A review of science-policy interface for water governance in the Caspian Sea postprint

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Abstract

Science and policy have been interlinked for decades and perform essential nexus conditions in the governing aspects of environmental scenarios. This review paper examines the present challenges in the science–policy interface in terms of water governance in the Caspian Sea and identifies effective conditions that may be used in the current context to enhance the mechanism. The evaluation of the science–policy link in the water policy of the Caspian Sea reveals a gap between knowledge producer and governance system, impeding the translation of scientific information into action. Complicated and context-dependent solutions make it challenging to establish effective science–policy processes in the Caspian Sea water governance settings. Establishing a common governing authority, implementing water and resource management regulations, and protecting the natural environment through legal frameworks are crucial steps to address these concerns and ensure sustainable development. Collaboration among coastal states is essential in environmental, economic, and social aspects of regional development. However, the lack of a comprehensive approach, coherent activities, and effective utilization of national and regional power has hindered efforts to halt the environmental degradation of the Caspian Sea. Local governments need to recognize their responsibility to protect and utilize the Caspian Sea for present and future generations, considering both environmental and human security. The interlinkage of the Caspian Sea water governance with the Organization for Economic Co-operation and Development (OECD) water governance principles offers a framework for policymakers to assess gaps and make necessary amendments to existing mechanisms. Effective science–policy interaction, engagement of diverse stakeholders, institutionalizing agreements, and addressing collective action issues are critical for successful water governance.

Full Text

Preamble

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A Review of Science–Policy Interface for Water Governance in the Caspian Sea

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Abstract: Science and policy have been interlinked for decades and perform essential nexus conditions in governing environmental scenarios. This review examines the present challenges in the science–policy interface regarding water governance in the Caspian Sea and identifies effective conditions that may enhance the mechanism. Evaluation of the science–policy link in Caspian Sea water policy reveals a gap between knowledge producers and governance systems, impeding the translation of scientific information into action. Complicated and context-dependent solutions make it challenging to establish effective science–policy processes in Caspian Sea water governance settings. Establishing a common governing authority, implementing water and resource management regulations, and protecting the natural environment through legal frameworks are crucial steps to address these concerns and ensure sustainable development. Collaboration among coastal states is essential across environmental, economic, and social aspects of regional development. However, the lack of a comprehensive approach, coherent activities, and effective utilization of national and regional power has hindered efforts to halt environmental degradation. Local governments must recognize their responsibility to protect and utilize the Caspian Sea for present and future generations, considering both environmental and human security. Linking Caspian Sea water governance with Organization for Economic Co-operation and Development (OECD) water governance principles offers a framework for policymakers to assess gaps and make necessary amendments. Effective science–policy interaction, engagement of diverse stakeholders, institutionalizing agreements, and addressing collective action issues are critical for successful water governance.

Keywords: resource management; Organization for Economic Co-operation and Development; water security; water governance principle; Caspian Sea

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1 Introduction

The Caspian Sea is a unique natural reservoir on Earth as a landlocked body of water located on the border of two major portions of the Eurasian continent and is the planet' s largest inland reservoir (Akhmadiyeva and Abdullaev, 2019). With a surface area of 392.6$×10^{3}$ km^2, its level is 27 m below sea level (Baltic elevation system) (Ragimova et al., 2020). The Caspian Sea has a comparable surface area to the Baltic Sea (387.0$×10^{3}$ km^2) (Yekimov et al., 2021) and is larger than the Adriatic Sea (139.0$×10^{3}$ km^2) (Modabberi et al., 2020). The sea is traditionally divided into three sections based on morphological structure along with physical and geographical conditions: the northern (25%), middle (36%), and southern Caspian Sea (39%) (Akbari et al., 2020). The conditional border between the first and second sections passes through Chechen Island-Cape Tyub-Karagan, while the line connecting the middle and southern Caspian Sea runs from Chilov Island to Cape Gan-Gulu (Ghaffari et al., 2019). The depth of the southern basin, known as the South Caspian Depression (or Lankaran Depression), reaches 1025.0 m, while the average depth is 208 m (Lahijani et al., 2019).

Baku is the Caspian Sea' s largest port and the Absheron Peninsula' s capital city, with a total area of 2130.0 km^2 and a population of about 2.2$×10^{6}$ people (Serykh and Kostianoy, 2020). Other major coastal cities include Rasht (Iran) (Haghighi et al., 2018), Makhachkala (Russia), and Astrakhan (Russia) (Yekimov et al., 2021). Additional coastal cities have populations ranging from 100$×10^{3}$ to 500$×10^{3}$ people (Koriche et al., 2022).

Coastal inundation occurred to varying degrees during previous water level rises (1978), depending on coastal slope characteristics, leading to the emergence of new coastal ecosystems such as beach ridges and coastal lagoons (Barannik et al., 2004; Sapanov, 2018). The Caspian Sea level rise caused significant economic impacts, prompting protective measures in several metropolitan areas. However, the rising water level trend of the Lankaran Depression ended in 1995 (Jing et al., 2012). Since then, a general downward trend has persisted, with a notable drop in 2010 due to exceptional summer drought in the Volga Basin (Lahijani et al., 2010). According to Baku gauge data, the Caspian Sea level at the end of 2021 was 1.9 m lower than in 1995 (CASPCOM, 2022). Satellite altimetry reflects this shrinkage, detecting a modest increase of 25.0 cm between 2001 and 2005, followed by continual reduction between 2005 and 2022 (Lahijani et al., 2023). The decline accelerated in recent years, with a 30.0-cm drop between 2021 and 2022, compared to an average of 9.0 cm per year between 2005 and 2021 (Khaledian et al., 2020). This shrinkage affects coastal infrastructure, aquatic ecology, water circulation, and navigation (Haghighi et al., 2020).

