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REVIEW

Macroeconomic modeling of water resources: Conceptual and methodological challenges in CGE frameworks

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Abstract

Water scarcity is increasingly recognized as a systemic economic constraint, with impacts that extend far beyond directly water-using sectors. Computable General Equilibrium (CGE) models constitute a powerful tool for capturing the indirect and structural effects of water scarcity across interconnected markets, yet their application to water resources poses distinctive conceptual, methodological, and data challenges. This paper reviews how water has been conceptualized and operationalized within CGE models, focusing on the treatment of water scarcity, allocation mechanisms, and economic valuation under conditions characterized by weak or missing price signals. Rather than providing an exhaustive catalogue of applications, the analysis compares alternative modelling strategies—embedding water in land, treating water as an independent production factor, representing water implicitly through productivity effects, and modelling water as a produced commodity—highlighting their respective advantages, limitations, and suitability for different policy questions. The review shows that no single approach dominates across contexts: implicit representations are often sufficient for climate-impact assessments, whereas explicit formulations are required to analyse water markets, allocation rules, and infrastructure investments. A central challenge across all approaches is the fundamentally non-market nature of water, which complicates calibration, pricing, and the interpretation of economic rents. Additional difficulties arise from spatial and temporal heterogeneity, basin-level constraints, return flows, and water quality differentiation, which standard CGE structures struggle to represent. The paper also shortly discusses recent advances in hybrid modelling frameworks that couple CGE models with hydro-economic models (HEMs). The paper concludes by outlining key directions for future research, emphasizing the need for improved water accounts, dynamic and seasonal modelling, and closer integration between economic and hydrological modelling communities.

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1. Introduction

Water is a scarce economic resource with competing demands across production and consumption sectors, yet comprehensive studies of its system-wide effects remain limited [1,2]. While recent research has focused on the Water-Energy-Food-Environment (WEFE) nexus [3–10], this approach fails to capture how water availability affects the broader economic structure, including non-water-using industries. Countries facing water scarcity may tend to specialize in relatively less water-intensive activities, engaging in "virtual water trade" [11–17], although empirical evidence shows that institutional and trade factors can offset pure resource-based comparative advantages [14].

Computable General Equilibrium (CGE) models are particularly suited to this task, as they simulate entire economies through interconnected markets and sectors, tracing the ripple effects of policy changes or external shocks across the economic system [18]. CGE parameters are typically calibrated using national accounts. However, as already discussed in Calzadilla et al. [19], conventional national accounts do not report sectoral water use because they focus exclusively on monetary transactions.

In this respect, the progressive development of environmental and “green” accounting frameworks—most notably the System of Environmental-Economic Accounting (SEEA)—has significantly improved the availability of physical flow information. In parallel, global databases such as GTAP and WIOD have incorporated environmental satellite accounts, including data on water withdrawals and consumption [20–22]. Over the past decade, these datasets have become increasingly consistent and spatially disaggregated, enabling more accurate calibration of water-augmented CGE models and facilitating the reconciliation of physical and monetary units. Nevertheless, substantial gaps remain, particularly with regard to water quality differentiation, return flows, and basin-level consistency.

Modeling water within CGE frameworks presents distinctive challenges. Because national accounts record only market transactions in monetary terms, they fail to capture water use when it is freely available (e.g., rainwater) or priced below its scarcity value. This creates fundamental modeling problems: if water is priced at zero, the optimal quantity becomes indeterminate; if it is artificially underpriced, models tend to generate unrealistically high consumption levels.

Furthermore, water acquisition often operates outside market mechanisms. Rainwater availability depends on climatic conditions, while irrigation water is administratively allocated. Under rationing, optimization generates implicit shadow prices reflecting water’s true economic value, but these remain external to CGE equilibrium conditions driven by explicit market prices. Moreover, water-related economic rents become embedded in profits, land values, or capital payments, making it difficult to isolate water’s value. When water availability lacks allocation rights, its impact manifests through productivity effects, requiring estimation of industrial productivity responsiveness to water supply variations.

