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Vertical fit of water governing systems: A regional assessment

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ABSTRACT

To promote environmentally sustainable water governance, this study emphasizes the necessity of aligning institutional structures with ecological scales. The research focused on the Urmia Lake Basin in Iran facing the serious problem of drying up. Beyond the political and economic determinants shaping the water governance system in the region, the study evaluated the effect of Urmia Lake Restoration Program (ULRP), an environmental movement, on the basin's water governance structure. Employing statistical mechanics methods to scrutinize Hamiltonian system costs related to administrative interactions for water supply-demand, the study assessed the structural fit of the water governance system to the basin across distinct stages: without- and with-including the ULRP. Results revealed diminished costs following ULRP involvement, notably in entities with higher water demands, head offices and the system overall, further improved by water-saving measures. These findings highlighted the efficacy of vertical (re)arrangements and structural reform through ULRP incorporation in enhancing system fit, stressing the significance of its water-saving policy. The methodology provides a fast and explicit scan of the system structure, demonstrating its ability to project the effect of institutional reforms on the system state. Serving as a constructive tool for policymakers, it facilitates rapid, efficient and informed decision-making in water governance. Furthermore, following the UN SDG 6, this framework supports integrated water resources management (IWRM) across sectors and regions, particularly targeting water-stressed contexts.

1. Introduction

Water conservation is closely intertwined with its governance (Furlong and Bakker, 2011). In recent times, the urgency of protecting water resources has been greatly intensified due to climate change (Altieri et al., 2015). Challenges associated with water governance, for instance, referred to as the global water crisis (WWAP, 2016), are closely linked to its conservation efforts. This connection is further underscored by the conventional association of water governance with developmental and environmental objectives in diverse regions (Hirsch, 2006). To this end, developing countries still face crucial challenges to achieve environmental conservation objectives, despite a generally upward trend evident in developed countries (Postel, 1984). According to Woodhouse and Muller (2017), water management reforms at the national level have been recently agreed upon in the European Union, Australia, and South American countries, specifically Mexico, Chile, and Brazil, as well as in South Africa. Regrettably, some rapidly developing economies like China and India have continued with the business as usual approach without appropriate environmental considerations. The business-as-usual approach is present in post-growth economies, including the US. However, there is a remarkable divergence in the form of a substantial investment in environmental protection. In Turkey, where the water management system is subject to politicization and centralization, the same trend prevails, yet with limited emphasis on

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environmental requirements. A comparable situation exists in Iran, where the centralized water management system is influenced by political interests (e.g. Ketabchy, 2021; Ghorbani et al., 2021). Moreover, there, water scarcity exacerbates the issue, presenting challenges in regulating water supplies during increased demands (Zehtabian et al., 2010). Consequently, the water governance arena in Iran is confronted with specific hurdles in managing the balance between developmental objectives and environmental measures (Arjomandi A., 2023).

Generally, in Iran water governance systems are unaltered, and early water governance systems did not address the impacts of climate change, as the latter emerged relatively recently. There, regional governance systems were established with inadequate provisions for water and environmental objectives and now face severe climate change challenges (Nouri et al., 2023). Thus, many Iranian regions may face significant pressures unless they make the necessary adaptations (Rahimi et al., 2023). This stagnation issue can be linked to the level of environmental awareness within the governance system itself (e.g. Pahl-Wostl, 2017; Nguyen et al., 2021; Nelson, 2022) and/or the objectives other than environmental preservation that take preeminence over them (e.g. Schulz et al., 2017; Sultana and Loftus, 2019). Failure to consider the environmental dimension in the design of (water) governance systems can have serious repercussions (Camkin and Neto, 2016); thus, understanding the problems arising from the poor fit of the institutional and biophysical scales is fundamental if the natural resource management systems (NRMS) are to be properly restructured (e.g. Epstein et al., 2015; Rubiños and Del Carpio, 2022).

One of the most dramatically affected environments in northwestern Iran is the Urmia Lake Basin (ULB), where, in addition to human-related risks, the survival of specific species and endangered creatures is severely threatened (Parsinejad et al., 2022; Schulz et al., 2020). There, deficiencies in water governance, climate change, and other factors in recent decades have substantially impacted the lake's volume, resulting in serious ecological consequences (Esmailzadeh et al., 2023).

The governance issue relates to decisions at the institutional scale levels, mainly aligning with political agendas and not principally concerned with the environment (Saatsaz, 2020), that affect water flows in the basin. Such issues, referred to as problems of fit (Folke et al., 1998), highlight spatial externalities and inefficiencies at the hydrological and institutional scales (e.g. Cash et al., 2006; Young, 2006; Moss and Newig, 2010; Daniell and Barreteau, 2014; Whaley, 2022). The concept of the problem of fit speculates that the effectiveness of institutions depends on how well they align with the biophysical domains in which they operate (Young and Underdal, 1997). Therefore, identifying problems of fit can help with the design of more effective water governance systems at the institutional and hydrological scales.

To enhance the ecological fit of the governance system and address environmental concerns in the region, the government set up the Urmia Lake Restoration Program (ULRP) in 2013–2022. This action was to strengthen the management of water resources in the basin with the ultimate goal of revitalizing Iran's largest wetland (Shadkam et al., 2020). The ULRP implemented institutional restructuring to restore the lake, resulting in an alternation of the water governance system structure in the region (Salimi et al., 2019). Given the largest water consumption in the agricultural sector, the plan aimed to provide tailored support and coordinate agricultural water management initiatives within the basin according to the government's newly confirmed environmental protection goals (Sima et al., 2021). The ULRP was a vertical provision above the provincial level, by a national-level committee to dictate and supervise the implementation of related policies and to oversee water requirements at the regional level. While the success of such a movement can depend on various factors such as setting it up in time, its function was expected to improve the fit of (political-)administrative system with biophysical system.

In order to assess the impact of such a structural reform, this study aimed to investigate the use of a newly introduced framework for evaluating the fit of water governance systems (Arjomandi A. et al., 2022). As its specific property, this method can overcome the challenges posed by varying scales, levels, parameters, and dimensions inherent in water governance realm. Such complexities may hinder the assessment of the efficiency of water governing systems (Cash et al., 2006). Another benefit of this approach is the ability to quickly determine the state of the system by scanning its structure. The method utilizes a theoretical computational tool called the (Hamiltonian) system cost function to monitor the effects of institutional interactions and forces on managing the water supply-demand process within the governing body. The (Hamiltonian) system cost, in this case, serves as a conceptual measure to quantify the impact of administratively authorized interactions and externally imposed forces on the operation of the water supply-demand process in the basin. This method adopts concepts of Statistical Mechanics (Lagrange, 1811; Hamilton, 1834; Lagrange, 1855; Boltzmann, 1872; and Gibbs, 1902) for Hamiltonian formulation of the water governance system. Although some methodologies have proposed solutions for distinguishing problems of fit by incorporating supranational environmental legislation (e.g. Moss, 2003; Moss, 2012) or national and local institutional resources (e.g. Thiel and Egerton, 2011; Herrfahrdt-Pähle, 2014; Hack, 2015), they do not provide a rapid scan of the system structure, including a theoretical measure (unitless quantity), while overcoming the scales and levels hurdle, for evaluating system fit.