The Caspian Sea region hosts the world' s greatest sturgeon spawning grounds and is rich in biological resources. While biological diversity is minimal, it stands out for high endemism, with over 130 fish species and uncommon lotus fields (Mirrasooli et al., 2019; Vasilyeva et al., 2019). More than 100 bird species use marsh areas for nesting and migration (Rasekhi et al., 2023). The sea is also home to the unique Caspian seal, the sea' s only marine mammal (Sanaee et al., 2020). However, many Caspian species are now endangered due to climate change, pollution, habitat destruction, and overexploitation (Tasmagambetova et al., 2019; Verbitsky et al., 2019), negatively impacting human well-being, social and economic sectors, and environmental services. The most common economic activities in the Caspian region are oil production, fishing, and shipping (Leroy et al., 2020), with strongly developed industry and agriculture in the basin (Akbulaev and Bayramli, 2020).

Owing to issues including water level decline, water pollution, and ecosystem degradation, a considerable gap exists between scientific research conducted to abate these problems and the water governance mechanisms in place (Jonson, 2001; Ghaffari et al., 2019; Modabberi et al., 2020; Yekimov et al., 2021; Koriche et al., 2022). Therefore, this paper focuses on assessing existing issues in the science–policy interface regarding water governance in the Caspian Sea and suggests effective conditions that can improve the mechanism.

2 Methodology

This paper aims to understand water governance issues in the Caspian Sea in terms of science and policy interlinkage. To this end, secondary research and reports highlighting water governance issues have been utilized for qualitative analysis. Google Scholar, ResearchGate, Scopus, and Web of Science were searched using various permutations and combinations of terms related to the Caspian Sea, water governance, and policy. The research period analyzed spans 2001–2023, presenting the journey and development of water governance through different treaties and policies signed for the Caspian Sea.

Studies were scrutinized based on: (1) water security in the Caspian Sea; (2) existing issues in water governance; and (3) gaps in current policies and OECD water governance principles. Furthermore, we suggest that potential and feasible measures should be incorporated into existing governing mechanisms to reduce disruption of the science–policy interface by including different effective conditions. Meanwhile, the potential of nature-based solutions was assessed concerning Caspian Sea water governance, and their relevance to reducing science–policy interface gaps was described.

3.1 Environmental Security in the Caspian Sea

Environmental issues in the Caspian Sea have been shaped by economic development of the sea itself (Akbulaev and Bayramli, 2020), coastal regions (Modabberi et al., 2020), and watershed basins of rivers flowing into the sea (Serykh and Kostianoy, 2020). Each component has distinct environmental issues that often share similar implications. Pollution is the most serious environmental problem in the Caspian Sea (Modabberi et al., 2020; Behrooz et al., 2021; Hatami et al., 2022; Koriche et al., 2022).

Simultaneously, anthropogenic load on the region occurs against diverse natural (endogenous and exogenous) processes (Koriche et al., 2022). Natural processes include sea level variations (Serykh and Kostianoy, 2020), morpholithodynamic processes in the coastal zone (Gonikov, 2019), regular seismic events (Leroy et al., 2022), storm surge phenomena (Serykh and Kostianoy, 2020), and mud volcanism (Farhadian Babadi et al., 2021). The general environmental status in the Caspian Sea basin was assessed as precrisis toward the close of the previous century, accompanied by severe worsening of sanitary-toxicological and fishing conditions.

The Circum-Caspian region was considered a high environmental stress region in the 1990s, characterized by roughly equal areas with acute and relatively acute environmental circumstances (Leroy et al., 2020). Other sources describe it as a region under extreme stress, owing to combined negative natural and anthropogenic factors and the growing threat of degradation of natural complexes in the coastal zone and ecosystems throughout the sea (Zonn, 2005; Jafari, 2010; Yekimov et al., 2021). According to some authors, it represents the first stage of an environmental disaster (Lahijani et al., 2023). The environmental focus has shifted in recent years from industrial pollution (due to declining industrial production) to pollution caused by hazardous waste disposal due to sea level rise.

Furthermore, changes in the natural environment can impact economic, political, and demographic issues that determine power geography (Huitema et al., 2009). Limitations in resource use can be interpreted as a security risk (Leroy et al., 2020). Environmental dangers (natural or human) can lead to struggle and conflict over scarce resources (Madani, 2010). Environmental threats to national security are similar to military and economic challenges in that they weaken governments' material bases and can grow to endanger governments and their institutions (Garibov, 2018).