While comprehensive reviews of CGE water applications exist [3,19,23,24], this paper focuses on how water is conceptualized and operationalized within CGE frameworks. We compare explicit, implicit, and hybrid water representations, assess how they address pricing, allocation, scale, and data constraints, and discuss recent advances in hybrid frameworks coupling CGE models with hydro-economic models (HEMs) that combine economy-wide consistency with explicit hydrological processes.

The paper proceeds as follows. Section 2 discusses methodological approaches to integrating water into CGE models, along with modeling challenges and data requirements. Section 3 reviews selected applications illustrating how different modeling choices yield distinct policy insights, discussing recent advances in hybrid modelling frameworks that couple CGE models. Section 4 concludes with lessons learned and future research directions.

2. Integrating water resources into CGE models: Key aspects

The integration of water resources into macroeconomic models has evolved significantly over the past several decades, reflecting both advances in economic theory and growing recognition of water's critical role in economic development. Early economic models treated water as a free good or external input, largely ignoring its scarcity value and economic significance. Contemporary CGE approaches employ diverse methodological frameworks, each with distinct advantages, limitations and data requirements.

2.1 Modelling choices

The integration of water resources into CGE models has evolved through several distinct methodological approaches, each reflecting different conceptual understanding of water's role in economic systems. In contrast to earlier surveys [3,19], this review explicitly identifies the main water-modelling approaches implemented in the CGE models, describing their main characteristics, identifying advantages and limitations, as well as areas of ideal applications (Table 1). More in detail, building on earlier classifications proposed in Calzadilla et al. [19], we refine the taxonomy of water representations in CGE models by explicitly distinguishing between (i) implicit productivity-based representations, (ii) water embedded in land, (iii) water as an independent primary factor, and (iv) water as a produced commodity. The addition of the fourth category reflects more recent developments that model water services as outputs of dedicated production activities, thereby allowing explicit representation of infrastructure, treatment costs, and source differentiation.

The simplest approach treats water as an implicit factor of production, essentially a "hidden" input that affects productivity without being explicitly modeled in production functions [e.g., 1,25–28]. Under this methodology, changes in water availability translate into variations in multi-factor agricultural productivity, using elasticity parameters typically borrowed from agronomic studies. Reduction in water availability are converted in lower production volumes using a set of elasticity parameters, which express the percentage change in yield, ceteris paribus, for 1% increase in water delivery. These parameters are employed to translate changes in water availability for agriculture into changes in agricultural productivity. While this approach avoids some of the technical challenges associated with explicit water modeling, it sacrifices the ability to analyze water-specific policies or market mechanisms directly.

The earliest and perhaps most intuitive approach treats water as a factor of production combined with land [e.g., 29–34,43]. This methodology reflects the empirical reality that water rights are commonly attached to land titles, meaning that the market value of land implicitly incorporates the value of associated water resources [31,43]. When economists attempt to model water explicitly using this approach, they essentially extract the water rent component from total land rents, then model water as a distinct production factor while maintaining its fundamental connection to land resources. This approach is consistent with institutional settings where water rights are historically linked to land ownership and offers the advantage of relatively simple calibration when irrigation and land-use data are available. However, it provides limited flexibility for analyzing water-specific policies, intersectoral water transfers, or non-agricultural water uses. As a result, it is typically confined to crop production and makes it difficult to explicitly represent household water demand or environmental flows. This approach is therefore best suited to applications focused on irrigated agriculture, land-linked water rights, and analyses of virtual water trade embodied in crops.

Table 1. Methodological approaches to integrate water into macroeconomic models.