Thereupon, to investigate the influence of ULRP on the structural fit of the water supply-demand governing system to the ULB (spatial scale level) during a certain period (temporal scale level), the Curie–Weiss mean-field model (Curie, 1895; Weiss, 1907), a statistical mechanics approach, was employed. This model is widely utilized to create frameworks for studying interaction-based socioeconomic models (e.g. Durlauf, 1996; Durlauf, 1999; Guerra, 2005; Contucci et al., 2008; Gallo and Contucci, 2008; Kochmański et al., 2013; Seyedi, 2015; Deger and Flindt, 2020; and Bovier et al., 2021).

Correspondingly, the (Hamiltonian) cost of the governance system was estimated based on the three states: (i) without including the ULRP, (ii) including the ULRP, and iii) after the setting up of the ULRP along with the implementation of its water-saving policy. These cases adopted a simulated approach to highlight: (i) the existing system structure and (ii) the system structure after the inclusion of the ULRP in the Urmia Lake Basin water governance system. By comparing the resulting costs and the issues associated with their setup, the appropriateness of each of the system structures was analyzed and discussed. To the best of the authors' knowledge, no study to date has explored the effect of vertical institutional reforms in water governance systems using such methods. Even though a similar approach was recently taken by scholars in the realm of water governance to explore spatial (horizontal) fit issues (Arjomandi A. et al., 2022), there is still a lack of evidence for applying modeling to study the effects of (vertical) institutional arrangements on water governance systems' fit at hydrological scales. Hence, utilizing this method, to discover the effect of the recent goal of ecological revival of Urmia Lake—as well as the previous security, political, and economic objectives—on the appropriateness of fit of the water governance system in the region, this study aimed to explore the associated structural fit before and after the restoration goal. Ultimately, the study aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6, by introducing a framework that helps foster cross-sectoral and cross-regional collaboration for sustainable water and ecosystem management, covering multiple aspects of Integrated Water Resources Management (IWRM).

2. Problem statement

2.1. The case study region (spatial scale level)

The Urmia Lake Basin was selected as an appropriate region for the purposes of this study as, in addition to climate change effects, human-caused water and environmental problems have been frequently reported (e.g. Karami, 2018; Amini, 2019; Schmidt, 2021; Pouladi et al., 2021).

Urmia Lake—the world's second-largest hypersaline lake before it started drying up—is an endorheic lake in northwest Iran, a UNESCO-protected biosphere and a recognized wetland under the Ramsar Convention (Nhu et al., 2020). Urmia Lake has been reported to have a maximum area of 5000–6000 km^2 and an average depth of 5–6 m (Sabbagh-Yazdi et al., 2020). Due to the effects of climate change and human practices, the lake experienced a sharp decline in size between 1995 and 2003, accompanied by a fairly stable/positive period around 2005 (2003–2007) then with a fast shrinking trend from 2008 (e.g. Danesh-Yazdi and Ataie-Ashtiani, 2019; Hosseini-Moghari et al., 2020; Sabbagh-Yazdi et al., 2020).

The Urmia Lake Basin is 52,000 sq.km in size and has around 6.5 million inhabitants (Bakhshianlamouki et al., 2020). There, land has been used for agricultural and animal husbandry for millennia (Azizi and Rezalou, 2020). The agricultural sector, utilizing about 94% of the total water available in the basin (MOE, 2013c), stands as the primary consumer, critically affecting the lake's condition (Schulz et al., 2020). After that, the drinking water and industrial sectors use around 5% and 1%, respectively, ranking second and third in water consumption. In this context, there is a controversial debate as to how to balance environmental and (agricultural) development needs (Shadkam et al., 2016).

2.2. Political, security, and administrative arrangements

Following the early political and legal division of the region in 1958 (Chehabi, 1997), the basin is now surrounded by the three Iranian provinces of East and West Azerbaijan and Kurdistan (Fig. 1).

This division was initiated at a time when accurately predicting future climatic conditions was not feasible. It was primarily designed with a major focus on security (Etaat and Nikzad, 2016), in line with the development of policy and administrative mechanisms for managing resources and providing services within provincial boundaries. Along with this, the passage of the 'Water Independence of Provinces' law in 2005 led to the breakup of regional water authorities into independent provincial companies (Nabavi, 2017). Consequently, the water governance scheme transitioned from a regional and basin level to a provincial level. This passage initiated the emergence of the problems of fit within the basin (Arjomandi A., 2023).

Fig. 1. Urmia Lake and its surrounding provinces; East Azerbaijan: yellow, West Azerbaijan: Green, and Kurdistan: blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As a result of this political and administrative transformation, the authority for water supply and demand falls under the provinces with the local utilities in different areas of each province trying to service the water needs of various sectors within their jurisdiction (Fig. 2). To manage the water supply–demand initiatives, special administrative offices are located in capital of each province here called head offices. Then, there are three distinct head offices associated with the drinking, industrial, and agricultural (water) sectors in the main city of each province. Based on administrative and legal rules and regulations, promoted by political security sights, the local entities of a province could almost never request water from each other or from the entities of other provinces.

The security policy aims to employ restrictive control mechanisms (Almond and Genco, 1977) both horizontally and vertically within the governing system structure. Its purpose is to limit interactions among entities within specific spatial jurisdictional boundaries (i.e. provinces) for water supply-demand by setting up administrative interaction routes, following particular rules. This provision's goal is to push the governing system dynamism toward determinism (Almond and Genco, 1977).

Thus, the water supply–demand interactions took place only between a local entity and its relevant head office in a given province. According to the Iran Ministry of Energy report (MOE, 2014) at the time of analysis, the water supply-demand governing system in the region comprised the entities of (i) West Azerbaijan province, encompassing 14 local utilities and one head office, (ii) East Azerbaijan province, comprising 12 local utilities and one head office and (iii) Kurdistan province, consisting of one local utility interacting administratively with a head office that was not located in the hydrological scale of the basin (Fig. 2). In order to exclude this horizontal unfit issue in the same spatiotemporal scale level (Arjomandi A. et al., 2022), in this study, the only entity of Kurdistan province within the Urmia Lake Basin was

