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Water in computable general equilibrium models: Review, synthesis and avenues for future research

Saba Al Hosni [a,*], Scott J. McGrane [a,b], Gioele Figus [a], Cecilia Tortajada [c]

[a] Department of Economics, University of Strathclyde, 130 Rottenrow, Glasgow, UK
[b] Applied Physics, Stanford University, Stanford, CA, 94305, USA
[c] School of Social and Environmental Sustainability, University of Glasgow, Dumfries, DG1 4ZL, UK

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ABSTRACT

Water-extended Computable General Equilibrium (CGE) models are a class of economy-wide models widely used as tools to address research and policy questions for various water-related topics. This systematic review analyses 100 applications of water-CGE models, categorising them into key areas based on their structure and aims, including agricultural, industrial, combination of agricultural and industrial, energy, and combination of energy and agriculture, to examine the methodological approaches of incorporating water into CGE models, and to explore the various themes of the applications. Findings suggest that improvements in incorporating water in CGE models require improvements in the quality and detail of water data, explicitly specifying water as a factor of production, constructing models at smaller spatial scales, accounting for water seasonality, and improving transparency of calibration and validation methods. Addressing these challenges will enhance the representation of water in CGE models that can provide critical insights in addressing water-economy interconnections.

1. Introduction

Acquiring a comprehensive understanding of the role of water in an economy is crucial, with water being a non-renewable resource that directly and indirectly supports all economic activities. As water resources are facing severe pressure due to population growth, economic development and climate change, understanding this role is crucial for addressing the mismanagement of these resources and for developing policies that ensure sustainable economic growth, food security, and the well-being of people and the environment (Sivakumar et al., 2013; Susskind and Islam, 2012). Hence, water resources and their sectoral and production interconnections, including adopting a holistic perspective of the economy, are attracting increasing attention in the academic and policy environments (Bardazzi et al., 2024; Damania, 2020; Damania et al., 2017; Dudu et al., 2018; Nechifor and Winning, 2017).

The link between water resources and the economy has been subjected to various approaches. Economy-wide models, particularly Computable General Equilibrium (CGE) models, offer a distinct approach to assessing how water impacts the economy. These models can be extended to include water accounts to analyse the interconnections between primary and intermediate inputs, sectoral interlinkages, and final demand in an economy, allowing for integrated water-economic analysis (Babatunde et al., 2017). These models effectively address hypothetical questions and counterfactual policy and climate scenarios. However, despite their relative advantages, there are challenges in the representation of water in the CGE literature (Calzadilla et al., 2016; Fadali et al., 2012; Ponce et al., 2012).

The models are based on numerous assumptions, data availability and computational abilities. Incorporating water as an explicit factor of production for all sectors of an economy is difficult due to the limited information on water accounts. There are difficulties in tracking and monitoring water use by sectors, given that it is a final good, and an intermediate input, and is often re-used (Luckmann et al., 2014, 2016). Consequently, CGE modellers often rely on various approaches to modelling water into the structure of CGE models, such as focusing on a specific sector/s.

There has been significant progress in incorporating water into agricultural-focused models, given it is one of the largest water-using sectors, and because data on crop water use tends to be more available (Berrittella et al., 2007; Calzadilla et al., 2013; Peterson et al., 2005). However, even within these focused models, there are two approaches to integrating water: implicitly or explicitly. The former assumes water is embodied in land; thus, it is an unobserved factor of

* Corresponding author.
E-mail address: saba.al-hosni.2021@uni.strath.ac.uk (S. Al Hosni).

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production. The literature argues that there is less data on water use and market pricing for industrial and energy sectors. Consequently, there has been limited progress in incorporating water explicitly for these sectors, instead, water is often treated as an intermediate input (Hertel and Liu, 2016).

This variation in how water is represented highlights the need for a systematic review of water-CGE models. The last SLR with an exclusive focus on water-CGE models was published over a decade ago (Fadali et al., 2012), where the authors examined the structural challenges of incorporating water into CGE models and reviewed applications of these models to determine water values from a methodological perspective. Since then, the applications of water-CGE models and methods for integrating water have diversified and many new publications reflecting progress in data availability, modelling techniques, and growing policy relevance. Moreover, water issues have intensified due to climate change. Therefore, it is necessary to provide a new comprehensive analysis of the more recent research applications in the realm of water and CGE models to guide future research.

This paper conducts a systematic literature review (SLR) that focuses on analysing the current methodological approaches of applications of water-CGE models. It examines the methods through which water has been incorporated into these models and explores the various themes of the applications to identify the gaps and paths forward for future research on water in CGE models.

The aim of this paper is primarily methodological. Rather than reviewing the outcomes of previous studies, it examines how water has been incorporated into CGE models in terms of model design, data treatment, and sectoral representation, and analyses the context in which these models have been used. This methodological perspective is important as the assumptions made in CGE model design, such as how water is allocated, priced, and embedded in production drive the results of the model. By examining these methodological approaches, the review sheds light on existing evidence, find gaps, and guide future modelling efforts.

This SLR contributes to the literature of water-CGE models by providing an update and an expansion to the contributions of Fadali et al. (2012). While Fadali et al. (2012) reviewed studies between 1990 to 2012, this review extends the coverage from 2000 to 2023, capturing over two decades of research during which the modelling techniques and water-related challenges evolved considerably. To ensure a comprehensive coverage, the search strategy that was initially based on "water" and "computable general equilibrium models (CGE)" was later expanded to include synonyms "aqua" and "hydro". This expansion served as a robustness check, identifying 4 additional relevant studies to the initial 96 and reinforcing the review's conclusions. Based on the results of the analyses, the research gaps and challenges are identified, and avenues for future research are suggested.

The primary objectives of this review are:

1) to explore when, where and why water-CGE models have been used from an analysis of existing applications based on predefined thematic criteria, addressing the current gap in literature regarding geographic and thematic focus of these applications.
2) to investigate the methodological approaches of integrating water into CGE models by examining the technical features of the reviewed applications, responding to the need for understanding of how different modelling choices influence water representation in these models.

Previous literature reviews have taken into account a variety of methodological issues of incorporating water into CGE models, but none have applied the systematic review approach (Bryant, 2022; Calzadilla et al., 2016; Dinar, 2014; Dudu et al., 2018; Hertel and Liu, 2016; Ponce et al., 2012). There have been three SLRs that touched upon the topic of water-CGE models, but not as a primary focus (Bardazzi and Bosello, 2021; Bekchanov et al., 2016, 2017). Bekchanov et al. (2016, 2017) conducted an SLR of applications of both network-based hydro--economic models and economy-wide models, including Input-Output models and CGEs. In another SLR, Bardazzi and Bosello (2021) analysed the applications of CGE models on the Water-Energy-Food nexus. They reviewed the studies based on aims, spatial resolution and whether water was an endowment in the models.

Both reviews highlight the key differences in the applications and interpretations obtained using these models and emphasise the importance of explicitly accounting for water and its competing uses across sectors in these models. They further acknowledge the challenge of the availability of water data. However, as water-CGE models were not their primary focus, important characteristics and challenges of incorporating water were out of the scope of the review, such as water value estimation techniques and many applications of water-CGE models were not included in the review.

This SLR contributes to literature by analysing 100 studies that incorporate water into CGE models published between 2000 and 2023 based on predefined thematic and methodological criteria as an update and expansion on previous reviews (Bardazzi and Bosello, 2021; Bekchanov et al., 2017; Fadali et al., 2012). The thematic analysis identifies descriptive characteristics of reviewed applications, including temporal distribution, research aim, and geographical focus (river-basin, national, or global). The methodological analysis examines structural features of the models in terms of temporal and spatial resolution, sectoral aggregation, inclusion of multiple water sources, representation of water in production functions, and estimation of water valuation methods.

Section 2 outlines the methodology of the review process including a description of the review criteria: thematic aspects and methodological structures, and an explanation of five categories of focus of water-CGE models: 1) agricultural, 2) industrial, 3) combination of agricultural and industrial, 4) energy, 5) combination of agricultural and energy. Section 3 presents the results. Section 4 discusses the research challenges and avenues for future research. Section 5 concludes and discusses the limitations of this SLR.

2. Methodology

A SLR is a comprehensive method of reviewing literature that facilitates in-depth identification, synthesis, and evaluation of relevant studies based on a given research question to provide an unbiased summary of available evidence (Malede et al., 2024). This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) structure and guidelines, commonly used in Social Sciences and Economics (Fig. 1) (Chapman, 2021). The review also adopted Bekchanov et al. (2017) and Fadali et al. (2012) systematic approach to the literature review and review criteria.

To cover a wide range of applications, a search in two bibliographic databases was performed: Scopus and Web of Science, following Bardazzi and Bosello (2021) guidelines. Two sets of keywords were used to find studies on water and Computable General Equilibrium (CGE) models, employing Title-Abstract-Keyword searches in Scopus and Topic searches in Web of Science. The first search string specifically targets papers mentioning "water" and "Computable General Equilibrium." The second string was adapted from a recent SLR of climate change and CGE models (Wei and Aaheim, 2023), offers more flexibility. These limited keywords were chosen to retrieve relevant and representative studies of water-CGE models, as any study that does not mention these keywords jointly must be irrelevant or marginally relevant to the aims of this paper.

