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# Investigating Nexus Technologies in the Water, Energy and Food Systems: A Solution for Middle East Water Hydro Policies Through the Analysis of Transboundary River Basins

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## Abstract

Climate change, population growth and economic development create critical challenges in the supply of water, energy and food on a national and global scale. The Middle East is of particular importance due to rapid industrialization, fragile environment, unstable political relations and transboundary water disputes. According to this research, the factors affecting WEF security in the transboundary region are: water shortage, migration, extreme events, economic growth, urbanization, population growth, poverty and political stability. The results show that most countries in the Middle East face WEF resource insecurity due to poor planning or wrong management strategies. This review explores the WEF linkage as a comprehensive approach to seeking regional solutions to common challenges in these countries. This article examines the urban water shortage under the scenarios of sewage pollution risk, agricultural water stress, drought exposure, environmental water stress and human water stress, related to flood exposure, fish threats, nutrient pollution, political water stress. and etc. at the global level, using a critical water policy approach, examines the transboundary water nexus interaction framework. It also provides projections for the years 2030 and 2050 and provides estimates of the state of transboundary river systems for us and the next generation. This assessment uses indicators of stress factors using cluster analysis in the TWAP program to provide a comprehensive picture of the state of transboundary river basins, especially in the Middle East and Iran. Also, analysis was used in VOS Viewer software to identify keyword and topic connections, and the method based on this problem was generalized at the global level after identification.

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**Keywords:** Water, Energy and Food Nexus, transboundary river basins, Hydro policies, Middle east, Iran

## 1. Introduction

Climate change and human activities can alter large-scale patterns of hydrological fluxes (precipitation, runoff, evapotranspiration) [1,2] and deplete groundwater [3] and surface waters [4,5], with feedbacks to climate [6]. For example, the dramatic decline in Lake Urmia in Iran is a well-known destructive impact of hydrological change in this arid/ semi-arid part of the world [5,7,8]. Other surface waters in Iran have also changed in recent decades, including Lake Maharloo-Bakhteghan in central Iran [9], Lake Hamoon in the east [10], and Lakes Shadegan and Hoor-Al-Azim in the south and southwest [11,12]. Moreover, hydrological changes in Iran are not limited to surface waters, but also extend to groundwater resources, with substantial decreases in groundwater level reported for different parts of the country [13]. Surface and subsurface hydrological changes in Iran have previously been estimated for six major hydrological basins over a period of 11 years, based on general availability of remote sensing data for both surface water and groundwater [14]. Effects of surface water withdrawals on long-term average surface water storage have been estimated on finer spatial resolution (for 30 main hydrological basins in Iran), but without accounting for related groundwater changes [15]. Considering the extent and magnitude of water changes in Iran, and their impacts and consequences in such a dry and geopolitically important part of the world [13,16], there remains a need for more long-term, comprehensive, but still relatively fine resolution assessments of hydro-climatic variability and change in the country and the region. Such assessments are essential for understanding, mitigating, and adapting to key water resource changes.

The history proved the importance of water, food, and energy for survival of humanity during catastrophes in resource-limited settings. Water is one of the three basic needs of human being which can be supplied from different resources (surface, ground, etc.). Formation of civilizations territories and new socio-geographical boundaries, created the major limitations of transboundary water usage. Also, industrial activities generated new problems which caused a loss of balance between water demand–supply and increased costs and damages. The produced costs and damages classified as economic, environmental, and social which enhanced due to the mismatch between the human's expectations and what nature capacity. The term 'transboundary waters' refers to any surface or ground waters which cross or locate on political, economic, or social boundaries between two or more states [17]. Management of these resources is expected to be one of the serious challenges facing human Sustainable Development Goals (SDGs). Nowadays many countries of the world have bi-multilateral agreements on transboundary water resources which changes the regional conflicts to cooperation opportunities. In this case, one of the basic challenges is allocating shared water