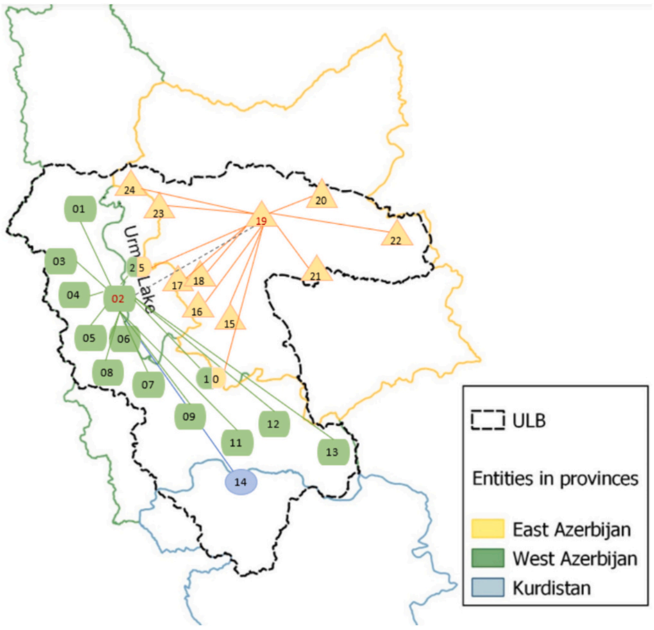

Fig. 2. The schematic map of the entities within the relevant provinces of the Urmia Lake Basin: yellow, green and blue colors represent the entities of East Azerbaijan, West Azerbaijan, and Kurdistan respectively. These entities are denoted by their assigned numerical codes, corresponding to specific geographical zones in the ULB, as reported by Iran Ministry of Energy (MOE, 2014). To this end, each of the Entities 10 and 25 were split in two eastern and western entities based on their administrative-jurisdictional affiliations to the East and West Azerbaijan provinces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reasonably assumed to interact with the team of West Azerbaijan province in the evaluation model. In fact, in the institutional hierarchy, the provincial-level entities are above the local-level entities.

2.3. Economic and developmental impacts

Throughout the 1980s and especially the 1990s, successive administrations emphasized agriculture as the central axis of Iran's economic development (Ehsani, 2006). This vision could result in a substantial allocation of resources to the agricultural sector to enhance Iran's self-sufficiency in strategic food production (Ehsani, 2006). Indeed, such political and economic objectives manifested as agricultural development could influence institutional and biophysical measures of water demand and supply, such as the allocation or supply of more water to extend agriculture (Nabavi, 2017). Based on this strategy, the expansion of water wells and the construction of dams for the benefit of the agricultural sector were exceptionally increased. According to Bashirian et al. (2020), the quantity of wells increased from 55,199 to 106,200 from the 1980s to 2017, and the number of dams grew from one in 1970 to 56 by 2017. Additionally, while the dams' capacity expanded from 197.8 to 1758 MCM, the water level in the lake decreased from 1278.5 to 1270.5 m during this period. On the other hand, this plan coincided with the severe and prolonged droughts that occurred toward the end of the 1990s (Golian et al., 2015), and implanted major problems thereafter (Nabavi, 2017). Schulz et al. (2020) concluded that agricultural extraction has had a considerable impact on the lake's resilience, amplifying the general trend of decreasing lake volume, specifically in the last two decades.

Nonetheless, adhering to regional development concepts, the politically favored construction of a causeway over the lake, devoid of adequate environmental considerations, led to the division of the lake into northern and southern subbasins (Henareh Khalyani et al., 2014). This causeway construction, in fact, disrupted water exchange between the lake's north and south, ultimately causing increased evaporation and impacting the overall volume of the lake (Esmailzadeh et al., 2023).

In addition to the natural factors such as climate change and droughts, the convergence of these factors, along with other determinants contributing to the lake's shrinkage, the identification of which overshadows the aim of this study, initiated substantial environmental issues in the region.

2.4. Environmental problems

Schmidt et al. (2021) outlined that the drying out of the lake will have significant effects on social, economic, health, and environmental issues in the region. The drying is causing a prevalence of hot summers and dry winters, which is environmentally disastrous (Delju et al., 2013). As a result, there is a danger of more saline dust being created with noticeable impacts on the health and livelihoods of inhabitants in the region (e.g. Maleki et al., 2018; Samadi et al., 2019; Ženko and Menga, 2019; Dehghani et al., 2020; Mohammadi Hamidi et al., 2022; Feizizadeh et al., 2022). The increase of cardiovascular, skin, and/or respiratory diseases have already been noted (Mohammadi et al., 2019). A decline in soil quality for farming and livestock disease has also been reported (Feizizadeh et al., 2021). Such issues can also have side effects such as the escalation of immigration, more jobless/unemployed people, health/land treatment costs, as well as reduction in income and living standards and loss of hope. Hamidi et al. (2021) have reported 17 environmental consequences of the fluctuations in the water levels of Urmia Lake.

2.5. Problems of fit

The geographical areas in which humans have developed their societies have been influenced by human-made systems with their diverse objectives. Commonly, such objectives have been shaped by social, political, security, economic, or other human-related factors which, either consciously or unconsciously, have been viewed as more important than environmental requirements. Consequently, biophysical cycles have been affected by the dynamics of human systems all over the world (e.g. Goudie, 2018; He and Silliman, 2019; Steinfeld et al., 2020). Climate change is now pushing societies to overhaul their systems to make them more environmentally friendly (e.g. Huntjens et al., 2012; Stefanakis et al., 2021; Seddon et al., 2021). This means that the problems emerging due to the mismatch between the natural and human-developed systems need to be distinguished (Ahlström et al., 2021). This controversial issue, known as problems of "fit" conveys the inadequacy of the fit of human-made systems to the biophysical systems at spatiotemporal scales (e.g. Folke et al., 1998; Cash et al., 2006; Moss and Newig, 2010; Daniell and Barreteau, 2014; Pahl-Wostl et al., 2021). According to Moss and Newig (2010), if levels of government and administration do not fit the environmentally relevant scales, this can result in institutional inefficiencies and spatial spillovers.

Within the ULB, in addition to the problem of horizontal fit of the water governance structure associated with the political-spatial division of the region, there may also be problems of vertical fit (Arjomandi A. et al., 2022). These issues are predominantly linked to the interplay of political and economic factors, resulting in a transition of the water (supply-demand) governance approach from a regional and basin level to a provincial responsibility. As a result, each province focused solely on meeting its water needs by satisfying the water requirements of the disparate sectors under its jurisdiction, without regard to the ecological needs of the basin. This became particularly contentious when the region experienced a huge increase in water demand due to the agricultural development plan. Such differentiated water management scheme led to neglect of the environmental well-being of the lake, reflecting the problem of institutional fit within the ULB in addressing the ecological requirements of the lake.

2.6. Institutional and environmental developments

The alarming circumstances of Urmia Lake obliged the government of Iran to implement special provisions to restore it (Saemian et al., 2020). Restoring the lake as an environmental policy objective (under the political shell of presidential election pledge in 2013) can be seen as a balancing factor for the economic policy objective of agricultural development. With this in mind, the Urmia Lake Restoration National Committee (ULRNC) founded the Urmia Lake Restoration Program (ULRP), a tool of the executive branch, which began its mission in 2013 (Salimi et al., 2019). The task of the ULRP was to uphold the new objectives laid down for the lake and to oversee environmental protection within the provinces surrounding it.