1. Water AND Computable General Equilibrium
2. ("water" AND ("computable general equilibrium" OR "CGE"))

Before applying any preliminary filters, the first search string retrieved 536 articles, while the second yielded 947. Discussions with reviewers indicated that including both search strings enhances

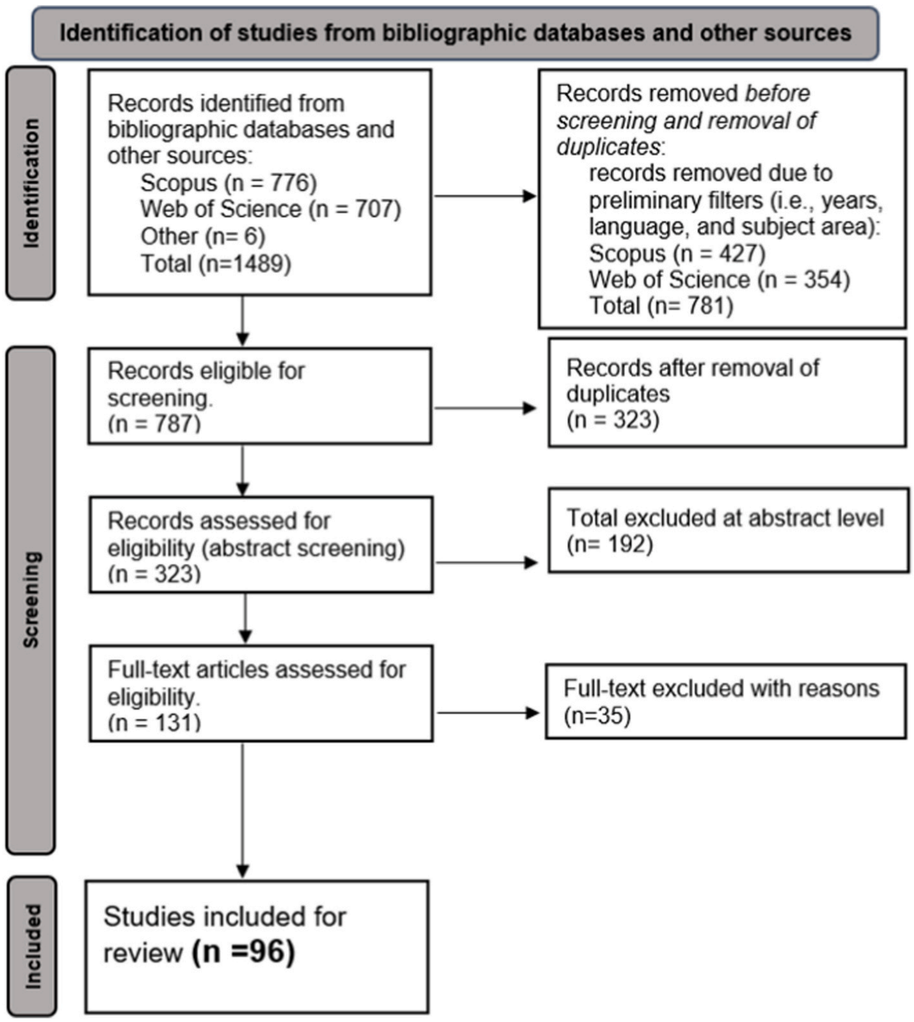

Fig. 1. Methodological steps of the systematic review process based on PRISMA structure.

coverage by capturing different subsets of literature. Before any preliminary filters, the combined total of the results from the search of the bibliographic databases was 1483 papers. Backward searching of previous systematic reviews (Bardazzi and Bosello, 2021; Bekchanov et al., 2017; Fadali et al., 2012) yielded 6 additional papers, bringing the total number of papers to 1489. Filters were then applied in bibliographic databases search that included a restriction of peer-reviewed articles written in English and published between 2000 and October 2023, as the last comprehensive review on water-CGE models was completed in 2012, and that included all papers before 2000 (Fadali et al., 2012). A selection of subject areas related to this topic was applied, and papers published in non-peer-reviewed journals were excluded. The new combined total of the search of databases with filters was 781 papers, and the records eligible for further screening were 787. After the removal of duplicates, 323 papers were eligible for abstract screening.

Three inclusion and six exclusion criteria determined the papers' eligibility for critical analysis, formulated to align with this SLR's research objectives. Following the guidelines of previous SLR on CGE models (Wei and Aaheim, 2023), the first inclusion criterion focuses on studies that extend Computable General Equilibrium (CGE) models to include water resources as the main analysis. This SLR is limited to CGE models that incorporate water. Papers that do not feature CGE models or that fail to adapt CGE models to include water are excluded under criteria 1 and 2. Additionally, studies that combine CGE models with hydrological, biophysical, or non-economic models are excluded under criterion 3, as they do not fall within the scope of this review.

The second inclusion criterion is adapted from the SLR conducted by Bekchanov et al. (2017) on water-economy models but tailored to the objectives of this review. As the second objective of this SLR focuses on analysing the methodological approaches, the retrieved papers must provide a clear methodology that shows the sources of economic and water data, water sources included in CGE models, specification of water in production functions, and water value estimation techniques. Hence, any study that does not include information on the criteria above is excluded under criterion 4 for lack of methodological clarity.

The third inclusion criterion (exclusion criterion 5) is commonly used in SLRs that focus on a specific model (Babatunde et al., 2017; Bardazzi and Bosello, 2021; Wei and Aaheim, 2023), any qualitative papers, such as theoretical frameworks and reviews, are excluded. Finally, exclusion criterion 6 is given when the full-text of an article is inaccessible.

For a paper to be included at both the abstract and full-text screening stages, it must meet all inclusion criteria, but it takes one exclusion criterion to be excluded, and only one exclusion reason is given to a single paper. Papers excluded with criteria 1,2,3, and 5 are given at the abstract screening level, whereas criteria 4 and 6 are given when full-text is reviewed.

The selection process for papers involves two stages: abstract screening and full-text review, guided by inclusion and exclusion criteria. In the first stage, 323 titles and abstracts were evaluated. Papers that could not be excluded based only on their title and abstract were retained for further evaluation. At the end of this stage, 131 papers proceeded to full-text review, while 192 were excluded, with reasons provided in Table 1.

The next stage is the full-text review of 131 papers to assess eligibility for inclusion for further analysis. This stage yielded 96 papers included for detailed analysis, and 35 papers were excluded with reasons as Table 2 demonstrates.

In addition, the search strategy was expanded to include synonyms “aqua” and “hydro” for “water” in search strings 1 and 2.

1. (Water OR aqua* OR hydro*) AND Computable General Equilibrium
2. (“water” OR “aqua*” OR “hydro*”) AND (“computable general equilibrium” OR “CGE”))

This expanded search identified 2171 records across Scopus and Web of Science. After applying the same preliminary filters (restricted to 2000–2023, English, and subject areas), 994 records remained. Following removal of duplicates, 426 abstracts were screened, the majority of which overlapped with original results. 12 abstracts were potentially eligible, of which 4 studies were included after full-text review. These papers have been combined with the review results, increasing the total from 96 to 100. The inclusion of the 4 additional papers did not change the overall conclusions of this review.

The second part of the systematic review that follows the selection of the relevant 100 applications of water-CGE models for extraction of information and coding according to the review criteria, both thematic and methodological. Each paper was fully read to extract information for coding which was then systematically analysed to identify methodological challenges, gaps, and potential avenues for future research.

The emergence of categories is a by-product of the synthesis process in systematic reviews (e.g., Ortiz-Partida et al., 2023). This involves analysing content to extract information on the aims, methodology, and findings of each study to identify patterns and commonalities across the chosen literature such that the main categories emerge. Five main categories of focus of water-CGE models were created based on the information extracted from the existing applications of the models: 1) agricultural, 2) industrial, 3) combination of both agricultural and industrial, 4) energy (hydropower), 5) combination of both agricultural and energy (hydropower). All 100 studies were analysed and categorised based on these model focuses, and a single category was assigned to each paper.

The categorisation of models is based on the main aim of the study, the aggregation and disaggregation of agricultural and industrial sectors, and the model results. Agricultural-focused water-CGE models disaggregate the agricultural sector into various crops while largely aggregating industrial sectors. In contrast, industrial-focused models disaggregate several industrial sectors and aggregate most agricultural sectors. The results typically highlight either agricultural crops or industrial sectors.

Models that disaggregate both sectors and reflect results for each are categorised as focusing on both agriculture and industry. Applications that include both agriculture and hydropower analyse both sectors in their results, while hydropower-focused models prioritise hydropower in their CGE framework. The categories of models' focus will often be used to describe or compare thematic and methodological aspects of the

Table 1
Details of exclusion of papers at abstract level.

Excluded with Criterion	
1	79
2	56
3	28
4	0
5	29
6	0
Total excluded	**192**

Table 2
Details of inclusion of 96 applications and exclusion of papers at full-text level.

Excluded with Criterion	
1	1
2	0
3	1
4	26
5	0
6	7
Total excluded	**35**

reviewed applications, as described below to support the aim of this review.