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resources and distribution of benefits between upstream and downstream countries [18]. It has been reported that cooperative or conflictive events associated with internationally shared water bodies are generally concerned with the allocation and use of water resources [19,20]. Natural endowments of the physical river basin and annual water stress are only one part of the relationship between water stress, conflict, and cooperation. Regulation of flow regime by dam construction is also linked to seasonal variability and environmental flows [21-23]. The politics of transboundary water negotiations between states are complex and are influenced by different elements. It would also be worthwhile mentioning that, the same issues can occur within a country, where rivers cross various jurisdictions (e.g., the Amazon in Brazil or the Murray-Darling Basin in Australia). Thus, knowledge of dependence relationships among water, energy, and food is increasing due to water crisis, energy pressure, primary resources insecurity, and climate catastrophes [24]. In this case, the concept of WEF nexus has drawn great concern in recent years due to the increasing attention for water, food and energy security. Endo et al. reported a comprehensive review on WEF nexus projects [25]. After study of 37 selected projects, they identified four types of nexus researches including Water–Food (WF), Water-Energy-Food (WEF), Water-Energy (WE), and climate related. Among them, 6 projects (16%) had a close linkage with WF, 11 (30%) with WEF, 12 (32%) with WE, and 8 (22%) with climate. They found it essential to develop a unifying framework of nexus research to share solution-oriented common goals. This framework should be shared not only among projects members, but also among stakeholders in society, to develop integrated methods to integrate research results and to understand the complexities of WEF systems in order to contribute to reducing tradeoffs and increasing synergies of three resources usages. The framework can also be used within interdisciplinary and transdisciplinary approaches and to encourage local-to-global connected nexus systems [25]. The Middle East is considered to be arid or semi-arid as the average annual rainfall does not exceed 166 mm [26,27]. In addition, influence of climate change in this area generated an unpredictable environment. The scarcity of water resources in the Middle East represents an exceedingly important parameter in the stability of the region and a vital element in economic development [28,29]. Therefore, the management of transboundary water resources needs innovative, comprehensive, and flexible solutions to increase the mutual collaborations in this region. The objective of this paper is to provide an overview on water conflicts in the Middle East region specifically in Iran, Turkey, Syria, Lebanon, Israel, Jordan, Armenia, Georgia, Armenia, Azerbaijan, Iraq with focus on transboundary water resources. Also, this review aims to provide a clarity and framework for the WEF nexus approach in the specific context of transboundary water resources. Therefore, we focus on the nexus from WE management point of view. We started by evaluating the current status of water resources in Iran, Iraq, and Turkey. Then, we discussed the importance of cooperation among these countries with their capacities and potentials to overcome transboundary challenges by efficient solutions especially nexus concept. We mentioned

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various solutions and compared the limitations of these approaches which lead us to choose the ‘‘Nexus” as a holistic approach.

Global water withdrawals have increased significantly throughout the twentieth century and during the first decades of this century. As a result, many basins around the world have experienced pervasive water scarcity conditions and related management challenges [30,31]. These challenges are expected to become more critical in the coming decades, driven by impending socioeconomic developments [32]. At the same time, the supply of freshwater resources to meet the ensuing increase in water demand is subject to large uncertainties due to the impacts of changing climatic conditions, water quality degradation, and increasing demand for environmental flow protection. As such, policymakers in vulnerable basins need to adapt management practices for securing reliable future water supply that can meet the demands of different sectors. However, the choice of water management options is often associated with tradeoffs across multiple societal objective such as agricultural production, energy supply, and ecosystem health, as well as across space and time [33]. In recent years, the concept of nexus thinking has been gaining ground, providing an opportunity to shift from a sectoral focus on production maximization to improving cross-sector efficiencies [34]. The nexus approach is increasingly applied in the context of the linkages among water and food, but also including energy, ecosystems, and economy. This approach gives equal importance to each sector and aims to better understand the tradeoffs and synergies involved in meeting future demands of interconnected resources. Water is a key sector in the nexus system, given that all the other sectors are affected either directly or indirectly by water availability.

This paper provides a review of the water scarcity challenges in the coming decades and suggests a nexus modeling framework that could address the identified challenges in an integrated way across scales and sectors.