Nikraftar et al. (2021) indicate that the ULRP was designed to preserve the ecology of Urmia Lake in three stages, (i) stabilization, (ii) restoration and (iii) final restoration. The key target of this program, in fact, was the ecological revival of the lake via integrated water management with a strong emphasis on sustainable agriculture in the basin (Bakhshianlamouki et al., 2020). The prime aim was to bring about a 40% reduction in the water allocated to the agricultural sector. This showed recognition on the part of the government of the prevalent environmental risks along with various socioeconomic, political, health, and other consequences (e.g. Schmidt et al., 2021; Zucca et al., 2021). The implementation of the ULRP communicated the strength of environmental policy objectives, interlinking to the water and environmental risks, in (re)structuring the governing systems of the region in addition to the risks previously considered, namely the economic and/or security issues.

Institutionally, the ULRP was situated above the provincial-level entities and was given greater authority (Salimi et al., 2019) over water allocation, particularly for the ecological needs of Urmia Lake and also with respect to water demand from different sectors. Hence, the activities of the head offices of the various sectors dealing with water supply and demand were under the supervision of the Monitoring and Evaluation Body of the ULRP. This gave the latter a mediating role in terms of water supply and water demand rates.

Based on the administrative hierarchy, only these head offices—and not the local utilities—were allowed to interact directly with the ULRP. The ULRP had two main representatives in the capital of the West and East Azerbaijan provinces; these are called, respectively, the ULRP-W and ULRP-E. There were thus two ULRP units interacting with the head offices of the different sectors. Consequently, after the establishment of the ULRP, the existing structure of the water governance system within the basin was transformed by the inclusion of the two additional entities at the institutional-vertical level above the provincial organizations (head offices), with the main authority (ULRP) above all the entities (Fig. 3).

2.7. Analysis timeframe (temporal scale level)

This study investigated if the arrangements to restructure water supply-demand governing system based on the establishment of the ULRP to define the new goal of reviving the Urmia Lake was promising at the time of analysis. Therefore, the emphasis was directed only on the system state during the analysis period. To this end, a temporal scale level, the year 2005, was targeted as the analysis time. In fact, aside from having the pertinent official data (MOE, 2012, 2013a, 2013b, 2013c, 2014, and 2015) for the purpose of the analysis, the year 2005 was stressed as a critical milestone in the distinguished stages of water resource development in the region (Shadkam, 2017). The significant development of reservoir capacity and irrigation area in the region started around 10 years prior to 2005. The adverse effects of these developments, coupled with growing evaporation loss and droughts in that period, led to the explicit shrinkage of the lake starting later on (Shadkam, 2017).

Applying several methods, Schulz et al. (2020) identified that between approximately 2004 and 2013, despite a substantial rise in the capacity of reservoirs and surface water consumption for irrigated agriculture in the basin, there was no specific alteration in the trend of precipitation. To this end, however, they reported that in the vicinity of 2005, the lake's volume experienced a notably stable period. It appears that the water management administration has failed to seize this prominent opportunity to implement revitalization measures, resulting in a rapid decline starting in 2008 (Danesh-Yazdi and Ataie-Ashtiani, 2019; Hosseini-Moghari et al., 2020). Furthermore, the law that was passed in 2005, Water Independence of Provinces, led to changes in the water governance structure in the region. This dispensation of authority from a regional and basin level to a provincial level impacted the water supply-demand initiatives (Nabavi, 2017). Thus, even though the ULRP was established in 2013, the research aimed to explore if such institutional implementation might have been helpful in 2005 (Fig. 4) when the shrinkage of Urmia Lake was slight, having increased over time since then (Hosseini-Moghari et al., 2020).

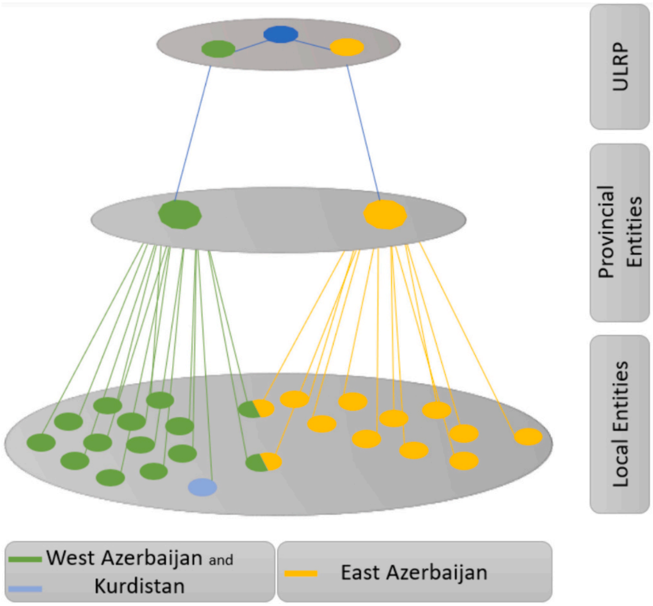

Fig. 3. The hypothetical vertical hierarchy of the water governance system after the establishment of the ULRP: the first layer includes the entities of ULRP, comprising the main authority (dark blue), ULRP-W (green) and ULRP-E (yellow); the second layer encompasses the head offices of the West (green) and East (yellow) Azerbaijan provinces; and the third layer includes the local utilities of West (green) and East (yellow) Azerbaijan provinces, besides the local entity of Kurdistan province (sky blue) which is assumed to interact with the head office of West Azerbaijan province for its water supply-demand. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.8. Study aim

Detection of problems of fit can lead to the design of human systems that are more in harmony with environmental circumstances. For evaluation and identification of fit-related issues, scholars have suggested pragmatic solutions through the introduction of supranational environmental legislation or national and local institutional resources (e.g. Moss, 2003; Moss, 2012; Thiel and Egerton, 2011; Herrfahrdt-Pähle, 2014; Hack, 2015; Haque and Doberstein, 2021). Although the methodologies have been beneficial in recognizing the problems of fit at relevant scales/levels, they were not able to quickly show several system states within one window; this has meant that any comparisons made for detecting the most suitable system structure have had to rely on the status quo. Arjomandi A. et al., 2022 proposed a framework based on the Hamiltonian system cost to explore such problems. This is a computational approach which helps identify a fitter (administration) system structure for a given hydrological scale level based on the system cost. Using this method, it is feasible to overcome the intricacies stemming from the issue of multiple scales and levels in the realm of water governance. The asset of this methodology lies in its ability to enable the analyst and the decision-maker to simultaneously and immediately capture the feasible fitter governance structures of for an ecological system. In fact, given the existing or feasible conditions, the fittest systems are those resulting in the lowest costs. Incorporating the framework, this study has tried to establish a twofold innovative approach regarding the assessment of the fit of the water governance system to the Urmia Lake Basin with the inclusion of the ULRP: first, to gauge the effect of vertical (institutional) reforms associated with the regulation of the ULRP and its water-saving policy on the structural fit of the water governance system; second, to experiment the potential merit of the method for this assessment.

3. Methodology

3.1. Model and scenarios

The Hamiltonian formulation offers a framework for describing physical system dynamics through a mathematical function, the Hamiltonian (Thompson, 1979). When applied to social systems, it creatively adapts physics concepts to human interactions and societal dynamics (Durlauf, 1996). This comprehensive function, captures the energy of social systems (e.g., water governance) and considers elements such as the behavior of social entities (e.g., administrative) and societal structures (e.g., political-administrative).