Approach - Water as:	Main characteristics	Advantages	Limitations	Ideal applications	Main references
1. Implicit input	- "Hidden" input not explicitly traded - Scarcity enters via productivity/yield shocks - Crop water-yield elasticity parameter drawn from agronomic/hydrologic evidence	- Low data and modelling requirements - Useful for broad climate-economy assessments	- Cannot analyze explicit water policies (prices, markets, rights) - Typically confined to crop yields (limited coverage of households and ecosystems)	- Climate change impact studies - Scenarios where water markets/prices are absent and policy is not water-specific	- Roson and Sartori [1] - Koopman et al. [25] - Roson and Damania [26] - Dudu et al. [27] - Taheripour et al. [28]
2. Embedded in land (water–land composite) or other factors	- Water tied to land - Water value inferred from land rent - Often implemented for irrigation	- Consistent with land-linked water rights - Relatively simple calibration when irrigation data exist	- Limited flexibility for water-specific policies and inter-sectoral transfers - Typically confined to crop production - Difficult to represent households/environment explicitly	- Irrigated agriculture - Land-linked water rights - Virtual water trade focused on crops	- Berck et al. [29] - Seung et al. [30] - Calzadilla et al. [31]; - Taheripour et al., [32] - Hertel and Liu [33] - Aragie et al., [34]
3. Independent factor	- Water as separate primary factor - Allocation across sectors possible - Can include environmental flows and municipal/industrial uses	- Enables analysis of water markets, quotas and shadow pricing - Supports inter-sectoral reallocation - In principle can cover non-ag uses	- May not match institutional land-water constraints - Requires water accounts by sector - Non-agricultural uses still often simplified in practice	- Water scarcity policies - Economy-wide impacts of allocation rules - Sectoral transfers - Drought scenarios	- Decaluwé et al. [35] - Goodman [36] Gomez et al. [37] - Horridge et al. [38] - Berrittella et al. [39] - Diao et al. [40] - Luckmann et al. [41]
4. Produced commodity	- Water services produced by activities (abstraction, treatment, conveyance, desalination, reuse) - Multiple water types/sources can be differentiated - Final and intermediate demand can be modelled	- Natural way to represent alternative sources and costs - Can incorporate households and industry alongside agriculture - Clarifies links to energy and capital requirements	- Highly data-intensive (engineering, costs, losses, tariffs) - Requires assumptions on utility regulation/market structure	- Alternative water sources - Water-utility pricing and investment - Integrated WEFE assessments - Urban–rural competition	- Luckmann et al. [41,42]

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An alternative methodological approach separates water entirely from land, treating it as an independent factor of production [e.g., 35–41]. This strategy allows for more flexible analysis of water-specific policies and market mechanisms, since water can be allocated independently of land use decisions. Such models prove particularly valuable when examining water markets, inter-sectoral water transfers, or policies that specifically target water use rather than broader agricultural land use patterns. The separation of water from land also enables analysis of non-agricultural water uses, including industrial processes, municipal consumption, and environmental flows. Nonetheless, this approach may not always align well with institutional constraints that tie water access to land, and it requires detailed water accounts by sector and region. In practice, non-agricultural uses are still often represented in a stylized manner due to data limitations.

Beyond treating water as a primary factor of production, Luckmann et al. [41] conceptualize water as a produced commodity, supplied by specific activities such as abstraction, treatment, desalination, and distribution. In this framework, "effective water" is generated using capital, energy, and raw water inputs, and is subsequently demanded by productive sectors and households. This approach offers several advantages: it facilitates the modelling of water infrastructure investments, quality differentiation, and cost-reflective pricing mechanisms, and it allows water use to be represented beyond agriculture. At the same time, this approach is highly data-intensive, requiring detailed engineering information on costs, losses, tariffs, and infrastructure, as well as assumptions about the regulation and market structure of water utilities. It is particularly well suited to the analysis of alternative water sources, water-utility pricing and investment decisions, integrated WEFE assessments, and urban–rural competition for water resources.

Each methodological approach carries distinct advantages and limitations that make it more suitable for specific types of analysis. The choice between approaches often depends on the research questions being addressed, the availability of relevant data, and the institutional context of water management in the study region. Models focusing on broad climate change impacts might appropriately use implicit modeling approaches, while studies of water market design require explicit representation of water as a tradable factor.

2.2 Modelling challenges

The incorporation of water into economic models confronts several fundamental challenges that distinguish water from conventional economic inputs. Table 2 summarizes the main challenges and the modelling responses most commonly adopted in the literature.