## 2. Literature Review

### *2.1.A challenging future for water resources*

Water scarcity has become a crucial environmental issue worldwide. The reasons are the large increase in global water withdrawals in the last century from 600 to 3900 km3, driven by the intensive growth of population and income, coupled with a questionable performance by regional water governance [35-37]. This huge abstraction of water resources has resulted in many regions undergoing pervasive water scarcity conditions such as in the western part of the United States, parts of the Middle East, northern Africa, southern Europe, parts of Australia, northern China, as well as many parts of Northwest India and Pakistan [38]. Water resources are being heavily depleted in these regions and their quality degraded, with obvious impacts on river and groundwater systems and valuable aquatic ecosystems [39]. The scarcity problems were induced at first by extractions of surface waters, with the level of over extraction (i.e.

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extractions that occurred at the expense of environmental flow requirements) amounting to 270 km3 per year in 2010 [40]. But recently water scarcity is worsening because of the unprecedented depletion of groundwater. Between 1960 and 2010, global groundwater extractions increased substantially from 372 to 952 km3 per year, pushing depletion (i.e. extractions in excess of natural recharge) from 90 to 304 km3 [41]. The consequence of this overuse of water resources has been a severe biodiversity decline in aquatic ecosystems that exceeds by far that of terrestrial and marine ecosystems [42].

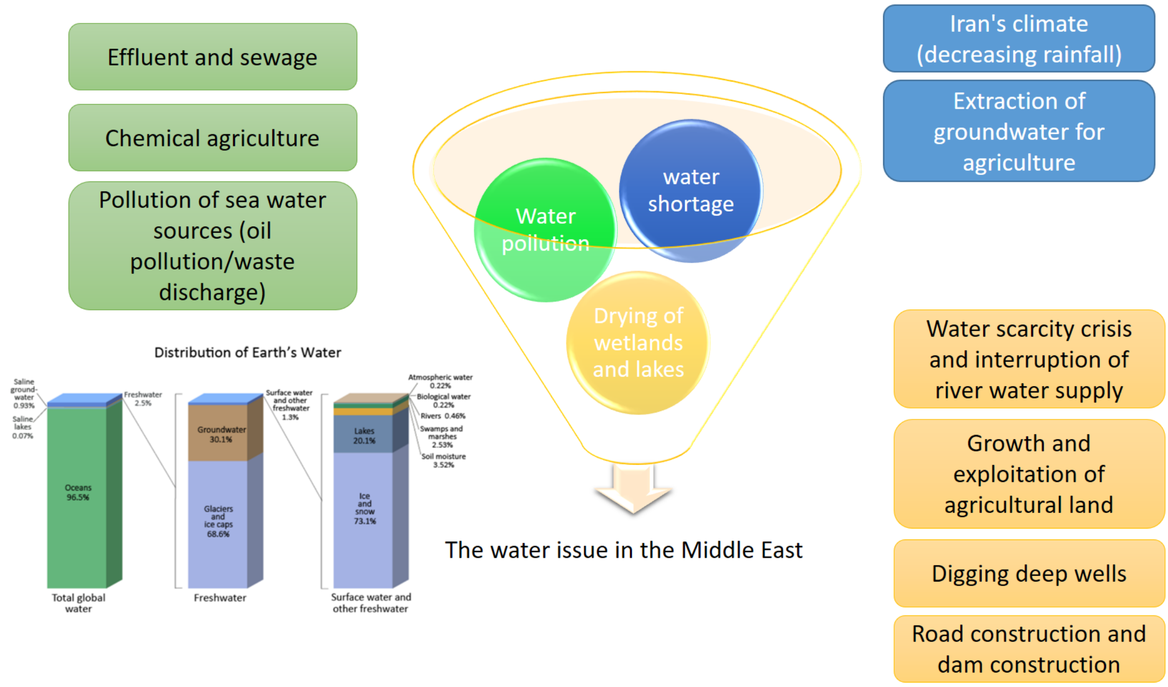
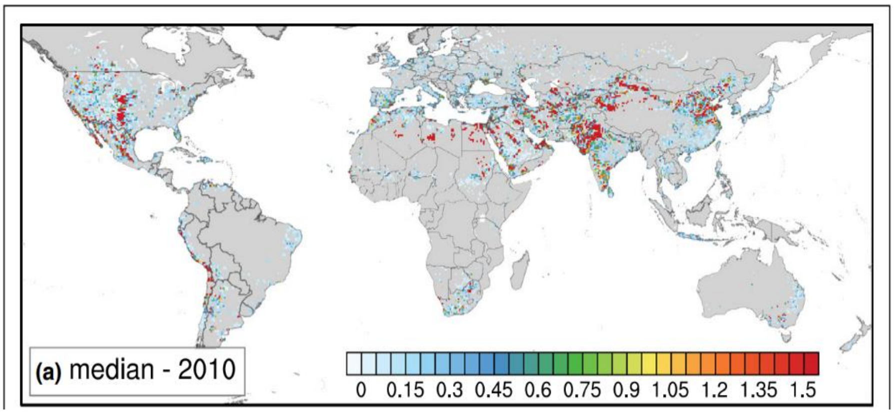