To represent the dynamic state of a system, Hamilton formulated total energy as the sum of the kinetic and potential energies in the system (Hamilton, 1834). This structure reveals all the physical information of a system along with the external forces acting on it. In fact, the

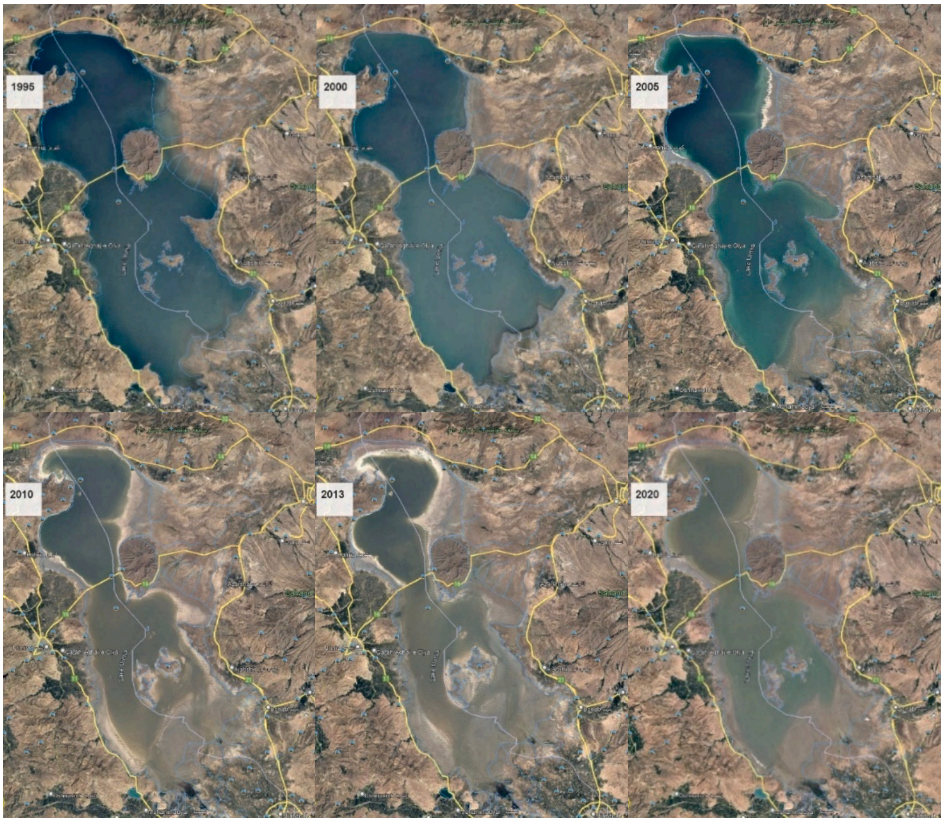

Fig. 4. Urmia Lake satellite images during the years 1995, 2000, 2005, 2010, 2013, and 2020, Landsat (Google Earth Pro).

Hamiltonian system formula determines the true dynamic trajectory between the initial and final configurations over a fixed time period by identifying the least measure of all possible true trajectories within the system (Cline, 2017). Generally, in modern mathematical physics, statistical mechanics methods (Gibbs, 1902), like Hamiltonian one, explore the macroscopic behavior of systems emerging from microscopic interactions on the part of their components. Through mean-field theory, such methods can convert many population problems into simpler forms (e.g., one or two populations) allowing their global behaviors to be studied much easily (Seyedi, 2015; and Contucci et al., 2017). To this end, the Curie-Weiss mean field method was exploited to study the population-wide characteristics in human networks (e.g. Arthur et al., 1997; Mantegna and Stanley, 1999; Contucci and Ghirlanda, 2007; Castellano et al., 2009; Kusmartsev, 2011; Barra et al., 2014; Contucci et al., 2017; Agliari et al., 2018; and Contucci and Vernia, 2020), decision-making (e.g. Ortega and Braun, 2013; and Bensoussan et al., 2013), management (e.g. Braha and Bar-Yam, 2007), politics (e.g. Meyer and Brown, 1998) and other fields. One of the most widely used families of these theoretical mean-field approximations is the multi-population extension of the Curie-Weiss model (Fedele et al., 2013). There, the interacting particles (entities) can be recognized based on their binary spins (σ_i) which resemble their trait values. The average effect of binary spins (here called as magnetization) is notable, and this attribute is discussed in the next part.

To elucidate the method for the aim of this study, we assume that an interacting system of N particles (entities) is generally Hamiltonized with uniformly binary random spins (trait values), as

$$H_N(\sigma) = -\frac{J}{2N}\sum_{i,j=1}^{N}\sigma_i\sigma_j - h\sum_{i=1}^{N}\sigma_i, \tag{1}$$

where (h) is similar to the influence of the external force resulting from the influence of exogenous factors (such as political security), and (J) represents the interacting positive constant and its value embodies the rate of the nature of interaction (here water supply/demand amounts). Measuring this total greatly increases access to overall system cost (H_N) through the visibility of interaction rates and transparency of exogenous variables.

Corresponding with this concept, the formulation of the water governance system structure (Fig. 5, and section 3.2) was initiated obeying the rules of interaction for water supply and demand (sections 2.2 and 2.6): (i) the local entities can almost never interact with each other, (ii) in a certain province each local entity can almost always interact with its relevant head office, (iii) head offices may contact each other for information, and (iv) sectors should be treated separately.

Three scenarios were conceptualized to evaluate the effects of the ULRP on the water (supply–demand) governing system. In the first scenario, administrative interactions were mapped in two provincial groups, East and West Azerbaijan, including their local water utilities and responsible head offices (see section 2.2). In the second scenario, in addition to the two groups mentioned, a group of vertically positioned ULRP entities was added to the system, that its West and East Azerbaijan representatives (ULRP-W and ULRP-E) act closely with the provincial head offices below them and with the central ULRP entity above them. In other words, the head offices can interact with their relevant ULRP representatives, and the ULRP branches interact with their parent unit (section 2.6).