As discussed in Calzadilla et al. [19], perhaps the most significant challenge stems from the fact that water is predominantly a non-market good, making it impossible to estimate marginal productivity parameters through standard calibration techniques used for other production factors. Most observed water transactions involve payments for distribution and treatment services rather than compensation for the water resource itself. This creates a fundamental mismatch between the economic value of water as a production input and its observed market price, which is often close to zero, as much agricultural water comes from rainfall or direct groundwater extraction at virtually zero cost to the user. From a modelling point of view, this makes the integration of water into standard economic models problematic: a freely available production factor should be consumed in infinite quantities and may create theoretical inconsistencies. Further, even when water is

Table 2. Key conceptual challenging in integrating water into CGE models.

Challenge	Description	Typical modelling approaches	Main References
1. **Non-market allocation and missing scarcity prices**	- Water is often allocated through administrative rules, historical rights, or quotas rather than markets. - Existing tariffs frequently reflect average costs instead of marginal scarcity value.	- Quantity constraints with endogenous shadow prices. - Modelling water rights with associated rents. - Explicit water-supply sectors capturing abstraction and delivery costs.	- Taheripour et al., [32] - Luckmann et al. [41] - Hertel and Liu [33] - Aragie et al. [34]
2. **Physical scarcity vs. “free availability”**	- Even when water is unpriced, supply is constrained by hydrology, infrastructure, regulation, and conveyance capacity. - Treating water as freely available can produce unrealistic use quantities.	- Explicit physical availability constraints (e.g., supply functions, infrastructure costs). - Modelling water-supply activities with energy, capital, and operating and maintenance costs.	- Calzadilla et al. [31,43]
3. **Heterogeneous uses and the withdrawal–consumption–return distinction**	- Water withdrawals differ from consumptive use, as part of the water may return to the system, often with reduced quality. - Many models focus mainly on irrigation, under-representing other uses.	- Separate accounting of withdrawals and consumptive use. - Inclusion of return flows. - Modelling wastewater treatment and reuse.	- Calzadilla et al. [19] - Luckmann et al. [42] - Dunn et al. [44]
4. **Water quality and multiple water sources**	- Economic impacts depend on water quality and the availability of alternative sources (e.g., groundwater, desalination, treated wastewater).	- Differentiation of water by type and quality. - Modelling transformation processes such as treatment, desalination, and conveyance.	- Berrittella et al. [39] - Diao and Roe [45] - Tirado et al. [46] - Sahlén [47] - Luckmann et al. [41,42]
5. **Spatial heterogeneity and boundary mismatches**	- Hydrological boundaries rarely coincide with administrative regions used in CGE models, complicating the representation of basin-level scarcity and policy.	- Spatially disaggregated CGE models. - Basin-based SAMs. - Coupling CGE models with basin-scale hydrological or HEM modules.	- 42 - Basheer et al. [48] - Valle-García et al. [49]
6. **Temporal dynamics and seasonality**	- Water availability varies seasonally and across years due to climate variability and storage. Static models are inadequate for analyzing droughts or long-term adaptation.	- Recursive-dynamic CGE model. - Seasonal time steps. - Integration with hydrological models.	- Aragie et al. [34] - Valle-García et al. [49]

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freely available, physical water supply is fundamentally constrained by natural hydrology, storage, infrastructure capacity (e.g., reservoirs, canals, pumps), and regulatory or institutional restrictions. If water were modelled as free and unlimited, the model would predict unrealistically high water use and fail to capture the real economic and environmental impacts of water scarcity. In this sense, physical scarcity means recognizing that even if water has zero market price, its supply is not infinite and that scarcity has economic consequences that need to be modelled explicitly. This is a key reason why advanced CGE water models include explicit supply functions or constraints tied to physical availability and infrastructure costs rather than assuming free availability [e.g., 31].