**Figure 1.** The water issue in the Middle East is based on the distribution of water resources in the world



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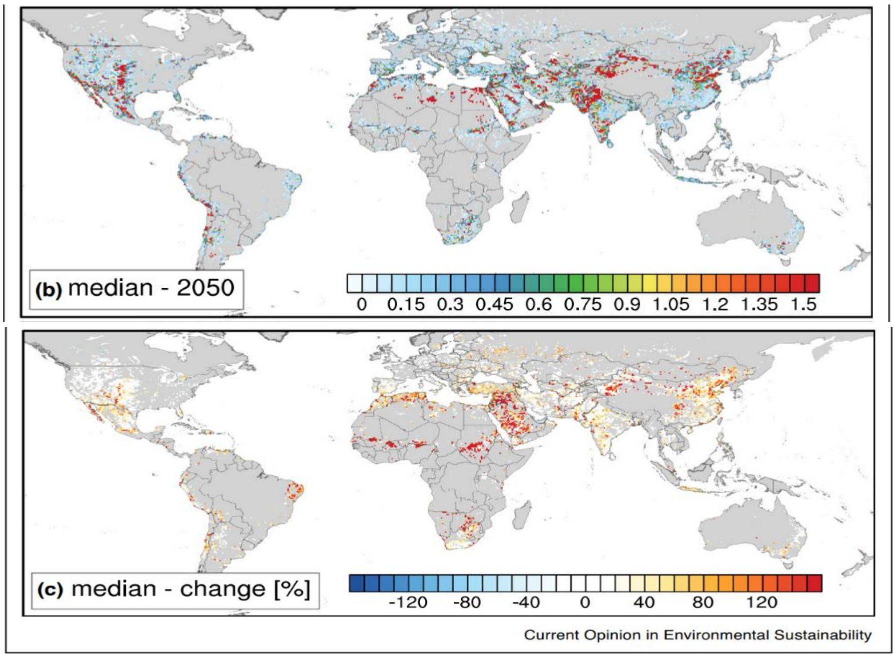

**Figure 2.** Median of the Water Scarcity Index (WSI) for 2010 (top row) and 2050 (middle row) derived from a multi-model, multi-scenario ensemble of 45 global water scarcity projections. WSI is the ratio of total withdrawals for human use to total available surface water resources. Regions are considered water-scarce if the ratio is between 0.2 and 0.4, and severely water-scarce if the ratio is greater than 0.4. All grid points with the WSI being below 0.1 are considered as non-water scarce and are masked. Grid points with very low average water demand are also masked. Relative changes [%] in the median of the WSI between 2010 and 2050 are displayed in the bottom row. For irrigation water demand projections, historical values (the year 2000) are used for irrigated areas and irrigation efficiency [32]