The thematic analysis aims to produce the main descriptive characteristics of the reviewed papers (Purssell and Gould, 2021). There are three thematic aspects to this SLR. First, the focus of the water-CGE model and the distribution of published papers across the years. Second, analysis of the main theme of the application of the models. Third, the applications were categorised into three different geographical scopes: river basin, country, and global or regional scale (Bekchanov et al., 2017).

The methodological analysis examines the structural features of water-CGE models based on reviewed applications, focusing on five key aspects. First, it describes the spatial dimensions and temporal scales of the CGE models. Second, it enumerates the aggregation and disaggregation of agricultural and industrial sectors in the models. Third, an assessment of the variety of water sources included and whether multiple sources are integrated into CGE models. Fourth, an outline of the modelling choices for water representation in production functions. Finally, it discusses the determination of water values for estimating water prices used in these applications.

3. Review findings: water in CGE models

3.1. Results of thematic analysis

3.1.1. Distribution of applications across years and by category

The first thematic aspect considered in this review is the distribution of the 100 applications analysed from 2000 to 2023 by the total number of papers published in each period (3-year window) and by the category of water-CGE models' focus (Fig. 2). There is a growing trend in the applications of water-CGE models in a broad range of water-related topics, as the applications increased from 2 studies between 2000 and 2003 to 29 between 2020 and 2023. This finding suggests that the

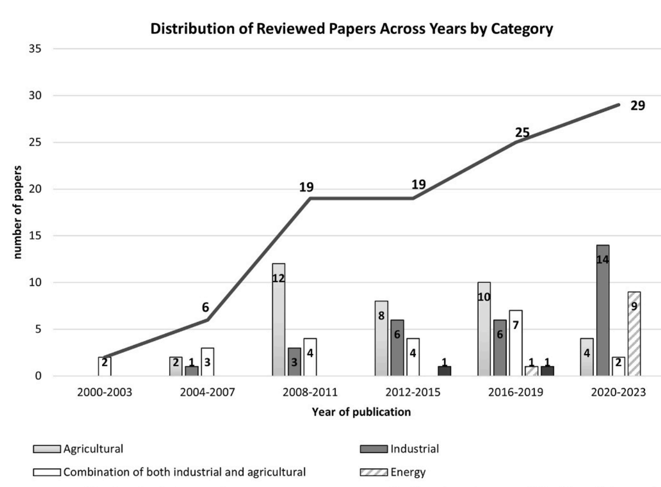

Fig. 2. Number of papers published per period in each category of water-CGE model focus. 100 reviewed papers in total.

interest in water and its economic implications using CGE models is still under-researched.

This analysis suggests that the models mostly focused on two categories of focus, agricultural and industrial, but with varying concentrations over the periods. Early applications of these models were primarily concentrated on the agricultural sector and the impacts of water changes on agricultural crops. This finding is expected for a variety of reasons and is in line with other systematic and reviews on this topic (Bardazzi and Bosello, 2021; Calzadilla et al., 2016; Dudu et al., 2018; Fadali et al., 2012).

First, agriculture is one of the largest water users and the most climate-sensitive of all economic sectors (Calzadilla et al., 2013). Therefore, it comes as no surprise that the largest number of reviewed water-CGE models' focus is on agriculture (35 out of 100 applications in total). Second, literature is abundant on the derivation of agriculture water demand curves and elasticities of price, which facilitates the building of an agricultural-oriented CGE model (Harou et al., 2009). However, there has been a decline in this pattern towards industrial-focused models in the later periods (Fig. 2).

There are limited water models outside agricultural use before 2008–2011. This may be the result of the absence (or restriction) of information regarding the consumption of water in industrial or commercial settings, combined with minimal research on the economic value of water in industrial sectors, which induced difficulties in building such models (Bryant, 2022). However, there was a shift towards an industrial focus and a combination of both industrial and agricultural in subsequent periods (2012 onwards). This can result from an increased interest in the links between water resources and the economy, using CGE models as analysis tools. This integration of industrial and agricultural water use with CGE is useful for several reasons: to use CGE models to find the marginal value product of water and/or its shadow price for industrial sectors (He et al., 2006); for water policy analysis (Zhao et al., 2016); to the water-energy-food nexus (Teotónio et al., 2020); to investigate the vulnerability and resilience of both agricultural and industrial sectors to climate change.

Finally, CGE models that incorporate both energy and water in the same models continue to be limited (Bardazzi and Bosello, 2021). Only 12 applications were found to include hydropower; 10 of those study the link between water and energy, and 2 applications analyse the link between water and agriculture.

3.1.2. Main theme of application

This review analysed the main themes of the reviewed applications to investigate the most prevalent topics explored by water-CGE models to understand how these models are applied. Fig. 3 illustrates the distribution of the 11 most common themes by category of models' focus for the 100 reviewed applications.

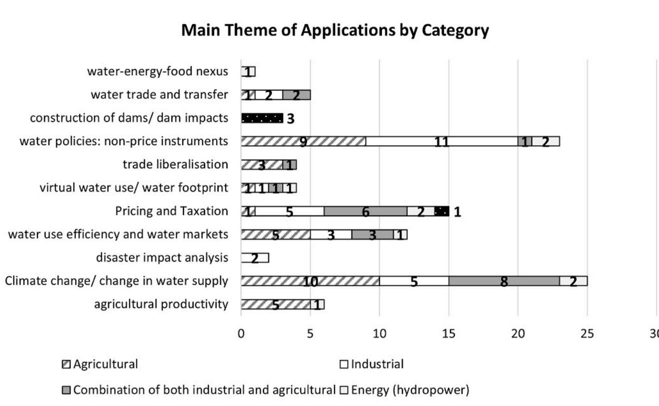

Fig. 3. A comparison of the reviewed studies by their main research theme by category of model's focus. Note: Only one main theme is assigned to each study.

The results indicate that the largest number (25 out of 100) of studies reviewed utilised water-CGE models to analyse the effects of and adaptations to climate change in terms of water supply reduction or water scarcity scenarios. These studies report adverse impacts on agricultural output, tourism sectors and household welfare under reduced water availability, while emphasising the role of irrigation efficiency and water reallocation as key adaptation strategies. Notably, only 2 studies focus on energy, despite hydropower being a critical sector for analysing water-related issues in dam management (Kahsay et al., 2019).

23 applications have focused on water policies (non-price instruments). The applications of the models for this aim were mainly agricultural and industrial-focused models. These applications generally analyse different policy scenarios such as technological improvements and water subsidies, and they show that such interventions influence water use and sectoral output in varying ways depending on context analysed.

The review finds 15 studies that have addressed water pricing and tax rates. The applications on this topic include a monetary valuation of water, estimating the shadow price of water, and finding optimal water tax rates for the economy, hence the majority's category focus is industrial and combination of agricultural and industrial.

The review also shows that the models have been used to analyse water use efficiency and introduce water markets (12 applications). These studies occasionally considered industrial transformations in water consumption to improve water efficiency (Jiang et al., 2014; Wu et al., 2014). The applications are almost equally distributed among the three models' focus, but none with an energy focus.

Other less recurrent topics include virtual water use and footprint analysis despite the models' methodological advantages (Sun et al., 2022). Studies employing these models generally find that water scarcity constraints shift production and trade patterns, generate net virtual water outflows, and produce varying welfare effects depending on context and market analysed.

Similarly, there was only 1 study to address the interconnections between the WEF nexus. This is perhaps linked to the issue of finding reliable sources of data that can link water consumption with all three components of the nexus (Dudu et al., 2018). Few applications used water-CGE models to analyse disaster impacts, trade liberalisation, and water trade and transfers.

3.1.3. Geographic scopes of applications

3.1.3.1. River basins. Given the importance of river basins to economies and that most water-related management decisions are studied at the river basin level, this review analysed the applications of water-CGE models to identify which river basins have been studied using these models. Of the 100 applications, only 17 studies are applied to river basins located in the countries below (Fig. 4).

This review found a single application of water-CGE models that studies the economic effects of changes in irrigation availability for 126 river basins in 19 regions worldwide (Liu et al., 2014). The authors used the GTAP database to obtain information on global land and water usage and the total water availability in each river basin.

The Murray-Darling Basin in Australia has been extensively studied using water-CGE models with 5 applications. The researchers can build these models at the river basin level due to the availability of water data in the Australian TERM (The Enormous Regional Model), which contains information on water supply, water use and water market prices (Peterson et al., 2005).