According to the Caspian Environment Programme, sturgeon catches in Iran and former USSR countries decreased between 1929 and 1998 (Bayramov, 2020). The volatile political climate explains fluctuations in sturgeon output. Following World War II, industrial restoration gradually increased, peaking at over 28.9$×10^{3}$ t in 1977 (Guliyev, 2012; Koriche et al., 2021). The demise of the USSR and lack of environmental restrictions in newly independent republics led to large-scale organized poaching, a major contributor to the steep drop in

sturgeon capture (Bayramov, 2020). Some species are now endangered due to increased oil production, pollution, alien species invasion, habitat degradation, and poaching (Verbitsky et al., 2019; Modabberi et al., 2020; Farhadian Babadi et al., 2021; Lama et al., 2022). Creating a joint governing institutional authority, providing a legal structure for water and resource management, and protecting the natural environment are critical for eradicating environmental stress in the area.

3.1.1 Water Governance in the Caspian Sea

The Soviet legacy has left intricate relationships among Central Asian states at both national and regional levels, interconnected by pre-existing water infrastructure and intrastate regulations (Mihr, 2020). During the USSR era, water management was centralized in Moscow, with regional bodies only executing decisions. Following the USSR' s demise, each independent country developed its own institutions and responsibilities, marking the emergence of the water governance paradigm in Central Asia (Bota and Nataliya, 2022). The adoption of Integrated Water Resources Management (IWRM) represented a significant milestone, involving principles such as managing water based on hydrographic boundaries and public participation (Zonn et al., 2020). While Central Asian states have encountered challenges common to Global South countries, such as limited resources and IWRM ownership, specific issues persist. Implementing IWRM has revealed limitations: water user associations struggle with self-governance, coordination between administrative and hydrographic management scales is challenging, and numerous institutions with overlapping functions exist (Zonn et al., 2020).

The current trajectory of water governance concerning the Caspian Sea can be traced by examining interstate pacts, which fall into two main categories: delineation of the seabed and safeguarding the environment (Akhmadiyeva and Abdullaev, 2019; Fig. 1 [Figure 1: see original paper]). Nearly all agreements related to seabed delineation have been bilateral and primarily aimed at facilitating hydrocarbon extraction from beneath the seabed (Akhmadiyeva and Abdullaev, 2019; Koriche et al., 2022). Nevertheless, lack of agreement regarding legal standing and conflicts over ownership of specific oil and gas fields has hindered extensive offshore projects. The uneven distribution of hydrocarbon reserves in offshore areas has been the primary factor contributing to disputes over legal status among the five littoral states (Azimi et al., 2020; Ivanov et al., 2020). Additionally, littoral states have been embroiled in disputes over legal status and resource delimitation, causing a pause in environmental negotiations for over a decade. None of the five states have taken responsibility for environmental degradation or depletion of natural resources and biodiversity, instead prioritizing extensive hydrocarbon extraction and using only limited environmentally friendly technologies (Bayramov, 2020).

The Tehran Convention, signed in November 2003 by all littoral states after years of disagreement, marks the first legally binding regional pact for protect-

ing the Caspian Sea' s marine ecosystem. It includes three protocols and sets out requirements and institutional mechanisms for preserving and sustainably developing the marine environment (Akhmadiyeva and Abdullaev, 2019). However, its practical implementation has been delayed due to inability to reach consensus on various protocols related to biodiversity conservation, pollution, oil incident response, and environmental impact assessment. The Aktau Protocol, in force since July 2016, mandates littoral states to prepare for and respond to oil contamination incidents (Seyrafi, 2020). The Moscow and Ashgabat Protocols, ratified by some countries, are still pending enforcement (Akhmadiyeva and Abdullaev, 2019). The Tehran Convention Secretariat, managed by the United Nations Environment Programme (UNEP), is the sole regional institution overseeing protection of the Caspian Sea' s marine environment, assisting states in adhering to the Convention and its Protocols (Garibov, 2018). While the newly established Convention on the Legal Status signifies progress toward sustainable water governance, its emphasis largely centers on regional security, with limited attention to environmental concerns, mostly pertaining to scientific research on hydrobiological resources (Amiraslani and Dragovich, 2023).

3.1.2 Unsolved Issues in the Caspian Sea

Despite the latest treaty signed by the five littoral states—Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan—on 12 August 2018, numerous issues remain unresolved: (1) the treaty grants sovereign and exclusive rights to littoral states for exploiting natural resources in their seabed sectors; (2) the northern Caspian model extends to the southern Caspian, allowing Azerbaijan, Iran, and Turkmenistan to establish bilateral agreements for sector delimitation; (3) Iran compromises by accepting this disposition, abandoning its demand for a condominium approach, resulting in a smaller share of energy resources; (4) delimitation of the southern Caspian seabed remains unagreed due to the Iranian President' s refusal of the median principle; (5) Iran' s claims to the Araz-Alov-Sharg oil and gas field challenge historical tensions with Azerbaijan over field ownership; (6) the treaty resolves only 30% of Caspian delimitation issues, signaling Iran' s limited willingness to compromise further; (7) Turkmenistan and Azerbaijan contest the Serdar/Kapaz oil field, affecting efforts to unlock the Trans-Caspian Pipeline (TCP); (8) the treaty potentially revives border negotiations between Turkmenistan and Azerbaijan; (9) Turkmenistan' s vast gas reserves face economic challenges, prompting infrastructure development for increased domestic production and western gas exports; (10) Turkmenistan' s gas exports to Russia and Iran ceased due to pricing disputes; and (11) Turkmenistan exports 30$\times$10^{12}$ m^3 of gas to China via the Central Asia–China pipeline, facing pricing challenges and limited demand (Akbari et al., 2020; Bayramov, 2020; Pietkiewicz, 2021; Amiraslani and Dragovich, 2023). Among these issues, exploitation of natural resources in seabed sectors is a major water governance problem causing disruption in the science–policy interface.