A need for a nexus modeling approach to assess water scarcity solutions A wide range of solution options could be implemented to address the growing water scarcity, including supply-side and demand-side management options that span the water, energy, and agricultural sectors. The supply options are investments in water infrastructure and advanced treatment technologies (e.g. storage facilities, water transfer, water recycling and reuse, and desalination). The demand management options are improvements in water-use efficiency (e.g. use of more efficient irrigation systems and domestic devices, reducing leakage in water infrastructure), changes in water allocation mechanisms (e.g. use of market-based allocation), improvements in crop water productivity (e.g. Use of new cultivars or higher efficiency of nutrient application), production reallocation and virtual water trade (e.g. reducing the production of water-intensive products and relying on imports from areas with abundant water resources), and reducing water demand through lifestyle changes related to food and energy consumption

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(e.g. adopting healthy diets, reducing food waste), among many others [33,43–48]. However, these options involve tradeoffs among various societal objectives, especially when the interactions between these objectives are not properly considered. For example, Dalin et al. [49] showed that international trade aiming to achieve food security triggered large irrigation-based groundwater depletion in many parts of the world threatening water security. Liu et al. [50] found that pursuing sustainable irrigation may constrain achieving food security and other environmental goals due to higher food prices and cropland expansion. Despite these tradeoffs, synergies among options also exist. For instance, advancements in treatment technologies have increased the energy efficiency of wastewater treatment plants, thereby reducing energy use while increasing water supply for irrigation [51], and development of drought-tolerant crops could at the same time reduce irrigation water use and save energy used by irrigation systems [52]. From a modeling perspective, significant efforts have been made to analyze nexus issues from various aspects including calculation of resource flows and their dependencies, assessment of technology and policy applications, and quantification of system performance. Mathematical programming with optimization [53] or simulation models [54] have been used to create tradeoff frontiers between water supply and quality, irrigation production, power generation, economic benefits, and environmental requirements. Embedded resource accounting approaches have also been used, such as life cycle and footprint assessment methods [55,56], which reveal the hidden linkages between nexus resources, the challenges facing the achievement of some of the Sustainable Development Goals (SDGs), and the tradeoffs and synergies throughout the value chain [57,58]. Another method is Computable General Equilibrium (CGE) modeling to evaluate the impacts of policies on the entire nexus system, rather than focusing only on how economics affects one sector [59]. Integrated assessment models have been employed to establish tradeoffs between climate change mitigation, energy system transformation and water supply [60], and between agricultural production and water scarcity [61]. Other nexus methods that have been used in the literature include system dynamics and agent-based modeling, econometric analysis, and ecological network analysis [62]. Despite significant advances in nexus modeling, there are still many challenges that face the development of efficient nexus tools capable of concurrently integrating the different sectoral objectives and resource constraints. One important challenge is related to methods of analysis that vary in response to the scale, sectors, and research priorities of a specific nexus system. Specifically, a higher degree of data aggregation is required as the system scale moves up. Conversely, more detail of the processes of nexus system should be represented, as the system scales down. However, the ability to model at multiple spatial scales and across sectors is increasingly necessary given that local conditions constrain nexus supply systems, while some policy interventions such as international trade and transboundary agreements can only be assessed at global and regional scales. Moreover, solutions identified at the large scale need to be validated in the local context given that

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management, policy, and investment decisions are made at national and subnational levels. This level of complexity indicates that no single model or tool could cover the entire nexus system challenges [63]. Therefore, there is a pressing need for new tools and methods that connect inputs and outputs between well-established models, followed by analysis of the results in an integrated way. The CLEWS framework (climate, land-use, energy, and water strategies) [64] goes some way toward this and is being tested for various locations. It included the use of publicly available tools such as LEAP and WEAP (respectively, Long-range Energy Alternatives Planning System and the Water Evaluation and Planning System). Nevertheless, integrating models across scales to enable decision-makers to distil information and consider the impacts at a range of scales, is still required [65].