The conceptual challenges are not limited to pricing. As stressed by Calzadilla et al. [19], they extend to fundamental questions about what constitutes water "consumption" versus water "use". In many applications, water is used without being consumed in any meaningful sense. Household wastewater can be recycled for agricultural irrigation, creating grey water systems that challenge traditional input-output relationships. Similarly, only a small fraction of irrigation water reaches plant roots, with the remainder either evaporating or percolating back into soil and groundwater systems. Industrial cooling water is returned to its source, albeit at elevated temperatures, while navigation uses require water presence rather than consumption. Many applications restrict attention to consumptive irrigation use, which is often justified by agriculture's dominant withdrawal share, but this leaves household demand, industrial uses and environmental flows under-represented. Fewer analyses include separate accounting of withdrawals and consumptive use, inclusion of return flows, and the explicit modelling of wastewater treatment or reuse [42,44].

Water quality considerations add another layer of complexity that most CGE models struggle to address adequately. Water is decidedly not a homogeneous commodity, and quality variations can dramatically affect its suitability for different uses. Water quality heterogeneity further complicates model design. As discussed by Calzadilla et al. [19], water is not a homogeneous commodity, and several CGE applications introduce a dedicated "water sector" that transforms raw water into effective water suitable for productive or household uses [e.g., 35,39,45–47]. More recent modelling efforts extend this logic by differentiating multiple water sources (surface water, groundwater, desalinated water, reclaimed wastewater, see [41,42] and by linking production costs to energy and capital requirements. While conceptually appealing, such representations are highly data-intensive and often require stylized assumptions on infrastructure efficiency and regulatory settings. An additional and often underappreciated challenge concerns the mismatch between natural hydrological boundaries and political or economic jurisdictions. Water availability and flows are determined at the level of river basins and aquifers [e.g., 48,50], while economic decisions and policies operate within administrative borders. This scale mismatch complicates the representation of water constraints and governance in CGE models and limits their ability to capture transboundary impacts and coordination failures. To overcome this limitation, recent studies have increasingly relied on hybrid modeling frameworks that combine CGE models with hydro-economic models (HEMs). By explicitly representing hydrological processes and basin-level water allocation within an economy-wide framework, these hybrid approaches allow for a more consistent treatment of spatial water interdependencies and institutional fragmentation, improving the analysis of transboundary water management and policy coordination (further discussed in Section 3). A related and still insufficiently addressed issue concerns temporal and climatic heterogeneity. As noted in earlier reviews [19], most CGE models represent annual equilibria at relatively aggregated spatial scales. Under this structure, water is implicitly treated as temporally homogeneous: seasonal snowmelt, monsoon rainfall, and stored reservoir water are modelled as equivalent inputs once aggregated to annual totals. Seasonal variations in water availability and demand create complex storage and allocation problems that annual equilibrium models struggle to capture. Similarly, the spatial distribution of water resources within regions is typically ignored, despite significant variations in water quality, accessibility, and economic value across different locations. While earlier CGE applications largely treated water as a static endowment, more recent work has introduced dynamic, spatially disaggregated and infrastructure-based representations to address these conceptual limitations. For example, Valle-García et al. [49] address this limitation through explicit coupling with hydrological modules. However, fully integrating intra-annual variability into economy-wide equilibrium models remains an open research challenge.

Overall, these challenges highlight the limits of standard CGE structures when applied to water-related questions. While a variety of modelling strategies exist to address individual issues, no single approach fully resolves the disconnect between physical water systems and economic market functioning.

2.3 Data collection and parameters

Economic data dealing with water are scarce and fragmented. For instance, agricultural water use is often estimated rather than directly measured. Industrial water use may be reported to environmental agencies for regulatory purposes, but this data is rarely integrated with economic production statistics. Municipal water systems typically maintain detailed records, but these focus on treatment and distribution costs rather than economic value generation.

In this context, the development of water satellite accounts represents a significant advancement in data availability [20,22]. These accounts extend traditional economic accounting frameworks to include physical flows of water, enabling the calculation of water intensity coefficients for different economic sectors. Price data for water resources remains, however, particularly challenging to obtain and interpret. Where water markets exist, they are often thin and may not reflect broader economic values. Water pricing schemes frequently incorporate cross-subsidies and non-economic objectives, making it difficult to extract information about marginal values. Shadow pricing techniques, derived from optimization models or econometric analysis, provide alternative approaches to valuation, though these require strong assumptions about underlying economic relationships.