3.2 Existing Gaps in Science-Policy Interface for Water Governance

Environmental stress in the Caspian Sea may worsen as economic potential grows due to hydrocarbon extraction, construction of new seaports, rehabilitation of existing ones, revival of merchant tanker fleets, enhancement of naval components, and construction of oil and gas pipelines (Yekimov et al., 2021).

The Caspian Sea, influenced by geological, hydroclimatic, anthropogenic, and spatial factors, has undergone significant environmental changes in the last decade (Nadim et al., 2006; Dero et al., 2020). These changes influence climate variations and sea level shifts, particularly along coastal regions. Water level fluctuations have been pronounced, with rapid declines from 1931 to 1940 and subsequent rises between 1978 and 1995. Since 1996, a declining trend has persisted, with a significant drop from 2006 to 2015 and stabilization in 2016–2017 (Modabberi et al., 2020; Lahijani et al., 2023). These changes result from combined factors including evaporation due to elevated temperatures and alterations in precipitation and river discharge. Prolonged trends could lead to disappearance of the northern Caspian Sea and surrounding areas within 75 years, while heightened salinity threatens biodiversity, soils, infrastructure, and public health (Akbari et al., 2020; Lahijani et al., 2023).

Escalating air and water temperatures are also concerning, impacting ice cover, water circulation, and chemical and biological processes. Global warming has increased air temperatures by about 0.7°C–0.8°C and surface water temperatures by 0.4°C–0.5°C during the latter part of the 20th century (Dero et al., 2020). The region is vulnerable to extreme weather patterns attributed to climate change, resulting in economic losses from floods, agricultural impacts, and population displacement. Flash floods triggered by heavy rainfall and poor land use practices exacerbate challenges (Koriche et al., 2022). Desertification affects over half of the Azeri coastline and interior Iran. In summary, the Caspian Sea region faces complex environmental issues including water level fluctuations, rising temperatures, extreme weather events, and desertification, with broad repercussions affecting various sectors, livelihoods, and ecosystems. Main contributors include direct drivers—habitat deterioration, population expansion, tourism, fishing, and agriculture—and indirect drivers such as urban development, oil and gas operations, unauthorized fishing, and agricultural practices (Dero et al., 2020; Koriche et al., 2022).

Additionally, the risk of harmful effects from hydrocarbon deposit development in the bottom and coastal regions is especially evident in the shallow-water northern Caspian, which is crucial for unique commercial biological resources while also serving as a nature-reserve zone (Azimi et al., 2020; Ivanov et al., 2020). Table 1 highlights major gaps in the Caspian Sea' s science–policy interface for water governance.

Due to the importance of environmental protection in sustainable development, states must include sustainable development goals in their regulations, laws,

and policies (Madani, 2010). If environmental rules are internalized as part of the domestic legal system, they become more prominent and respected (Cook and Bakker, 2012). The existence of common interests and problems has made coastal state cooperation inevitable across all fields, extending beyond environmental cooperation to economic and social dimensions of sustainable regional development (Jonson, 2001; Nouri et al., 2008; Alipour et al., 2017). Destruction of the Caspian Sea ecosystem can occur rapidly, but recovery is unlikely and certainly time-consuming if not impossible in some areas (Barannik et al., 2004; Leroy et al., 2020; Modabberi et al., 2020; Ragimova et al., 2020; Koriche et al., 2022; Lahijani et al., 2023). In some cases, including extinction of rare species (for example, the genetic reserves of Caspian sturgeons), there will be no alternative (Tasmagambetova et al., 2019; Verbitsky et al., 2019).

Governmental measures alone cannot ensure sustainable conservation and exploitation of the Caspian Sea. Failure to halt environmental degradation stems from the lack of a comprehensive approach, coherent activities, and effective utilization of national and regional power (Yekimov et al., 2021). The severity of pollution and destruction makes it impossible to rely on issues such as the uncertainty of the agreed legal regime (Mirzaei et al., 2017; Sapanov, 2018; Akhmadiyeva and Abdullaev, 2019).

Table 1 Gaps in science–policy interface for water governance in the Caspian Sea

Environmental stress factors	Challenges in conservation	Description in terms of water governance	Reference
Severe contamination by substantial amounts of heavy metals from sewage discharge	Pollution from organic compounds due to agricultural and industrial discharges	Governmental measures alone cannot ensure sustainable conservation and exploitation of the Caspian Sea	Akhmadiyeva and Abdullaev (2019); Akbulaev and Bayramli (2020); Ghayebzadeh et al. (2020); Farhadian Babadi et al. (2021); Yekimov et al. (2021); Mokarram et al. (2023)
Eutrophication	Water level fluctuations	Lack of a comprehensive approach and coherent activities, as well as lack of utilization of national and regional power	Modabberi et al. (2020); Dero et al. (2020)