Nevertheless, to portray the effect of ULRP policy in the agricultural sector associated with a 40% reduction in water consumption, another scenario was considered, and the system state was analyzed accordingly. A third scenario was considered as a complementary condition for the second scenario in which, in addition to the presence of the ULRP, the 40% water-saving policy was also included. This scenario therefore encompassed a 40% drop in water supply-demand rates (FDWSD) in the system after the establishment of the ULRP. Accordingly, the system structures were derived based on the circumstances conceptualized (see

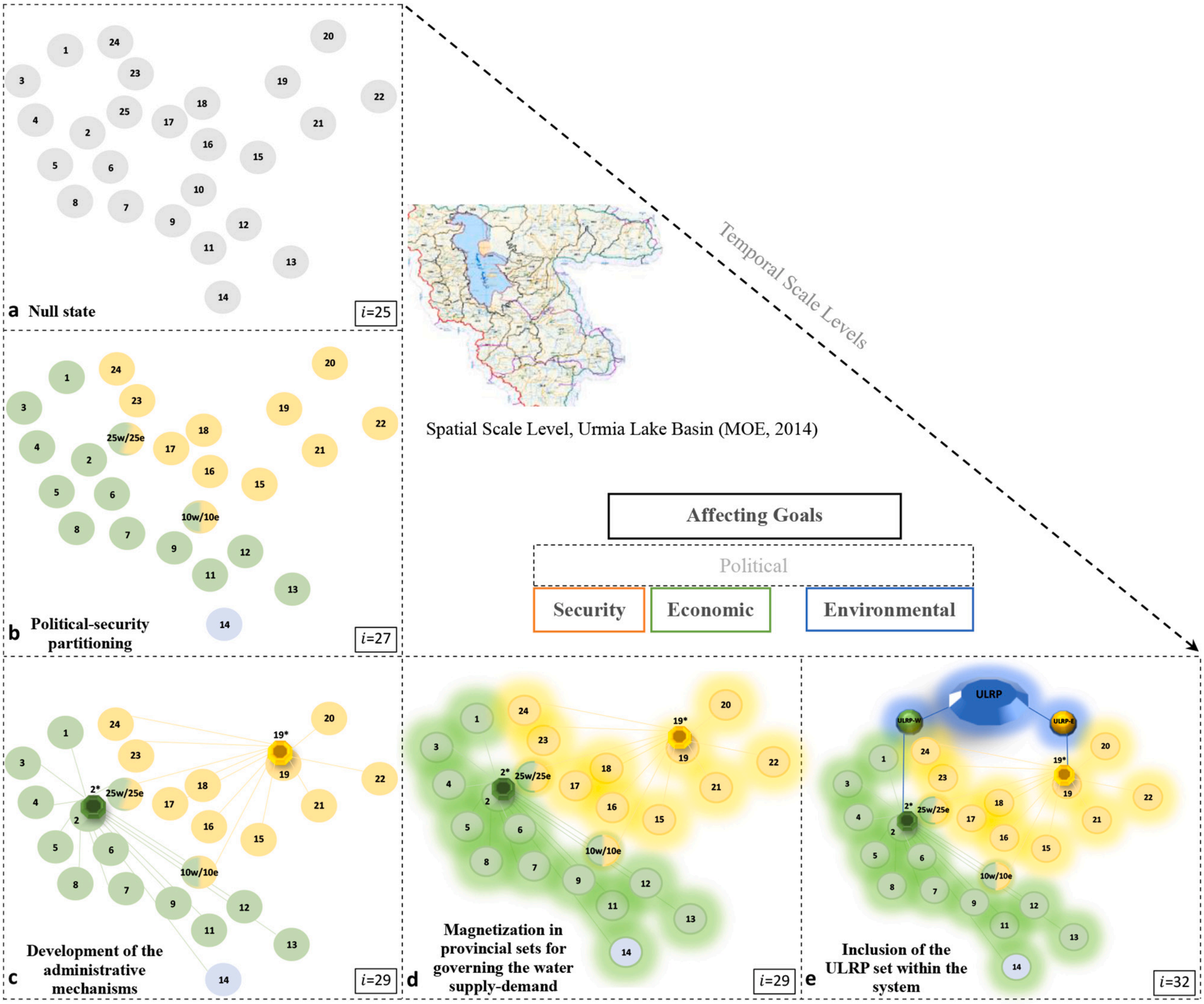

Fig. 5. The evolution of governance mechanisms within the ULB: a) unaffected state, b) political-spatial division of the entities in the basin, c) establishment of political-administrative routes in the provinces according to rules of interaction, d) regulation of water supply-demand under provincial magnetization, e) system reform through the establishment of the ULRP associated with changes in the number of entities and sets.

next section) and the costs of entities and system were estimated based on the scenarios studied.

3.2. *Formulating the concept*

According to the entities' interaction orders based on the first and second scenarios, a binary trait value (σ_i) was set for each player. In this context, the sign of σ_i was inversely adopted between the solicitor (demander) and responder (supplier) entities within their associated community. This provision was deemed to systemize connectivity between them based on the principles of electromagnetic absorption. This was in line with a network analog of Gauss's law that relates a measure of flux through a group's boundary to the connectivity among the group's entities (Sinha et al., 2018). Accordingly, due to the rules of interaction and hierarchy (Fig. 3), the connection was formed between the water-demanding entity (solicitor) and the water-supplying entity (responder) based on the (inverse) values of their association attributes as $\left((\sigma_i, \sigma_j) = (+1, -1) \text{ or } (-1, +1)\,; i,j = 1, 2, \dots, N\right)$.

Despite this, the global configuration of connection attribute values in the system was supported under all scenarios. Literally expanding Eq. (1), the interested mean-field approximation by Curie-Weiss can be summarized as follows:

$$H_N(\sigma) = -N\left(\frac{1}{2}\sum_{i,j=1}^{N}\alpha_i\alpha_j J_{ij} m_i m_j + \sum_{i=1}^{N}\alpha_i h_i m_i\right) \tag{2}$$

where the magnetization of the binary configuration or in other words, the value of the group trait in a social community, is defined by $m_N(\sigma) = \frac{1}{N}\sum_{i=1}^{N}\sigma_i$. The magnetization ($m$), a unique feature that can be observed in the phenomenon of ferromagnetism within ferromagnetic particles, has a counterpart in Curie-Weiss systems of socio-economic interactions (e.g. Barra et al., 2014; Contucci et al., 2017; Seyedi, 2015; Arjomandi A. et al., 2022). Such an average trait value of participants in a countable community has a meaningful relationship with their proportional subset's size α_k, $\alpha_k = \frac{N_k}{N}$ (k is the number of sets). Furthermore, Fedele et al. (2013) have proposed the solution for quantification of the effect of exogenous factors on interactions as the abstract of external forces (h_i) by inverting the abovementioned many-body approximation (Eq. (2)):

$$h_i = tanh^{-1}(m_i) - \sum_{j=1}^{N}\alpha_j\left(J_{ij}\right)m_j \tag{3}$$

To estimate the costs of the system and entities for each scenario, the group trait values ($m(\sigma)$) of distinct sets of each system and the sizes of their proportional subsets (α_k) were calculated based on the entities' trait values (σ_i) subject to the order of the interactions. Then, the water supply-demand amounts of the entities were rescaled to place rational extents admissible in the evaluation device (J_{ij}), and the external forces (h_i) were estimated thereupon (Eq. (3)). Correspondingly, the entities' costs and the eventual cost of the system were estimated in the three states (antecedent and subsequent to the ULRP, as well as following the ULRP plus achieving its FDWSD policy. The system cost is interlinked to the (i) forces of interactions (kinetic) and (ii) external forces (potential) which influence the interactions. Next, the cost function acts as a