Recently, remote sensing technology has revolutionized the availability of water-related data, particularly for agricultural applications [51]. Satellite-based measurements of precipitation, soil moisture, and crop water use provide spatially explicit information that can be integrated with economic data to develop regional models. The challenge lies in translating these physical measurements into economically meaningful variables that can inform policy analysis.

The temporal dimension of water data presents additional complications. Water availability varies significantly across seasons and years, while economic production decisions may be based on expectations of long-term average conditions. Climate change adds another layer of complexity, as historical relationships between water availability and economic outcomes may not persist in the future.

Overall, data constraints do not simply limit empirical implementation but shape modelling choices in CGE applications to water. Improvements in water accounting, pricing information, and the integration of physical and economic data are therefore essential for advancing the robustness and policy relevance of macroeconomic models of water resources.

3. CGE applications and hybrid modelling frameworks

This section reviews selected applications of CGE models to water-related issues with the specific purpose of illustrating how different representations of water translate into distinct policy insights across scales, regions, and institutional contexts. Rather than providing an exhaustive survey, the discussion emphasizes common patterns and lessons that emerge from existing applications, linking empirical evidence to the modelling choices outlined in Section 2.

A consistent finding across CGE studies is that water scarcity generates economy-wide effects that extend well beyond directly water-using sectors. Constraints on water availability affect relative prices, factor allocation, trade patterns, and income distribution, reinforcing the relevance of general equilibrium approaches for water policy analysis. At the same time, the magnitude and channels of these effects depend critically on how water is represented within the model.

At the global scale, CGE applications have primarily focused on the interaction between water scarcity, climate change, and international trade. These studies typically rely on implicit or factor-based representations of water and show how differences in water endowments shape comparative advantage, sectoral specialization, and virtual water trade flows [e.g., 33,39,52,53]. While well suited to analysing trade and climate impacts, these approaches provide limited insight into the design of water-specific policies such as pricing or allocation rules.

At regional and basin scales, CGE models are often applied to economies where water scarcity directly constrains production in agriculture, industry, or urban services. These applications highlight how water shocks propagate through local economies, affecting employment, income, and welfare even in sectors that do not directly use water [54,55]. Studies focusing on investments in desalination or wastewater reuse typically adopt more explicit representations of water, often treating it as a produced commodity supplied by water-related activities [41]. These models are better suited to evaluating infrastructure investments and urban–rural competition for water, but they require substantially more detailed data and assumptions.

Despite the progresses made in the modelling approaches so far discussed, a correct representation of the physical water system remains a limitation of CGE models. Hydrological constraints, basin-level processes, spatial heterogeneity, and seasonal variability are difficult to model explicitly within standard CGE structures. Hydro-Economic Models (HEMs), by contrast, constitute a complementary modelling class that explicitly integrates hydrological processes with economic decision-making [56]. By integrating hydrological balances, infrastructure capacity, storage dynamics, and operating rules with economic objectives, HEMs are particularly effective for analysing reservoir management, drought response strategies, inter-sectoral allocation under binding physical constraints, and investment decisions in infrastructure such as desalination or wastewater reuse, including their energy and capital requirements [57,58]. Their strength lies in their ability to reflect the physical reality of water systems and the trade-offs faced by water managers.

The main weakness of HEMs is their limited representation of the broader economy. Because they typically focus on specific basins and a restricted set of sectors, they may overlook important general-equilibrium effects such as economy-wide price adjustments, factor reallocation, trade responses, and distributional impacts across households and regions. As a result, policy evaluations based solely on HEMs may underestimate or misrepresent second-round and rebound effects [57,59].

In this regard, CGE models and HEMs are therefore best viewed as complementary, where HEMs provide physically consistent water supply and allocation responses, while the CGE component translates these into economy-wide impacts. In a recent contribution by Valle-García et al. [49], a basin-scale HEM determines water availability, allocation, and shadow values under explicit physical constraints of the Guadalquivir River Basin, while a regional or national CGE model propagates these shocks throughout the economy, providing a more comprehensive basis for water policy analysis.