This review finds that 4 applications were built for the Nile River Basin countries, including Egypt, Ethiopia, Sudan, and the Equatorial Lakes regions (Kahsay et al., 2019). The modellers utilised the GTAP-Africa database to obtain the relevant data to build these models. No applications were found for other transboundary rivers in the Middle East (Western Asia), such as the Tigris and Euphrates, despite the

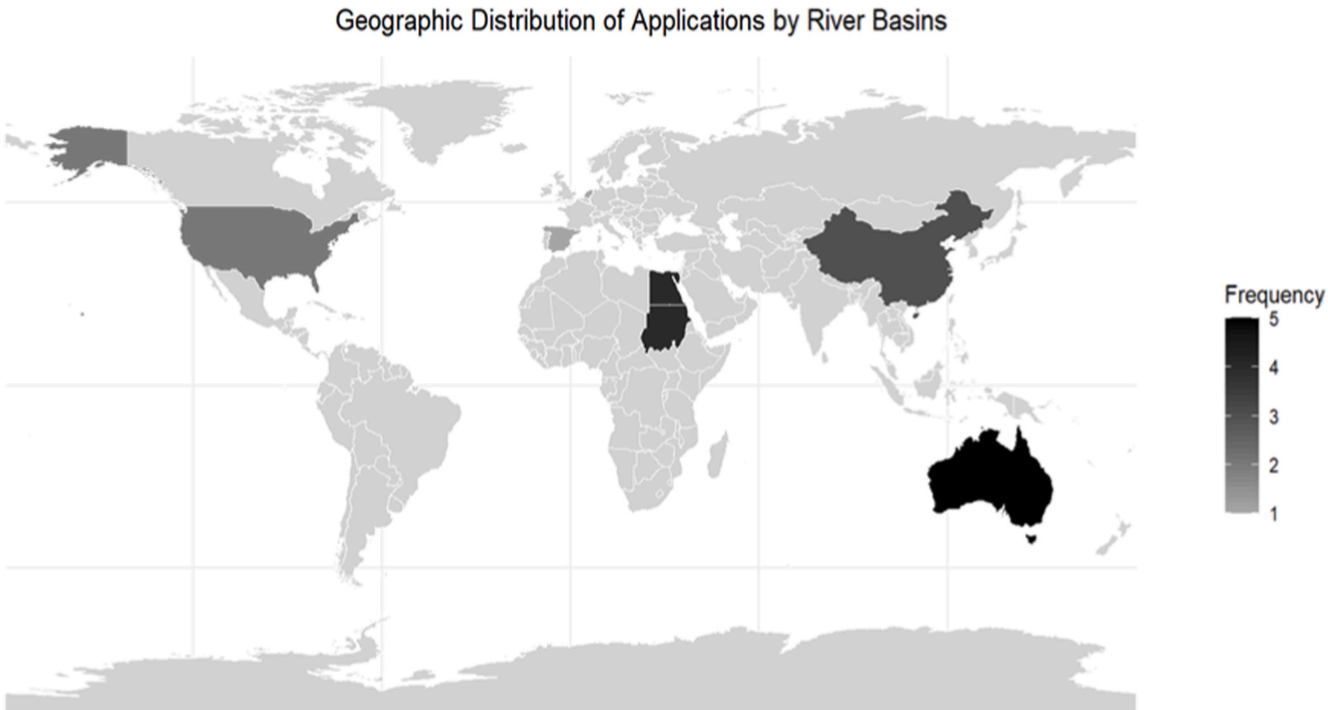

Fig. 4. The distribution of applications by River Basins studied. Note: The map does not include Liu et al. (2014), who analysed 126 river basins worldwide.

hydro-political issues emerging from overwater usage, dam construction, general mismanagement among the countries that share the river (Iraq, Iran, Turkey, Syria, and Kuwait), besides population growth (Voss et al., 2013).

The review finds 2 applications for river basins in the US: the South Platte River Basin in Colorado (Watson and Davies, 2011), and the Arkansas River Basin (Goodman, 2000). However, the review found no applications to other major river basins in the Americas, such as the Amazon and the Mississippi Rivers.

Two applications focused on river basins in Europe. First, Koopman et al. (2015) built a water-CGE model for two rivers flowing through the Netherlands: the Rhine and the Meuse. Hence, the model accounts for the transboundary water issues for the Netherlands, Belgium, Luxemburg, Germany, and France. Second, Philip et al. (2014) assess four alternative technological improvements to address future water availability for the Ebro River basin in Huesca province, Spain.

There are 3 applications covering river basins in China. 2 studies cover the Heihe River Basin and Huaihe River Basin, respectively, and a single study analyses water use efficiency in 9 river basins in China. The researchers utilised the TERM database to overcome data constraints and build this large multi-region, multi-basin water-CGE model.

3.1.3.2. Country level. As Fig. 5 illustrates, this review analysed the applications of water-CGE models by the most extensively researched countries worldwide from 2000 to 2023.

The highest number of applications of the models found by this review is for China, with 31 applications. The figure encompasses applications at the national, regional, and river basin levels within the context of China. The country faces significant water resource challenges such as water scarcity, management issues due to the uneven distribution of water across its regions, large population, and rapid economic development (Fan et al., 2018; Qin et al., 2013). Thus, the Chinese government prioritised water governance and water-related research, acknowledging the necessity of integrating economics with water dynamics for a comprehensive understanding of its challenges (World Bank, 2018). Furthermore, China comprehensively publishes water data at national and regional scales, thus enabling the building of water-CGE models (e.g., (Boudmyxay et al., 2019; Lin et al., 2021). Thus, the highest number of applications.

Many studies examining water-related challenges were conducted in South Africa and Spain (7 and 6 applications, respectively). Modelling water issues using water-CGE models for South Africa and Spain is feasible as both countries publish water accounts for various sectors in local statistical reports. Furthermore, the review finds three applications focused on Egypt and Israel, and four applications focused on Nile River basin countries, including Egypt, Sudan, South Sudan, and Ethiopia. Two applications were found for each of Brazil, Turkey, Switzerland, Netherlands and Iran. Finally, the review also found a single application of the models for each of Canada, Chile, Guatemala, Kenya, Morocco, New Zealand, Portugal, Tunisia, Uganda, and Uzbekistan.

The light-grey areas in Fig. 5 indicate the regions where no study has been found by this SLR, identifying the geographic gaps in the country-level applications of water-CGE models.

No nationwide applications were identified for most West Asian countries, South America, and Western Africa, even though agriculture is crucial to their economies (Sivakumar et al., 2013; Sultan and Gaetani, 2016). Water issues pose significant challenges in the Middle East (West Asia and Northern Africa). The region suffers from water scarcity, over-extraction of groundwater, and low precipitation throughout the year (arid regions) (Sivakumar et al., 2013). Similarly, Central and South America face various water issues, such as reduced water quality (pollution) and extreme weather events (droughts and floods) as a consequence of climate change (Campuzano et al., 2014). However, as the map illustrates, there are a limited number of applications of water-CGE models built for countries in the Americas.

No country-level water CGE models were found for Northern (excluding a single application for Scotland), Eastern, and Western (excluding Netherlands and Switzerland) Europe. Perhaps this can be attributed to the variation in European water issues and interest in this topic or models. Northern and Western Europe still have a relatively abundant supply of freshwater resources, thereby positioning the issues of water and water-economic modelling to an end of lesser importance in the water research spectrum in the region (European Environment

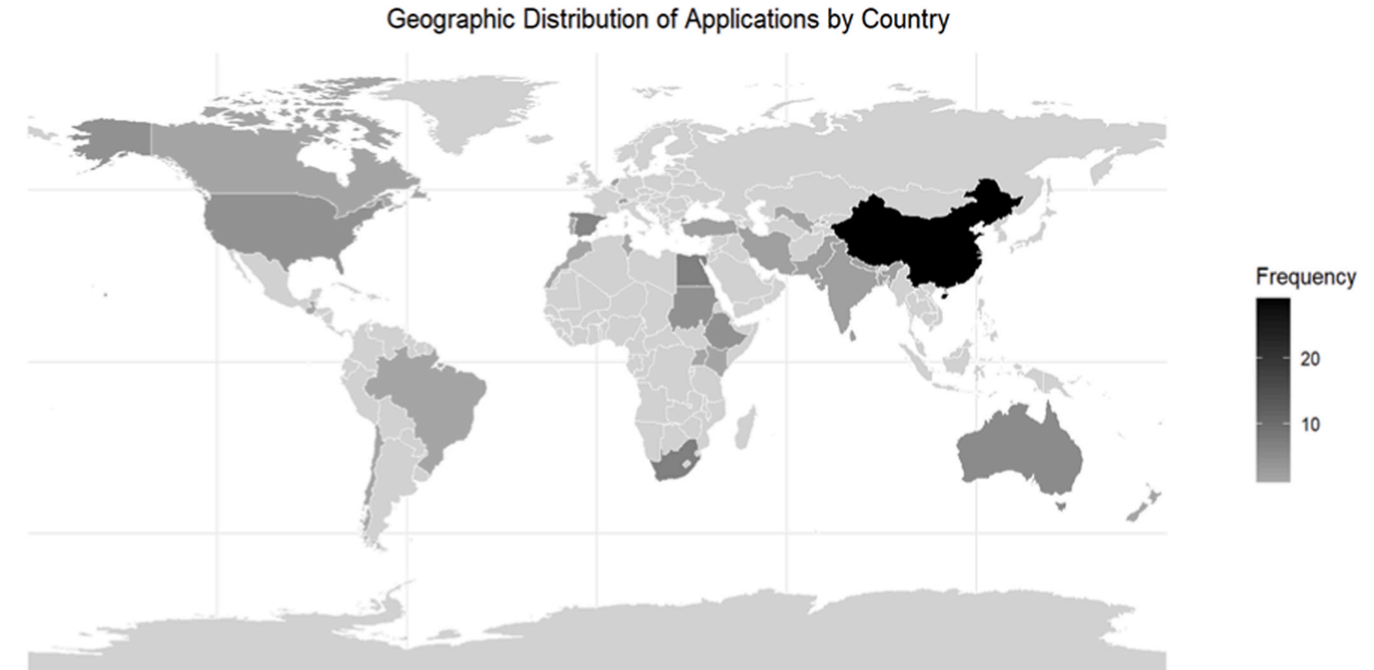

Fig. 5. The geographic distribution of the reviewed applications by their case study countries. Note: The map also highlights the applications of regional and multi-regional applications.

