is essential to evaluate possible trade-offs between maintaining and managing different water endowments across key sectors dependent on the Great Lakes' water supply. Also here the impacts of climate change on water regulation planning in the Great Lakes have been a major concern and priority area for more than a decade since the publication of the Third Report to Governments on the IJC's International Watersheds Initiative in 2009. The model presented in this paper allows the Canadian government to assess the impacts of climate change on the economy of the Great Lakes region and Ontario as a whole through changes in water supply levels.

Finally, the developed model also makes the so far unknown and often invisible value of water more explicit to local, regional, provincial and federal policy and decision-makers, local residents and the public at large. The perceived abundance of water in Canada in general and Ontario more specifically due to the presence of the Great Lakes is considered somewhat misleading. These water resources are under increasing pressure due to a growing population, urbanization, agricultural intensification and climate change, increasingly limiting their availability for different water-dependent economic activities, and thus affecting their economic values. The modeling framework presented here provides policy and decision-makers not only a comprehensive and systematic decision-support tool to assess the impacts of increasingly limited water supply on the regional, provincial and national economy, it is also an important tool to raise policymaker and public awareness of the Great Lakes' economic values, and create support for the necessary policy interventions to protect these values.

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