Such integration is particularly relevant in the context of the water–energy–food nexus. HEMs can be particularly valuable for representing the water–energy linkage associated with pumping, treatment, desalination and storage operations, and for quantifying the reliability and timing of water supply that underpins agricultural production and ecosystems. Conversely, CGE models can capture how these physical changes translate into welfare, trade and structural change.where water scarcity interacts with energy production, agricultural output, and ecosystem services [3,60–62].

4. Discussion and conclusions

This paper has reviewed how water resources have been incorporated into Computable General Equilibrium models, with the specific aim of clarifying the conceptual choices, methodological trade-offs, and unresolved challenges that arise when modelling water at the macroeconomic level. Rather than cataloguing applications, the analysis has focused on how different modelling strategies conceptualize water scarcity, allocation mechanisms, and economic value in contexts characterized by weak pricing signals, institutional constraints, and strong spatial and temporal heterogeneity. Compared to earlier reviews, recent contributions over the past decade show a gradual shift from relatively stylized representations of water scarcity toward more structurally explicit frameworks. In particular, there has been increasing emphasis on modelling water services as produced commodities with infrastructure, treatment and conveyance costs, on differentiating water sources and quality, and on coupling CGE models with basin-scale hydrological or hydro-economic modules. These developments reflect a broader effort to reconcile economy-wide consistency with the physical and institutional realities of water systems, moving beyond static endowment representations toward more spatially, temporally, and institutionally grounded approaches.

The review highlights that no single modelling approach dominates across all research questions. Approaches embedding water in land, treating water as an independent factor, modelling it implicitly through productivity effects, or representing it as a produced commodity each offer distinct advantages while imposing important limitations. The choice among them depends critically on the policy questions being addressed, the institutional setting of water management, and data availability. Models designed to assess broad climate or productivity impacts may rely on implicit representations, whereas analyses of water markets, allocation rules, or infrastructure investment require more explicit and data-intensive formulations.

A central challenge that emerges across all approaches is the fundamentally non-market nature of water. Administrative allocation, missing scarcity prices, return flows, quality differentiation, and basin-level constraints all complicate the integration of water into equilibrium frameworks calibrated on monetary transactions. While shadow pricing and quantity constraints provide partial solutions, they do not fully resolve the disconnect between physical water scarcity and the price signals driving economic decisions in CGE models. These difficulties are further compounded by mismatches between hydrological boundaries and administrative regions, as well as by seasonal and interannual variability that static models struggle to capture.

The review also emphasizes the complementary role of Hydro-Economic Models. HEMs offer a more realistic representation of hydrological processes, infrastructure, and basin-scale allocation, but lack the ability to trace economy-wide feedbacks, trade effects, and distributional consequences. Recent advances increasingly point toward hybrid CGE–HEM frameworks as a promising direction, combining physical realism with macroeconomic consistency. Such coupled approaches allow water constraints to be grounded in hydrology while still capturing the broader economic adjustments that are central to policy evaluation.

Looking forward, further progress in the macroeconomic modelling of water will require advances along several dimensions. Improved water satellite accounts and the integration of remote sensing data can enhance calibration and spatial resolution. The latter can be integrated into CGE models by improving the calibration of sectoral water coefficients, by informing productivity–water response functions, or by spatially disaggregating water endowments at basin level. Seasonal dynamics can be incorporated through recursive-dynamic specifications, intra-annual time steps, or soft-linking with hydrological modules that provide seasonal water availability constraints. Dynamic and seasonal extensions of CGE models can better reflect climate variability and adaptation processes. Finally, closer integration between economic and hydrological modelling communities is essential to develop frameworks that are both economically coherent and physically meaningful.

As water scarcity intensifies under climate change and competing demands from agriculture, energy, industry, households, and ecosystems grow, the need for robust economy-wide assessments of water policies becomes increasingly urgent. CGE models, especially when combined with hydrological modelling, remain a powerful and evolving tool for informing water governance, investment decisions, and the management of trade-offs within the water–energy–food–ecosystem nexus.

Author contributions

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