Agency, 2018). Nonetheless, both European regions face hydro-hazards as a consequence of climate change, such as droughts and flash flooding (Elsner, 2023). Conversely, Eastern and Southern Europe face water scarcity issues and reduced water quality (Danilovich et al., 2023; Zapata-Sierra et al., 2022). Europe, in general, will benefit from more applications of water-CGE models that investigate the impacts of water-related challenges such as water scarcity and flooding to inform more sustainable water management policies.

3.1.3.3. Global and regional contexts. The final element of comparison in this section is an analysis of the applications of water-CGE models that covered large geographic spaces, i.e., global and regional models. Fig. 6 demonstrates this distribution by category of model focus.

The review found several applications of water-CGE models being employed in a global context to study water-related topics. These world models (GTAP-W) were built using the GTAP database that contains 16 regions and 22 sectors (Berrittella et al., 2007). The applications are mainly distributed between an agricultural and a combination of agricultural and industrial water-CGE model focus, but no applications focused on energy.

The figure shows that most global models have an agriculture focus

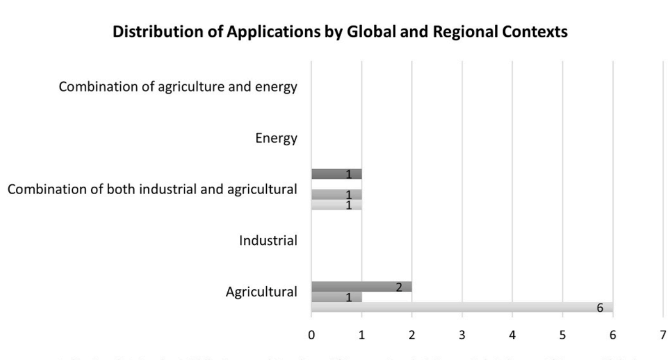

Fig. 6. The distribution of applications in global and regional contexts by category of focus.

(6 applications). The novelty of building a multi-region global model is its ability to be a tool that analyses the impacts of water issues on global agriculture and interactions with international trade (Berrittella et al., 2007; Alvaro Calzadilla et al., 2013; Liu et al., 2014). Since water issues are not restricted by national borders, a global water-CGE model overcomes the limited geographic scopes of national and single-region models. This review also found one global application with a combination of both agricultural and industrial models focus. The global model is utilised to analyse the economic impacts of water taxes (Berrittella et al., 2008).

There are several multi-regional (across several countries) applications. The review found a single agricultural-focused application of the models built to analyse climate change impacts on the crops in Sub-Saharan Africa (A. Calzadilla et al., 2013; Calzadilla et al., 2011). Similarly, we found 2 applications of multi-region water-CGE models with an agricultural focus built for South Asian countries, including Bangladesh, India, Nepal, Pakistan and Sri Lanka (Zeshan and Ko, 2019; Zeshan and Shakeel, 2020). Finally, a single model was built for four regions: India, South Asia, the Middle East, and Northern Africa (Nechifor and Winning, 2018). The model analysed demand-driven water scarcity for both the agricultural and industrial sectors in those regions and is, therefore, classified as a combination of industrial and agricultural model focus.

3.2. Results of Methodological Analysis

3.2.1. Temporal and spatial dimensions

The first methodological aspect considered in this section is an analysis of the structural features of the reviewed applications of water-CGE models in terms of temporal and spatial scales of the CGE models. Table 3 provides a summary of the results.

Water resources often share common characteristics in terms of usage by sectors across national borders within a region and also share a river basin between neighbouring countries. However, this review finds that the highest number of applications is at a national scale (36 out of 100). Country-level models tend to be easier to build given the limited or sometimes unavailability of water data for smaller regional scales (sub-national) and even across countries (Bardazzi and Bosello, 2021).

Table 3
Number of papers per classification of temporal and spatial dimension.

Spatial Dimension	Temporal Dimension		
	Static	Dynamic	Total
Global and Regional (across countries)	15	6	21
National (country-level)	29	7	36
Single-region (sub-national)	19	9	28
Multi-regional (sub-national)	9	6	15
Total	72	28	100

Nonetheless, there are a substantial number of single-regional applications of the models (28 applications) and a smaller number of multi-regional applications within a country (15 applications). Multi-regional water-CGE models can demonstrate the spatial distribution of economic impacts within a country and allow modellers to observe the regional heterogeneity in water use patterns (Lin et al., 2021). These small-scale models are useful for policy analysis, climate change scenarios, and water availability analysis within small economies.

Overall, the most common temporal scale was annual (January–December, static) across all spatial scales (72 applications). Static water-CGE models mainly focus on the short-term immediate impacts of water-related shocks or short-term policy responses, depending on the research questions. Dynamic models were found to be less common (28 applications) in the reviewed applications of the models. These models are known to be of vital importance when it comes to modelling the long-term climate change impacts and adaptation policies using water-CGE models (Tabesh et al., 2022; Wang, 2018; Zeshan and Shakeel, 2020). This temporal scale can incorporate the seasonality of water and annual variability to capture the impacts on irrigation, hydropower generation, and other water-intensive activities.

Incorporating seasonality in water-CGE models is essential to accurately capture water use dynamics, particularly in sectors like agriculture, where demand and crops can be variable throughout the year. As prices fluctuate based on seasonal demand or water scarcity seasons, incorporating season-specific water prices and sector-specific seasonality (crops) can capture the economic effects of water-related shocks. CGE models can make temporal adjustments to smaller time scales of months or even quarters. However, this review found no models adapted for a sub-annual temporal scale to capture seasonality regarding water, crops, or prices. This is mainly due to difficulties in gathering detailed data on seasonal variations in water availability, use by different sectors, and seasonal prices of water (Amaya et al., 2021).

3.2.2. *Sectors considered*

This section aims to provide a detailed account of the number of agricultural and industrial sectors compared to the total number of sectors included in each application of water-CGE models considered in this review to demonstrate the data requirements of building such models. Fig. 7 is a collection of 3 histograms: a) shows the most common disaggregation of the agricultural sector in the reviewed applications, b) shows the most common number of industrial sectors in all reviewed applications, and c) illustrates the most common total number of sectors included in water-CGE models reviewed.

Many of the reviewed applications can disaggregate the agricultural sector into multiple crops to be included in the SAM/CGE. The most common disaggregation of the agricultural sectors is found to be between 10 and 15 crops, as Fig. 7 (a) demonstrates (29 applications). This is due to the easier accessibility of data on crop water intensity, irrigation practices, and water withdrawals (Fadali et al., 2012). Furthermore, many of the reviewed studies use international databases, such as the GTAP database, which includes a default disaggregation of crops into 7 (22 sectors). Fig. 7(a) also demonstrates that 13 models included 5 or fewer crops in their models, and substantially fewer applications can disaggregate the sector into more than 15 crops.

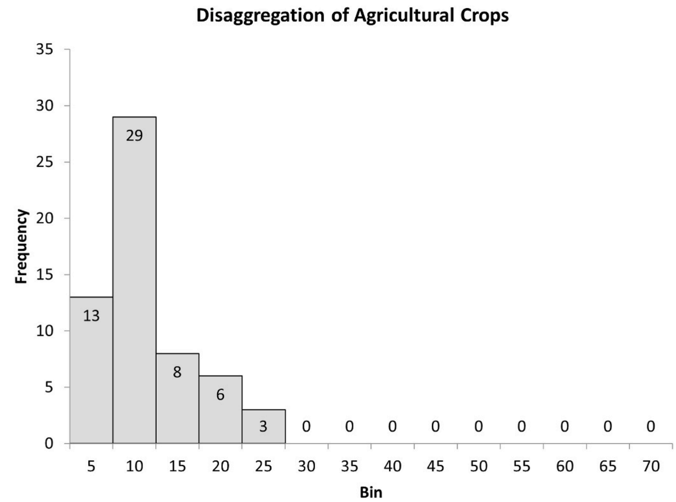

Fig. 7(a). Most common agricultural crop disaggregation from the reviewed applications.

Fig. 7 (b) demonstrates that most applications (29) included only 10 to 15 industrial sectors in their water-CGE models, and 10 applications had 10 or fewer industry sectors. Less frequently seen are applications that include more than 20 industrial sectors. However, a few outliers (10 applications) included more than 40 industrial sectors.

Including multiple sectors in CGE models allows for a more detailed and nuanced analysis of the interactions between water resources and the economy. Different economic sectors will have varying water use patterns. Some sectors are heavily water-intensive, and others have lower water requirements. Therefore, the number of sectors included in water-CGE models captures these variations and estimates the effects of disruptions in water supply on economic sectors.