Environmental stress factors	Challenges in conservation	Description in terms of water governance	Reference
Hydrocarbon extraction	Construction of new seaports and rehabilitation of existing ones	Severity of pollution and destruction is so great that it is not possible to rely on the agreed legal regime on the Caspian Sea	Koriche et al. (2021); Ghafourian and Sadeghzadeh (2022); Hatami et al. (2022); Zakeri et al. (2022)
Revival of merchant tanker fleet	Enhancement of navy component	Responsibility of coastal governments	Bayramov (2020); Pietkiewicz (2021); Ghafourian and Sadeghzadeh (2022)
Construction of oil and gas pipelines	Recognizing the right of present and future generations to protect the Caspian Sea	Unresolved disputes	Pietkiewicz (2021)
		Environmental characteristics of the Caspian Sea also have potential impacts on regional security	
		Lack of cooperation mechanism in the latest treaty	
		Communication barrier and hindrance in decision-making	

Environmental stress factors	Challenges in conservation	Description in terms of water governance	Reference
Human security implications	Sharp increase in unemployment rate in fishing industry due to reduction of fish stocks	Challenges in resource division	Yekimov et al. (2021); Koriche et al. (2022); Rasekhi et al. (2023)
	Shipping companies are affected	Oil and gas resources have caused each country to have different positions regarding the legal regime, lacking necessary consistency	Akbulaev and Bayramli (2020); Pietkiewicz (2021); Hatami et al. (2022)

Negotiations and diplomatic agreements, as well as overcoming existing political bottlenecks, are processes that require time to resolve, while protection of the Caspian Sea and the rights of interested parties are not subject to legal regime agreements (Bayramov, 2020; Pietkiewicz, 2021). Caspian ecosystems and their organisms do not depend on political borders and diplomatic agreements, and their right to life cannot be subject to coastal states' agreement (Tasmagambetova et al., 2019). Therefore, coastal governments and leaders should feel responsible for recognizing the right of present and future generations to protect and exploit the Caspian Sea. The sea' s environmental characteristics also potentially impact regional security (Ragimova et al., 2020). All coastal states must consider the stability of this water zone by utilizing maximum national power while developing regional cooperation and leveraging capacities of other international actors, including international organizations (Nouri et al., 2008; Pahl-Wostl et al., 2013; Sapanov, 2018). It is necessary to protect this water body by relying on intellectual and scientific principles, including prevention and possible use of all legal and executive capacities.

A comprehensive view of environmental security directly connects with human security (Pietkiewicz, 2021). Regarding the Caspian Sea, this is evident in the sharp increase in unemployment in the fishing industry due to reduced fish stocks, subsequently affecting shipping companies (Akbulaev and Bayramli, 2020). The Caspian region has become increasingly crucial for regional and

global environmental security. New geopolitical and economic requirements (post-USSR demise) have created a mixture of competition, cooperation, and ideological, economic, political, and legal controversy (Gonikov, 2019; Leroy et al., 2020; Koriche et al., 2022). The serious debate concerns how the Caspian Sea and its resources are divided among coastal governments. Oil and gas resources have caused each country to adopt different positions regarding the sea' s legal regime, lacking necessary consistency (Pietkiewicz, 2021).

3.3 Linking Water Governance of the Caspian Sea to the OECD Principles

The OECD is a unique platform where 37 democratic nations with market-driven economies collaborate to establish policy standards promoting sustainable economic growth (Blind, 2012). It serves as a space for governments to compare experiences, address shared challenges, identify best practices, and set high standards for economic policies. The Water Governance Initiative, part of the OECD Water Governance Programme, was created in 2013 as a multi-stakeholder platform involving public, private, and non-profit sectors (Akhmouch and Correia, 2016). This initiative convenes every six months in a Policy Forum to address water governance gaps and pursue goals established by the 6th World Water Forum, in which the OECD played a key role (Akhmouch and Correia, 2016).

The resulting OECD principles on water governance were developed recognizing that water challenges require tailored solutions, embracing the diversity of legal, administrative, and organizational systems within and across countries (OECD, 2015). These principles acknowledge the contextual nature of governance, the need to adapt water policies to specific resources and locations, and the requirement for governance responses to evolve alongside changing circumstances (OECD, 2015; Akhmouch and Correia, 2016). To promote uniformity in water governance concepts and achieve water security globally, the OECD has devised water governance principles (Akhmouch and Correia, 2016; Woodhouse and Muller, 2017).

However, Caspian Sea governance currently faces geopolitical issues at regional and national policy levels, leaving standardization of these principles pending (Orazgaliyev and Araral, 2019; Bayramov, 2020). The following subsection describes possible linkages between existing Caspian Sea water governance and OECD principles (Table 2).