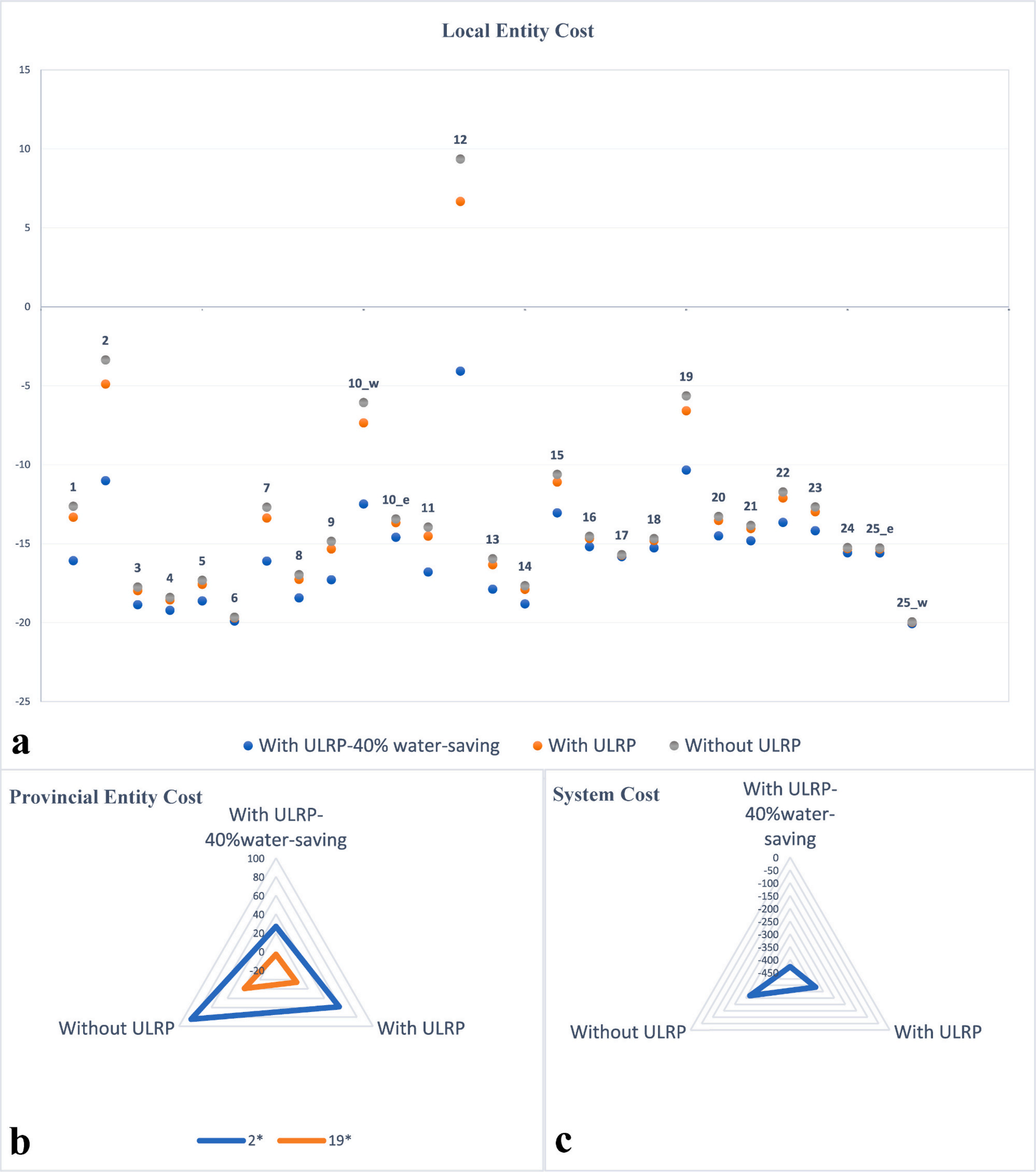

Fig. 6. Panel (a) displays the local entities' cost rates in which the gray dots represent the rates before the inclusion of the ULRP; the orange dots display the rates after incorporation of the ULRP, and the blue dots show the rates subsequent to the ULRP, along with accomplishment of its water-saving policy (FDWSD); the entities are demonstrated by their relevant codes/numbers (MOE, 2014) above the dots. In panel (b) the provincial-level entities' cost rates are shown, with the blue colour representing the values of the head office of West Azerbaijan and the orange colour displays the relevant extents of the head office of East Azerbaijan based on the specified scenarios. Panel (c) depicts the system cost rates based on the concepted scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

theoretical calculation tool to track the system state with respect to formable structures. Using this advantage, in this study, the authors tried to display how the water (supply–demand) governing system cost changes through (vertical) reform of the system structure, and also fulfillment of environmental policy.

4. Results and discussion

In the region, the agricultural sector exhibits the highest water demand rates among various sectors, exacerbating problems of fit in both horizontal and vertical dimensions (Arjomandi A. et al., 2022; Arjomandi A., 2023). On the other hand, the drinking water and industrial sectors consume a very small proportion of the available water (around 6%) within the region and they have priority of supply based on the government's decisions. Hence, in this article, the outputs of the assessment have been disclosed only for the agricultural sector which struggles to have the appropriate institutional fit with respect to its water demand. To give a transparent picture of the effect of the establishment of the ULRP at the institutional scale, specifically in the agricultural sector, the results are shown in three domains. First, the status of the local entities is disclosed in Fig. 6a, then the status of the provincial-level entities in Fig. 6b. Finally, the system state is demonstrated in Fig. 6c.

Consistent with the inclusion of the ULRP which structurally altered the system composition (σ_i, m_i and α_i) as can be diagnosed from Fig. 6a, the local entities' costs tend to decline. In fact, the extent of this decline varies per player. The costs of entities with greater water demands than others, were, however, especially reduced. For instance, the costs of local utilities: 2, 12, 19 and 10_w (see Fig. 2) were decreased by 46%, 29%, 17% and 21%, respectively. This diminishing cost profile on the part of local entities revealed the effective role of vertical reform in supporting their costs. However, these costs have been associated with the magnitude of these entities' interactions along with the extent of external forces that bring about the interactions. In fact, the interaction rates were associated with the volumes of water supply-demand (J) and the related effect of the system configuration on them (αm). Thus, the system structure post-ULRP inclusion was better suited to support the water supply–demand interactions within the system along with the function of external forces.

To this end, external forces are like a set of institutional political forces that attempt to manage the interactions of entities to keep the system dynamic in line with the system's goals. While this improvement in the condition of local entities after the inclusion of the ULRP is impressive, it is still known that local utility 12, is not skewed toward the direction of the local entity costs. This means that its interaction rate associated with the demand rate of this entity is not handled by any of the system formations. In such circumstances, external forces struggle to restrain the interaction of these entities, and this hurdle switches the direction of force to the opposite direction which imposes an additional cost on the system (for more information see Arjomandi A. et al., 2022). Depending on this issue, the situation expressed a space for further modifications in the system structure or water supply-demand rates. While this case is important, it is subjective in terms of the conditions of the case. In this context where water systems are governed based on specific conditions, the best attainable structure may not be reached, but several achievable good structures may be found that are fairly efficient in handling interactions, if water supply-demands are reasonable. To this end, the framework proposes the design of feasible structures that lead to lower costs.