As Fig. 7 (c) illustrates, most of the reviewed applications are concentrated on the left, where the total number of sectors (including agricultural and industrial sectors) included in each application of the models is between 5 and 25. The review also finds 7 applications with 5 or fewer sectors in their CGE models. This is a small number of economic sectors to be included in a CGE model and might limit the understanding of the role of water in an economy, as the over-aggregation of sectors reduces the representation of the economic impacts of a shock on water resource (supply, policy) on the majority of sectors and lead to aggregation bias (Lahr and Stevens, 2002). On the other hand, aggregating sectors might also be done for various reasons, such as allowing for a more focused analysis of the key sectors of interest or reducing

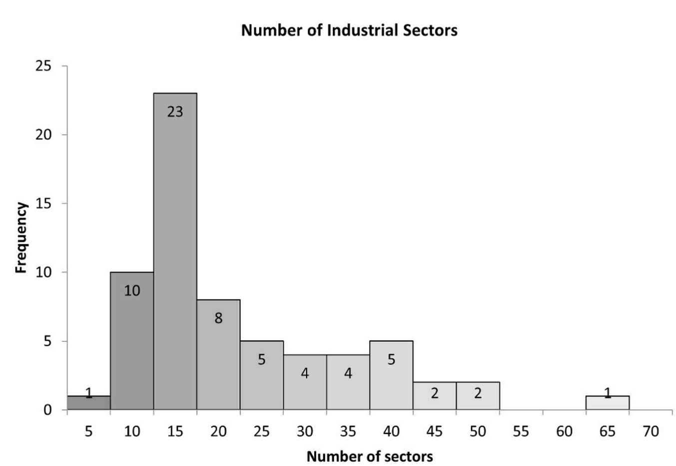

Fig. 7(b). Most common number of industrial sectors from the reviewed applications.

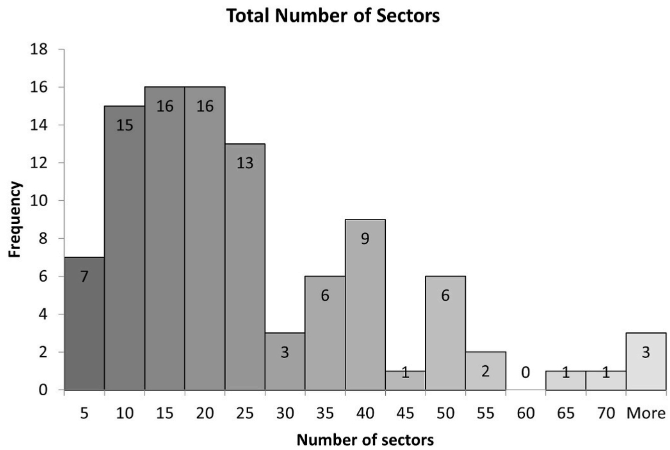

Fig. 7(c). Most common total number of sectors from the reviewed applications.

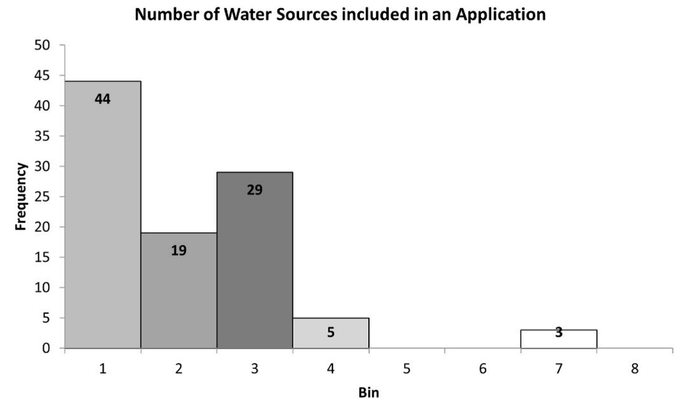

Fig. 9. Most common number of water sources included in a single application as analysed from the reviewed applications.

computational and interpretational complexities. If the quality and reliability of sectoral and water data are a concern, a focused water-CGE model with fewer sectors may be preferable, depending on the researchers' overarching aims.

3.2.3. Water sources included

This review aims to evaluate the degree to which alternative water sources were considered in the models' applications (Fig. 8) and whether an application incorporated more than one type or source into its models (Fig. 9).

Fig. 8 shows 7 sources of water often included in CGE models reviewed. Most applications, (44 %) included surface water flows in their CGE models followed by groundwater (30 %) (blue water). Fewer models incorporated wastewater or recycled water in their economic model, and a single model is found to include recycled mine water as a source. This could be due to data challenges or increased complexity in incorporating multiple water sources into CGE models. Furthermore, few studies included seawater or desalinated seawater, given that not many countries (included in this review) desalinated seawater (5 %) and 1 % of studies included brackish water.

As an economy can have multiple types of water sources that can be used for production activities to produce outputs, a water-CGE model must incorporate all water sources used as an input to represent the economy realistically (Dudu et al., 2018; Luckmann et al., 2014). Hence, this review analysed the reviewed applications to examine the number of water sources or types most included in water-CGE models.

Fig. 9 demonstrates that 44 applications (out of 100) included only one type of water source in their water-CGE models. The literature suggests that this is mainly due to a lack of water accounts and possibly due to the difficulties in tracking water use by water sources (Bardazzi and Bosello, 2021; Bryant, 2022; Dudu et al., 2018; Fadali et al., 2012). The figure also shows that 29 applications included 3 types of water in their models. This number stems from the applications that utilise the GTAP database that differentiates between surface and groundwater, and rainwater by default.

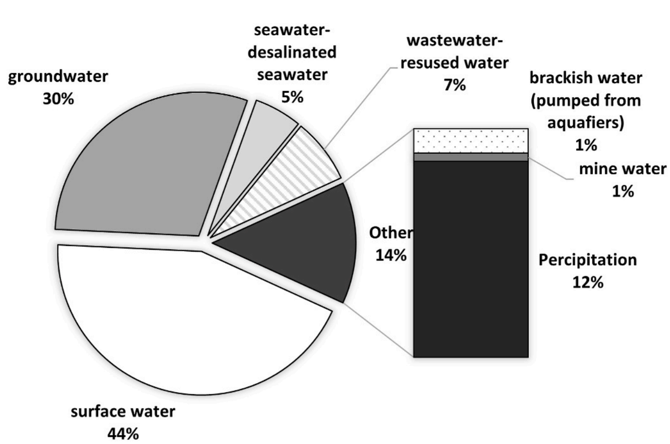

Fig. 8. Types of water sources or types included in applications reviewed.

3.2.4. Water in production functions

This section covers the different water specifications in production functions from the reviewed applications (Fig. 10). This review distinguishes between applications that include more than one nested production tree to reflect the differences between agricultural and industrial water uses in each application (Fig. 11).

3.2.4.1. Representation of water in production functions. Perhaps the most critical step in building a water-CGE model is to choose the way water is specified in production functions and the degrees of substitutability with other factors.[1] Water can be specified as either a primary factor of production or an intermediate input, depending on how it is used in production processes. Like capital and labour, water is essential

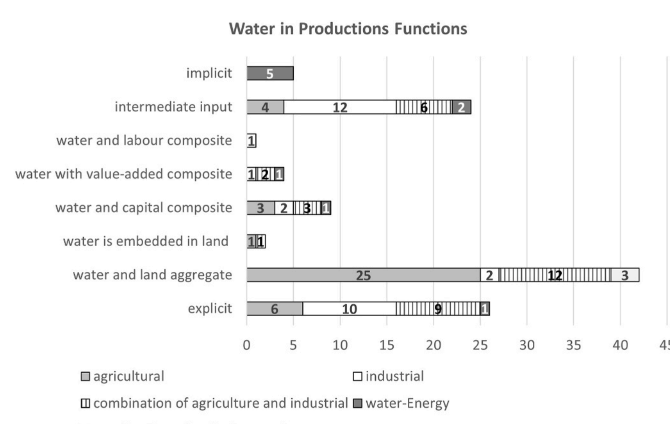

Fig. 10. Representation of water in production functions of the reviewed applications.

[1] This paper does not discuss elasticities of substitution. A recent literature review by Calzadilla et al. (2016) comprehensively discusses the issue of the elasticity of substitution of water with other factors of production in water-CGE models.

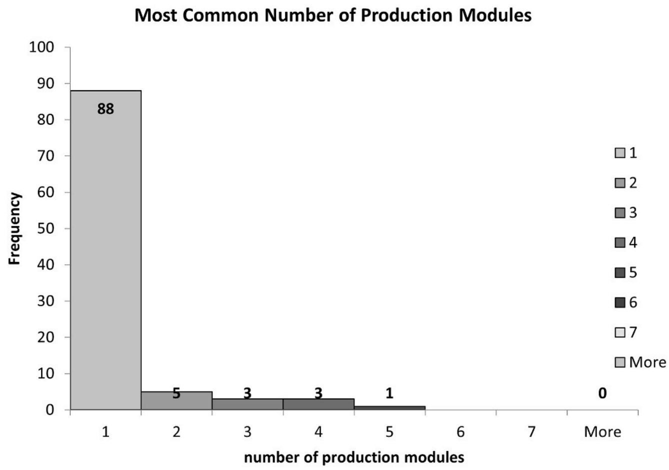

Fig. 11. Number of production function modules included in the reviewed applications.

for the production process. As an intermediate input, water is used to produce other goods and services. Therefore, the specification of water in production functions will demonstrate how water is used to produce outputs in an economy and determine the ability of CGE models to capture the role of water in an economy (Calzadilla et al., 2016).