Table 2 Interlinkage of OECD principles with water governance of the Caspian Sea

OECD principle	Category	Existing gap (Caspian Sea)
Allocation and identification of defined roles regarding water policy (formulation, implementation, management, regulation, and coordination)	Politics	Conflicts of interest and rivalry for influence among state actors have resulted from shifting power and influence in the region
Management of water at suitable levels within basin governance integration	Politics	Lack of definition of exact boundaries or specific allocation of territorial waters, common maritime space, seabed, and sub-soil to each state
Support coherence through efficient cross-sectoral coordination, particularly between water and environmental policies	Governance	Absence of robust regional cooperation and accord on water and environmental concerns continues to hinder states from safeguarding sea water and surrounding ecosystem
Adaptation of accountable authorities' ability level to the complexity of water concerns to be addressed, as well as their responsibilities and competences	Governance	Hydro-social cycle displays a gap; requirement of technical system platform to push the Caspian Sea region to reflexive modernity
Production, refurbishment, and timely dissemination of consistent, comparable, and policy-relevant water and water-related statistics and information for guiding, assessing, and improving water policy	Governance and research	Requirement of a model defining sources of investment in desirable economic projects, youth projects, and assistance in water security

OECD principle	Category	Existing gap (Caspian Sea)
Ensuring mobilization of water finances and efficient allocation of financial resources via governance arrangements	Governance and society	Unresolved issues in latest treaty causing vast gas reserves to face economic challenges, prompting infrastructure development for increased domestic production and western gas exports; exploitation of natural resources in seabed sectors
In the public interest, ensuring competent water management regulatory regimes are successfully implemented and enforced	Politics	Lack of coordination among Central Asian governments reduces their ability to tackle external water management problems
Encourage government and key stakeholders to adopt and implement innovative water governance methods	Governance and economy	Lack of consensus in negotiating protocols on environmental impact assessment, oil incidents, water pollution, and biodiversity conservation
Consolidate integrity and transparency standards into water policies, institutions, and governance frameworks to increase accountability and confidence in decision-making	Governance and research	Due to political issues on boundary conditions, citizen science projects are stagnated
Encourage stakeholder participation to make educated and outcome-oriented contributions to water policy creation and implementation	Society	Lack of coastal authority defining water share among states in bilateral and multilateral agreements

OECD principle	Category	Existing gap (Caspian Sea)
Encourage development of water governance frameworks that aid in managing trade-offs between water users	Governance	Requirement of a stand-alone body to monitor impact of paradigm shift in water governance in the Caspian Sea region and disseminate transparent analysis in public domain

Note: OECD, Organization for Economic Co-operation and Development. OECD principles are referenced from https://www.oecd.org/cfe/regionaldevelopment/OECD-Principles-on-Water-Governance-en.pdf.

3.4 Conditions for Effective Science–Policy Interface in the Caspian Sea

Disruptions in science–policy interaction primarily occur due to gaps in policy framework inception and implementation. To attain the most effective stage of the science and policy cascade, it is relevant to test the 'science-to-policy hypothesis' formulated in initial research steps (Armitage et al., 2015). This hypothesis is objective about policy pilot testing outcomes and must be qualified at each step in terms of acceptance and functioning (Brugnach et al., 2007; Willems and de Lange, 2007).

To employ effective coordination of science and policy aspects in water governance, multiple conditions are relevant (Fig. 2 [Figure 2: see original paper]). In addition to mandatory factors for incorporation into existing mechanisms, nature-based solutions also have an essential role in improving this balance. The following subsections analyze the potential and feasibility of nature-based solutions to provide an overall framework of improvement measures.

3.4.1 Scientific Approach Toward Policy Formulation

Perspectives of science–policy processes as linear relationships often ignore the complicated realities of decision-making (McNie, 2007; Vogel et al., 2007). A diverse set of stakeholders now participates in water decision-making, and the status and function of scientists in policy-making processes have shifted (Mirumachi et al., 2010). This movement is part of a larger societal transition toward increased public skepticism of science and democratization of information (McNie, 2007). Scientists working in these settings require government and institutional support and openness to better convey knowledge to wide audiences. Rewards, incentives, and requirements are necessary for scientists to participate in more open, collaborative, and learning-centered processes. A concern that scientific knowledge is not 'upgraded' above or appreciated to the disadvantage

of traditional knowledge and traditional knowledge bearers is implicit in this transition to more effectively exchange and transmit knowledge (Lejano and Ingram, 2009).

Environmental measures taken unilaterally by only one state will not have the desired effect but will instead contribute to increased hydrocarbon production in countries with less stringent environmental legislation, resulting in increased harmful substance emissions into the Caspian Sea (Jafari, 2010; Lahijani et al., 2019; Bayramov, 2020; Ivanov et al., 2020; Farhadian Babadi et al., 2021). Furthermore, increased participation by a broader range of non-governmental sectors can result in greater legitimacy, more effective and equitable resource allocation, better cost-benefit ratios, enhanced access to wide knowledge and expertise, and greater acceptance and success in policy implementation (Akhmadiyeva and Abdullaev, 2019; Ghafourian and Sadeghzadeh, 2022). Utilizing IoT (Internet of Things) to understand the relationship between science and policy performance in water governance is imperative (Armitage et al., 2015; Katyaini and Barua, 2016). Missing gaps and overlaps can be studied using post-processing and analysis of relationships between policy implementation tasks, guidance, experiences, and tools (Woodhouse and Muller, 2017).