Although the Entity 12 interaction associated with its demand rate is not handled by any of the structures (with/without the ULRP), once the ULRP reduces water supply and demand by 40%, this interaction is dealt with. This attribute shows that the structure of the system including dependent entities fits the interaction rates associated with FDWSD. Such a policy combined with a structural overhaul could result in a cost for Entity 12 which is 1.43 times lower than the cost before ULRP listing. This rate is about five times more than the cost reduction caused just by the structural change with the inclusion of the ULRP (which was 29%). Likewise, to meet this policy, costs for local utilities 2 and 10_w could fall, respectively, by 2.28 and 1.06 times compared to the era before the ULRP, and the Entity 19 could take advantage of an 83% reduction in its cost. Hence, the evaluation body disclosed transparently that local entities of the system can experience better conditions not just by structural reform of the system through the inclusion of the ULRP but also especially by fulfilling its policy.

As a scene, the head offices mode (Fig. 6b) further supported the local entities mode. These provincial-level entities also could experience mitigation in their costs by presence of the ULRP. To this end, the head offices of West and East Azerbaijan (2* and 19*) respectively showed a 31% and 70% reduction in their costs with the inclusion of the ULRP in the system. This improvement was notable and reflected the significant impact of this reform on provincial-level entities that interact with many (local) entities below their level and ULRP entities above their level. Moreover, with FDWSD policy, it is known that head offices can achieve additional cost reductions. In this connection, the West Azerbaijan head office showed a 68% reduction and the East Azerbaijan head office revealed 1.16 times reduction in their costs (relative to the rates without the ULRP). These cost reduction rates are, respectively, 2.18 and 1.64 times more than if there had only been vertical structural reform.

In the end, the cost of the system (Fig. 6c) showed a perceived improvement of approximately 25% by this vertical (re)arrangement. This rate was further enriched through the FDWSD policy. Accordingly, the system cost was reduced by 59% through this policy which is 2.39 times more than the effect of pure structural reform. As can be seen, due to this structural adjustment in the water governance system, there has been an enhancement at all levels of water supply-demand administration. In particular, the provincial-level entities that were handling water demand interactions of local utilities benefited greatly from the reform. Local entities with higher interaction rates also experienced their costs drop considerably. This constructive effect is encouraging in terms of system reform. In addition, FDWSD along with such a structural development, could incorporate a significant improvement in system fit to move the unhandled interaction of Entity 12 into the admitted arena. This means that by a 40% reduction in the volumes of water supply and demand, these quantities enter a standard that can be dealt with by the recent structure of the system.

These attributes, in general, reveal the function of political derivatives in the state of the system that are mediated by security factors (i.e., interaction rules; territorial divisions affecting σ, m and α), economic factors (i.e., agricultural expansion that increases J) and environmental factors (i.e., reviving Urmia Lake which decreases J). However, other political and administrative factors which their investigation can obscure the focus of this study, besides the timely and ad hoc implementation of the applicable environmental regulations may influence help achieve the goal of restoring Urmia Lake.

While this study has provided valuable insights into the real-time structural forms of water governing bodies and their association with political-administrative regulations, it is essential to acknowledge its limitations. Firstly, the study is constrained by the availability of data, which is limited to a specific timeframe. Furthermore, the focus on discussing the current state of political-administrative structure linked to permitted routes for administrative interaction may limit the exploration of potential reforms in alternative designs. To address these limitations, future research endeavors could prioritize the collection of longitudinal data to capture temporal changes and consider incorporating a broader timeframe to ensure a more comprehensive analysis. Moreover, exploring scenarios involving potential alterations in political-administrative rules and their impact on interactions within governing bodies could pave the way for innovative and adaptive designs of water governance structures in the basin. This approach would contribute to a more thorough understanding of the dynamic interplay between political-administrative frameworks and water governance, fostering more fit and responsive systems.

5. Conclusion

Using the tools of mathematical physics, the impact of institutional reforms on the fit of the structure of the water governance system within the Urmia Lake Basin was investigated. The methodology used the statistical mechanics approach to model the structure of the governing system of water supply and demand in the basin. In this context, through a mean-field model, the effect of vertical arrangements on the state of the water governance system was evaluated. To this end, the cost of the Hamiltonian system was calculated in three states related to the status preceding and subsequent to the ULRP, as well as the fulfillment of its water-saving policy. System structures were formulated with respect to interaction rules. The rules were directed through the administrative mechanisms associated with the past and recent goals of the governance system. In this field, the restoration of Urmia Lake as an environmental development program linked to political and ecological goals was placed alongside the initial plans for regional/territorial (geographical) division that met the goals of political security, and agricultural development linked to the political and economic goals in the region. The institutional fit assessment showed that the water volumes (J) which basically can be affected by such goals and policies, can also be affected by vertical interaction rules which (re)form the system structure (αm) and control the interactions for water supply and demand in the system ($\alpha J m$). The outputs of this study phase indicated that the vertical adjustments in the structure of the water governance system in the Urmia Lake Basin during the year 2005, could have been advantageous. Through the establishment of ULRP, the provincial-level entities and in particular, the local entities with larger water demands, could achieve a considerable decrease in their costs. The cost of the system was also reduced.

Besides this structural enhancement, the FDWSD-based evaluation in the agricultural sector agreed to improve the fit of the system after this water-saving policy was met. By accomplishing this policy, all entity interactions were handled by the new system structure, and entities could also experience further declines in their costs. As an important achievement of the combined effect of the vertical structural reform with the inclusion of the ULRP and the accomplishment of its policy in the agricultural sector, the system cost reduction reached more than twice the cost deterioration incurred by implementing only the structural reform. Hence, while the results acknowledged the varying fit of the anthropogenic system to the hydrological system with vertical (re) arrangements, they also indicated the importance of a water-saving policy in the agricultural sector that improves system condition and fit. This finding then communicates the critical relationship between water governance and its conservation, delineating how the latter affects the former. Based on this finding, in a broader perspective, the establishment of effective water governance systems requires not only structural reforms, but also a pivotal shift toward water-saving approaches. Therefore, in order to improve governance systems toward a more ecological fit, reforms should elaborately synchronize the delicate equilibrium between the structural form and the quantity of water supply-demand.

In fact, the analysis focused on the structural fit of the water governance system to distinguish the alteration of this fit through the incorporation of the ULRP and the impact of its agricultural water-saving policy. Basically, the aim of this study was to show the application of the method for assessing the vertical reforms' effect on system fit. Certainly, the success of the ULRP in reviving the lake is related to other determining factors whose identification overshadows the aim of this study and needs wider research. However, the results of this study can impart a kind of utilitarian information for the design of suitable water governance systems by providing a quick scan of the system structures, a rapid conceptual formulation of the feasible forms of systems, and a swift comparison of them to discover the more proper and fit systems based on their costs. Ultimately, the findings of this study can help develop and set productive policies for climate change adaptation and environmental conservation in the area of water management.

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.

Data availability

Data will be made available on request.

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