Water is introduced into the production function in at least one of these ways:

1. As an explicit factor of production (separated from other factors)
2. As a factor of production combined with other inputs (water is combined with either land, capital, labour, or the value-added nest)
3. As an intermediate input

If a CGE model specifies water as a factor of production directly and separately from land in the value-added nest in a production nest, then water is specified as an explicit factor of production-a "direct" approach (Calzadilla et al., 2016). Water has been specified as an explicit production factor 26 times in this review, 10 of which are industrial-focused models. Water as an explicit production factor reflects the allocation of water across economic sectors and the payments made by each sector to use water. This means that the price of water and the pricing of water differs from other production factors. Moreover, this specification allows modellers to consider the substitution possibilities between the primary factors of production and water (Teotónio et al., 2020). That said, there is a lack of this specification in the literature on water-CGE models due to the lack of information on water's competitive uses across sectors (Damania, 2020).

The most common way of introducing water in production functions -and therefore, in water-CGE models-is by combining water with other factors of production in an aggregate nest, i.e., an "indirect" approach (58 applications) (Hertel and Liu, 2016). The underlying assumption is that water perfectly complements other factors. Hence, water is not priced directly; the modellers rely on shadow prices for it.

Water is mainly combined with land (42 applications) in an aggregate nest, which is a common specification for agricultural-focused models (25 applications). This specification assumes that water can be substituted with land. If a modeller aims to incorporate water use for industrial sectors into the CGE model, then a different production tree can be added for the non-agricultural sectors in an economy.

This review found a single model that incorporates land (rather than water) in their production function and assumes that water is embodied in land (land is a proxy of water variations) in agricultural sectors (Seung et al., 2000). Hence, they assume that water use is equivalent to land use. This specification can only be used for agricultural production and not for industrial sectors that use water directly from other sources (such as the main piped supply).

Relatively few models specified water as a production factor combined with capital (9 applications), most of which are for agricultural-focused models (3 applications). To do so, the modellers estimated the cost of capital and water and the substitution degrees between them (Gómez et al., 2004). This specification allows us to see the transition to more water-efficient technologies in response to increasing water scarcity. Finally, the review process also identified one application that combined water with labour.

The third most common specification found is water as an intermediate input (24 applications). These models obtained data on water in the main piped supplies (Hassan and Thurlow, 2011; Li et al., 2015; Teotónio et al., 2020). Treating water as an intermediate input is common in industrial-focused models as these sectors mostly use treated water from the main water distribution lines. This means that in the SAM, the rows show water as a fixed intermediate input by other sectors, and the columns show the payments of water-using sectors to the water sector. A key implication of using this specification rather than treating water as a factor of production is the limited ability to see the impacts of a shock on sectoral water availability and use (Juana et al., 2012).

The energy (hydropower) models considered in this review mainly included hydropower in their production functions (7 applications). Hydropower is included as a factor of production rather than water in the production function nest; therefore, an assumption can be made that this is a case of water as an implicit factor of production.[2] This was done by creating a capital-energy composite and then disaggregating energy into electricity, which is then divided into hydropower and other renewables (Fan et al., 2018; Kahsay et al., 2015, 2019; Mardones and Ortega, 2023; Ni et al., 2022; Sun et al., 2021a, 2021b). This splitting of electricity enables modellers to estimate cost structures, the capital intensiveness of hydropower, and the various types of electricity generation.

3.2.4.2. Number of production function nests. Incorporating water into CGE models is complex because it arises from the numerous interconnections of water with economic sectors and the various ways of using water to produce output. To accurately capture the differences between agricultural and industrial water use, modellers can incorporate multiple production function nests in their CGE models (Briand et al., 2023). However, as Fig. 11 shows, this is not common.

88 applications of water-CGE models included only one production function nest, and only 12 applications included more than one. Including multiple production function nests is contingent upon the availability of data and computational abilities. There are complexities to adding more production function nests in CGE models with different levels. More nests mean more assumptions are to be made at each level in a nest regarding the elasticities of substitution between inputs as they differ at each level. Obtaining values for substitution elasticities for each nesting level has significant data requirements, which are often unavailable (Dudu et al., 2018).

3.2.5. Incorporating the benchmark value of water

A well-functioning competitive water market would allow modellers to observe water prices that can determine the value of water in an economy, and the shadow price of water equals its market price (Grafton et al., 2023). However, water markets are either imperfect or non-existent, or no data can track water use by water prices. Moreover, it is often the case that water is unpriced or under-priced- the price of water does not reflect its value (Das et al., 2023).

Estimating a "starting" price for water is necessary to use it as the benchmark equilibrium value used to calibrate CGE models (Bryant,

[2] Water is implicitly a factor of production, treated as an unobserved input whose impact is reflected in other measured inputs, such as land or hydropower.

2022). Calibration ensures that the CGE models reflect the base year's economic conditions. Furthermore, the specification of water in production functions (factor of production or intermediate input) and the benchmark value of water are interlinked. When water is specified as a factor of production, the benchmark value reflects the price of water as an essential input to production. Therefore, data on water consumption by sector is required to set this value (benchmark value of water equals water use (in volumes) multiplied by the price of water for each sector) (Juana et al., 2012).

When water is treated as an intermediate input, the value represents the cost of water in producing goods and services. Without adequate data, specifying the appropriate production function specification and estimating the water's benchmark value can be challenging. Thus, this section analysed the water price estimation techniques used by the reviewed applications (Fig. 12).

Most of the reviewed applications (62 applications) obtained the price of water from local or national data sources (prices set by regulatory authorities or administratively set prices). They assumed that the price is determined by market equilibrium. This assumption implies that the value does not reflect the true price of water paid by all sectors. For example, sectors that abstract water are often licenced and not charged (Das et al., 2023). There are also cases where water prices are heavily subsidised for sectors such as agriculture, so the prices they pay are much lower than market prices (Fadali et al., 2012). This estimation method can be useful as a starting point for analysis; however, a modeller must critically evaluate underlying market conditions in cases of any distortion in water markets.

Another case is to assume a functioning market and estimate the value of water from the value of land (16 applications). The theory behind this technique is that the value of land depends on soil quality and the water within (Berrittella et al., 2007; Calzadilla et al., 2014). Therefore, an estimation of water 'rent' is possible by splitting land into 'pure land', and then implicit water rent (marginal productivity of water) is estimated from the share of water rent in total production costs (A. Calzadilla et al., 2013; Calzadilla et al., 2014, 2011; Osman et al., 2019; Zeshan and Shakeel, 2020). However, this water assumption is only valid for the agriculture sector and not for industrial sectors that use water from piped supplies or other sources (Harou et al., 2009).

Another method employed by global water-CGE models reviewed (6 applications) is to assume that there is no water market in the baseline and that the water supply is in surplus; hence, water price is zero in the benchmark (e.g., Berrittella et al., 2008, 2007). Under different water scarcity scenarios, water gains economic rents as a product of price signals (Ponce et al., 2012). While this review previously established that there is limited literature on the economic values of water for all sectors in an economy, assuming that the price of water is zero in the benchmark is a serious understatement, one which does not reflect the

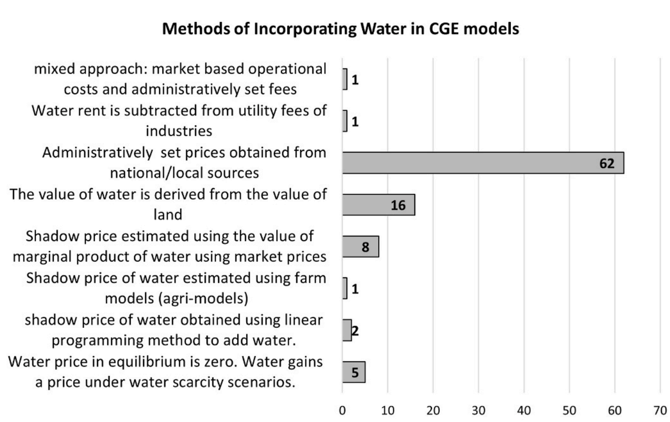

Fig. 12. Methods of incorporating the benchmark value of water into a CGE model from the reviewed applications.

competitive market price for water (Bardazzi and Bosello, 2021). On the other hand, this assumption captures the mechanism required if water is not scarce.

12 reviewed applications estimate the shadow price of water when the market price does not equal shadow prices. Shadow prices are used as a proxy value for water, representing the value of an additional unit of water (Bryant, 2022). These prices can be estimated using the sectoral marginal value of water from market prices to calibrate the SAM (e.g., Juana et al., 2012, 2011, 2008). This method adjusts the water use and output, as well as output and input prices, to equilibrium. In dynamic CGE models, the shadow price of water may vary over time, reflecting policy interventions or the effects of water scarcity on prices. However, only one dynamic water-CGE model application estimated the shadow price of water to simulate the effects of climate change (Goodman, 2000).

A less common method to estimate the shadow price of water for each sector is to use a linear programming method derived from an input-output framework (2 applications). The solution to the maximisation problem subject to water resource constraints along with other constraints gives the shadow price of water, which is then multiplied by the volume of water consumed by each sector to obtain the economic value of water for each sector (e.g., Feng and Duan, 2005).