3.4.2 Bilateralism and Multilateralism for Robust Commitments

Governance of water security challenges in the Caspian Sea necessitates collaborative efforts, including shared fact-finding, from which trust-building occurs at the start of science–policy cooperation (Yekimov et al., 2021). The legal status of the Caspian Sea was debated for 22 years (Akhmadiyeva and Abdullaev, 2019). The presidents of the five littoral republics signed the "Convention on the Legal Status of the Caspian Sea" on 12 August 2018 in Aktau, Kazakhstan (Pietkiewicz, 2021). While signing the agreement was greeted with optimism as a long-awaited solution, it left caveats in the final settlement of major maritime disputes (Löwis and Eschment, 2022). Persisting issues include demarcation of highly problematic sectorial seabed borders in the southern Caspian Sea (Arne et al., 2021), clarification of ownership of disputed fields (Bayramov, 2020), and construction of underwater trans-Caspian pipelines (Cutler, 2019).

Bilateral and multilateral agreements made by Russia, Azerbaijan, and Kazakhstan in 1997, 1998, and 2001, respectively, and by Turkmenistan and Kazakhstan in 2014, effectively eliminated disagreement about northern Caspian seabed borders (Orazgaliyev and Araral, 2019). However, major disputes in the sea' s southern part still disturb the governing mechanism. Consequently, further negotiations will most likely occur outside common Caspian summits in bilateral or trilateral talks between Baku, Tehran, and Ashgabat (Orazgaliyev and Araral, 2019; Bayramov, 2020).

Establishing relationships to overcome misconceptions about the distinct logic of science and policy takes time and produces few tangible results in early stages (Armitage et al., 2015; Woodhouse and Muller, 2017). Investing time upfront

in shared problem framing and engaging policymakers and other players, such as communities and industrial partners, in the knowledge generation process—rather than considering them passive end users—helps ensure that high initial transaction costs produce long-term returns (Huitema et al., 2009; Pahl-Wostl et al., 2013). Early time and resource commitments are required to develop shared understanding of fundamental problems and the larger political and social circumstances that frame water decisions (Madani, 2021). Furthermore, Caspian Sea states need to institutionalize agreement achievements via robust legislation (Leroy et al., 2020).

3.4.3 Creating and Applying Knowledge of All Kinds

All water management must balance different goals and competing interests. Because the hydrological cycle is interrelated, one user' s withdrawals from or discharges into a shared water source can affect quantity or quality accessible to others (Pahl-Wostl et al., 2013). Consequently, water governance raises intrinsic barriers to collaborative action (Cook and Bakker, 2012). Collective action issues occur when actors in interdependent systems act autonomously, rationally pursuing their own goals while imposing externalities on other participants and attaining lower joint value than mutually beneficial outcomes (Johannessen et al., 2019; Pahl-wostl, 2019).

Water governance today must rely on knowledge in all its forms. This knowledge is owned, formulated, and conveyed by a wide range of actors at all government levels, both inside and outside formal structures (Jiménez et al., 2020; Pahl-wostl et al., 2020). Due to varied, potentially contradictory, and often incompatible ways of knowing (e.g., between scientific and traditional knowledge systems), integrating different knowledge types in water decision-making can be highly difficult (Huitema et al., 2009; Pahl-Wostl et al., 2013; Mirzaei et al., 2017). Transparency about diverse knowledge use is vital for valid decision-making, as is commitment to 'knowledge co-production' procedures that bring together various data sources and types to define and address problems (Brugnach et al., 2007; Madani, 2021). A working knowledge co-production process is not meant to resolve situations where knowledge and comprehension of water conditions are incompatible (Katyaini and Barua, 2016; Yekimov et al., 2021).

The main pollution sources in the Caspian natural environment are land-based and offshore, including oil transportation via sea, river navigation, operation of oil and gas wells, municipal-domestic wastewaters, discharge of untreated industrial and agricultural wastewaters, wash-off with river flow, and transborder atmospheric and water transfer of pollutants from other regions (Barannik et al., 2004; Zonn, 2005; Nadim et al., 2006; Jafari, 2010; Haghighi and Kløve, 2018; Dero et al., 2020; Ragimova et al., 2020; Yekimov et al., 2021; Ghafourian and Sadeghzadeh, 2022). Furthermore, the southern and middle Caspian regions are vulnerable to significant geodynamic hazards, including seismicity (Leroy et al., 2022). Therefore, sharing water quality issues and potential remedial measures is relevant and intrinsic to improving water governance and the science–policy

interface (Nadim et al., 2006; Pahl-wostl, 2019; Yekimov et al., 2021).

3.4.4 Potential of Nature-Based Solutions to Improve Science–Policy Interface in the Caspian Sea

Coastal landscape planning ensures proper allocation of human activities while conserving and improving landscape characteristics. Since the Caspian Sea is under multiple jurisdictions and subject to conflicts of interest, policy solutions should be based on assessing coastal landscape characteristics, zoning, and recognizing sensitive regions to aid appropriate allocation of human use and activities in sustainable tourism development (Alipour et al., 2017; Akbulaev and Bayramli, 2020; Ghafourian and Sadeghzadeh, 2022). In such a large and dependable water body, the tourism sector plays an essential role in economic and sustainable development under each state. Furthermore, fostering nature-based solutions as an alternative to economic development provides supportive social ties among states.