Lastly, one application found by this review estimates the shadow price of water for crops using a FARM (Future Agricultural Resource Model) model. A FARM model is a micro-model that estimates the shadow price of water for crops, representing the marginal value of water in agricultural production by deriving profit functions subject to land and water constraints (Dinar, 2014). This would represent the additional value produced by using one additional unit of water in crop production.

4. Modelling challenges and avenues for future research

This systematic review analysed 100 applications of water-CGE models to identify potential ways to improve water's methodological and theoretical representation in CGE models. This review points to a range of potential developments in the modelling of water in CGE models that can enhance the value of these models: increasing the accessibility and quality of water data and thereby providing a basis for calibrating CGE models; incorporating water as an explicit factor of production; accounting for seasonality of water in CGE models to highlight the changing dynamics of water resources; conducting analyses using smaller spatial scales (i.e., regional, and river basins) to capture regional variations; and improving transparency of calibration procedures and validation methods. Finally, this review suggests future research agendas for extending the utility of water-CGE models.

Several literature reviews on water in CGE models contend that the main reason for difficulties in realistically representing water in CGE models is the limited availability of data that include information on water uses by sectors of an economy by source or type of water and other important hydrological information (i.e., water accounts) (Calzadilla et al., 2016; Hertel and Liu, 2016; Ponce et al., 2012). After comprehensively analysing the different methodological features of current applications (section 3.2 (Results of Methodological Analysis)), this review reaches two conclusions on the issue of the availability of water data. First, to some extent, adequate amounts and detail of water-related data exists (Larsen et al., 2019). This is seen in the relatively large number of applications reviewed (100) using water data obtained from different data sources such as national statistical offices, international databases, and municipal reports. Second, this review acknowledges that the challenge with water data often discussed in related literature is the lack of detail and quality.

Extending CGE models to include water resources that accurately capture the role of water in the economy studied requires water data must provide detailed mapping of availability, withdrawals, and usage by all economic sectors by all water sources in volumetric prices to be able to modify national accounts (SAM) to include water. As this review finds in section 3.2, most CGE models struggle with including large numbers of industrial sectors and a total number of sectors. The inclusion of different energy sectors in water-CGE models has been underrepresented despite being one of the largest water consumers in an economy (Jin et al., 2019). Other data gaps relate to including more than one source of water used by the economy, particularly waste and reused water, and water pricing, subsidies and tariffs.

The nature of methodological challenges varies across regions and applications. In China, where the largest concentration of studies has been conducted, applications cover a variety of spatial scales, from national and regional to multi-regional and river-basin analyses, including both agricultural and industrial-focused CGE models, with an increasing number focusing on energy. This diversity reflects the availability of detailed irrigation and industrial water-use data that allows for an explicit modelling of water as a factor of production. By contrast, applications in Sub-Saharan and South-Asian contexts more frequently highlight data constraints, as these models often rely on international databases such as GTAP, which are based on estimations rather than detailed data of individual (Ponce et al., 2012). Consequently, these studies are primarily agricultural-focused, reflecting both the structure of the GTAP model and dataset where water is combined with land in an aggregate nest, and the limited availability of water-use data in these regions.

Complementary to and a by-product of the challenge of data is the realistic representation of water in CGE models. Specifying water as an explicit factor of production in CGE models requires data on the real value of water, information on the income generated by water and the income distribution among economic agents is required to specify water as a factor of production (Bryant, 2022). However, due to the lack of efficient operating markets for water, accurately finding this information poses a formidable challenge. Therefore, it is unsurprising that relatively, a small number of applications use this specification in their models (Fig. 10). This is consistent with other literature reviews' findings that indicate a deficiency in this specification (Bardazzi and Bosello, 2021; Calzadilla et al., 2016; Hertel and Liu, 2016).

Further modelling developments relate to the seasonality of water (Graveline, 2016). Accounting for seasonality enhances the temporal realism of the models by reflecting the changing patterns in water availability and economic activities throughout the year, which is particularly important for sectors such as energy and agriculture that are significantly affected by seasonal variations. However, the reviewed literature neglects the seasonality of water and its impacts on demand and prices within a year (intra-annual), including both agricultural and energy (hydropower) focused water-CGE models, as none of the applications used sub-annual timesteps (months or quarters) in their models to reflect these seasonal changes (Table 3).

A major issue due to temporal aggregation is that the impacts of seasonality on production activities are undetected, and the models cannot assess the impacts of unforeseen disruptive events that occur within short periods during the year such as natural disasters (Amaya et al., 2021). A potential solution to incorporate seasonality into water-CGE models involves intra-year temporally disaggregating IO tables that have been augmented with environmental extensions (Avelino, 2017). This method allows for the effective connection between time-varying variables such as water resources and the economic structure, enabling the assessment of water resource fluctuations that occur within a year.

Another opportunity to further develop these models is to work at finer spatial scales. Although the models can adapt to various spatial resolutions to capture geographic variations in water use and environmental conditions, this review finds that most reviewed applications are aggregated at the country level (Table 3). Country-wide CGE models can demonstrate, at a macro-level, water use patterns interactions between water resources and economic sectors that allow for an analysis of various water-related policies. However, at this spatial level, the models might suffer from aggregation bias[3] as most economic and hydrological data are captured at the national level (Graveline, 2016). This is an important limitation as water resource availability and policies are often heterogeneous across a region. Depending on the research questions, future research employing water-CGE models needs to consider working on a regional and multi-regional level.

Water-CGE models can be adapted to river basin spatial scales, although it is necessary to carefully review the availability of water data and elasticities. Applying water-CGE models to river basins is recognised to be the appropriate spatial scale to address water-related challenges (Bekchanov et al., 2017) since river basins inherently involve upstream and downstream linkages. Moreover, many river basins play a crucial role in hydropower generation (i.e., Kahsay et al., 2015) and are vulnerable to climate change, which makes them ideal spatial scales for climate resilience studies (Expósito et al., 2020).

Finally, many studies adapt their model structures from standard CGE frameworks, but with limited transparency in the calibration process, such as not providing the model's equations, which makes it difficult to evaluate their robustness and reproducibility. Additionally, despite the fact that validation in CGE models is crucial for ensuring computational accuracy, data reliability, theoretical data consistency, and realistic economic behaviour representation (Dixon and Rimmer, 2013), almost none of the reviewed applications report formal validation.

Analysing the literature on water-CGE models based on thematic criteria allowed for identifying future research priorities for extending the utility of these models. In particular, future research needs to strengthen the integration of WEF nexus modelling within CGE frameworks and account for uncertainty to enhance robustness and policy relevance.

Although CGE models are well-suited for analysing and integrating all components of the WEF nexus, there has been limited research on this topic. The modelling of water-food (agriculture) is frequently addressed using these models, but the water-energy component is underdeveloped. Bardazzi et al. (2024) is an isolated example of methodology for integrating all components of the nexus into CGE models.

Assessing uncertainty is a crucial aspect for advancing CGE modelling, especially in environmental applications. CGE models are deterministic, with fixed parameter values and equilibrium responses that might not fully represent the effects of an exogenous shock to an economy. Several methods exist for incorporating uncertainty into CGE models, such as the Systematic Sensitivity Analysis (SAA) (Phimister and Roberts, 2017), and recent developments using stochastic optimisation models proposed by Giannelos et al. (2025), which demonstrates how endogenous and exogenous uncertainty can be integrated into power system planning.

5. Conclusions

This SLR examined 100 applications of water-CGE models to analyse recurring themes and gaps, as well as to identify potential improvements for water's modelling representation in these models. Notably, these models have been frequently used for climate and policy-relevant questions, such as changes in water availability, and water management and savings policies. The models provide a comprehensive assessment of the economy-wide consequences of water-related questions through an integrated framework. However, this depends on the assumptions and simplifications regarding how water is incorporated into the models' structure that are required for computational abilities and data availabilities. Given the methodological aim, this review moves

[3] Spatial aggregation bias occurs when data is aggregated and averaged across spatial units, leading to an oversimplification of the models' representations of the interactions between water and the economy, potentially neglecting regional variations.

beyond a summary of findings to a critical appraisal of the modelling tools used in existing applications, proposes methodological improvements, and identifies gaps in existing literature to support advancements in both academic research and policy development. It synthesises modelling practices across diverse geographic and policy context, which reveal how data availability, institutional practices and modelling transitions shape the evolution of modelling applications.

The literature analysis reveals limitations that future SLRs can address. First, this paper acknowledges the importance of analysing the assumptions about the degrees of substitutability between water and other factors of production, whether low or high. For instance, in a case where there is water scarcity in agricultural-focused models, were the factors of production mobile indicating an off-setting reaction in the form of growth in a less water-intensive industry as labour moves from agriculture to other industries? Second, this review focused only on applications that included hydropower as an energy sector in CGE models. Consequently, it is not possible to analyse how modellers captured water use across different energy sectors. Finally, the current review does not analyse simulation themes in the CGE models but focuses on the main aim of the paper.

CRediT authorship contribution statement

Saba Al Hosni: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Scott J. McGrane:** Writing – review & editing, Validation, Supervision. **Gioele Figus:** Writing – review & editing, Validation, Supervision. **Cecilia Tortajada:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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