Efforts focusing on enhancing overall water condition rather than targeting specific metrics hold greater promise for achievement, especially when they involve directly rejuvenating natural ecosystems through managing underlying pressures—commonly known as nature-based approaches or solutions (Boano et al., 2020). These solutions can be employed as citizen science projects that can be piloted and scaled up based on performance. Nature-based solutions play a dual role in managing flood and drought impacts by supporting stormwater control and water supply systems simultaneously (Bunclark and Hernández, 2022). They are crucial for preserving the natural hydrological cycle, especially as urban areas expand and surfaces become more impermeable. They maintain the balance between evapotranspiration and rainfall, mitigate urban heat effects, and facilitate green space growth using local water resources (Ferreira et al., 2023). Furthermore, they offer effective purification of diverse water sources such as greywater, rainwater, sewer overflow, and wastewater for various uses, yielding multiple additional advantages (Albert et al., 2021). Beyond water treatment, they can retain stormwater, facilitate food production through irrigation, and conserve energy (Babí Almenar et al., 2021).

Nature-based solutions can address the science–policy interface issue in the Caspian Sea region through planning, piloting, and replicating impact to larger geographical coverage (Fig. 3 [Figure 3: see original paper]). While not foreseen as mandatory for improving water governance, their feature of stabilizing water ecosystem activities drives their potential inclusion in the cascade of improving the science–policy interface. These solutions are also appropriate for combating water pollution in the Caspian Sea (Nesshöver et al., 2017; Raymond et al., 2017; Cousins, 2021). Since major water pollution is caused by oil spills, nature-based solutions can be deployed at regional and national scales to control and mitigate these problems with minimum damage (as caused by grey infrastructure) (Zingraff-Hamed et al., 2017; World Water Assessment Programme, 2018; Babí Almenar et al., 2021).

Seasonal and short-term Caspian water level changes occur due to meteorological forcing (Lahijani et al., 2010, 2023), tidal effects (Medvedev et al., 2017), river flooding (van Baak et al., 2019), and steric shifts. Long-term variations are mostly related to the water budget, including two critical components: riverine input and evaporation from the water surface (Soheil et al., 2018; Azizpour and Ghaffari, 2023). Therefore, another problem addressable through these solutions is water level changes and flood events that would otherwise cause hazardous impacts on coastal communities (Frantzeskaki et al., 2019; Senes et al., 2021; Strack et al., 2022).

4 Conclusions

Evaluation of the scientific-policy link strength in Caspian Sea water policy reveals a knowledge-governance gap. This refers to the communication barrier between knowledge producers and governance systems that impedes translation of scientific information into action. Furthermore, due to complex and context-based solutions, there is a lack of blueprints for effective science-policy processes in Caspian Sea water governance settings.

Environmental security in the Caspian Sea is shaped by economic development of the regions, coastal waters, and watersheds draining into the sea. Pollution is the most serious problem affecting the region, with both natural and human-induced processes contributing to ecosystem degradation. Seismic events, sea level variations, coastal zone changes, storm surges, and mud volcanism further compound environmental challenges. Over time, the environmental situation has shifted from industrial pollution to hazardous waste disposal due to rising sea levels. These natural environment changes impact ecosystems and have consequences for economic, political, and demographic factors shaping power dynamics. Environmental threats can lead to conflicts over scarce resources and pose severe risks to national security.

Establishing a joint governing authority, implementing water and resource management regulations, and protecting the natural environment through legal frameworks are crucial steps to effectively address these concerns. States must incorporate environmental protection goals into regulations, laws, and policies to ensure sustainable development. Cooperation among coastal states is inevitable, not only in environmental matters but also in economic and social aspects of regional development. Conservation and restoration of the Caspian Sea ecosystem are challenging and may be impossible in some areas, leading to extinction and destruction of rare species. The lack of a comprehensive approach, coherent activities, and effective utilization of national and regional power has hindered efforts to halt environmental degradation.

Negotiations and diplomatic agreements require time to address political obstacles, but protecting the sea and rights of interested parties should not be subject to legal regime agreements. Coastal governments should recognize their

responsibility to protect and exploit the Caspian Sea for present and future generations. The sea' s environmental characteristics also have implications for regional security, necessitating utilization of national power and international cooperation to ensure stability and protect the water zone. Environmental security is closely tied to human security, as declining fish stocks have increased unemployment in the fishing industry and affected shipping companies.

Furthermore, linking Caspian Sea water governance with OECD water governance principles provides a framework for policymakers to assess gaps and formulate amendments to existing mechanisms. This paper highlights the need for effective science–policy interaction in water governance, emphasizing the importance of testing the "science-to-policy hypothesis" at each step to ensure acceptance and functionality. It discusses the evolving role of scientists in decision-making, involvement of diverse stakeholders, and challenges of integrating different knowledge types, including traditional knowledge systems.

Emphasis should be placed on establishing relationships, sharing problem framing, and engaging policymakers and stakeholders in knowledge generation. It also highlights the need to institutionalize agreements through robust legislation and address collective action issues in water governance. Coastal landscape planning and promoting nature-based solutions can aid in appropriately allocating human activities, developing sustainable tourism, and combating water pollution. Additionally, addressing water level changes and flood events is crucial to protect coastal communities. Overall, collaborative efforts, comprehensive knowledge integration, and nature-based solutions are essential for effective water governance in the Caspian Sea region.

Conflict of Interest

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

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Author Contributions

Apoorva BAMAL: Literature review, theoretical development, analysis and interpretation of research studies, writing–original draft, writing–review & editing, and critical revision
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Note: Figure translations are in progress. See original paper for figures.