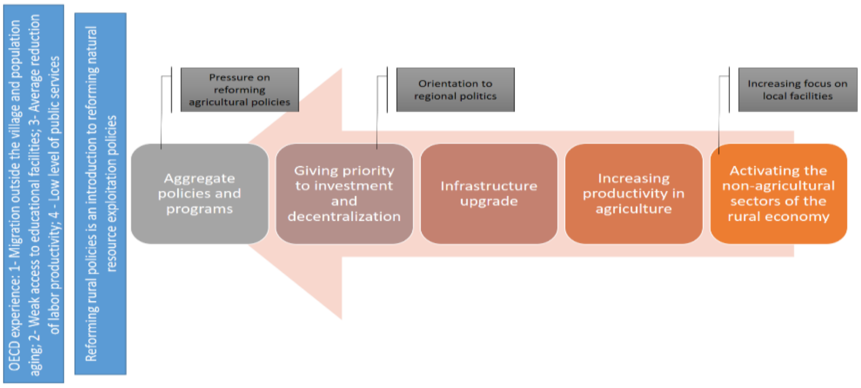

**Figure 3.** Reforming natural resource exploitation policies

### 2.2.Hydro politics and perception of cooperation and conflict

Hydro politics is a web of dichotomized approaches exploring the dynamics of interstate cooperation and conflict over shared water resources that transcend international borders [66]. In classical hydro political theories [67,68], sovereign states are the key players, mostly because they can multiply shared benefits, build mutual trust and stimulate other desirable outcomes from utilizing transboundary water resources. Optimizing transboundary water management is, therefore, an ultimate goal that must be pursued whatever it costs. The first systematic reconsideration of cooperation and conflict came in the critical hydro political literature [69,70], which refined existing research on transboundary water interaction and sought to find common ground among different academic fields [71]. Many scholars then recommend analyzing cooperation and conflict simultaneously [72], avoiding subjective judgement [70,73], recognizing differences between intensities of cooperation and conflict [73], and devoting more effort to studying external factors, particularly in terms of water governance and power [74-76]. Although existing knowledge about transboundary water interaction still lacks clear conceptualization on how to overcome the extreme complexity of water challenges [77], there are several key aspects that may determine the dynamics of both cooperation and conflict.

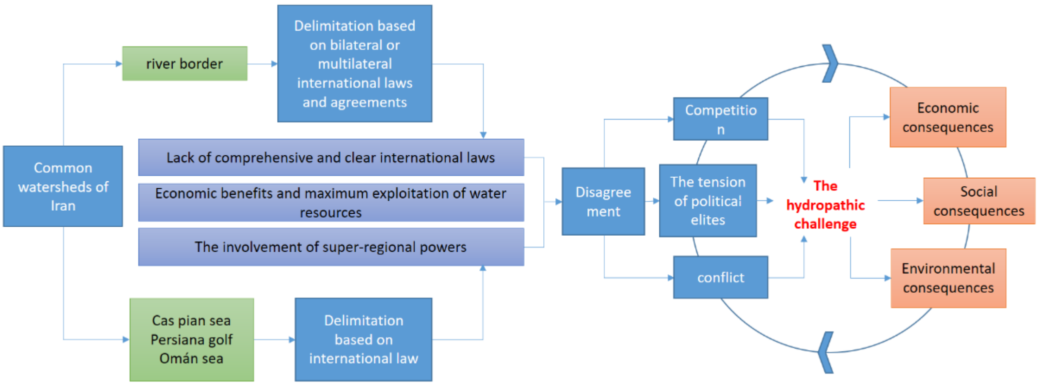

**Figure 4.** Creating challenges of engine hydro politics with the key role of Iran and its consequences

### *2.3.The Transboundary Water Interaction Nexus*

Drawing on the Basins at Risk Scale [78,79], we can see several indicators for intensity of cooperation or conflict. For cooperation, authors have considered incentives to cooperate, outcomes of joint actions, actors' intention to contribute to collective action, incentives for measuring willingness to cooperate, benefit sharing behavior, and level of responsibility and reciprocity [80-82]. Less attention has been paid to enforceability of legislation promoting cooperation in terms of binding ness of legislative acts (the agreement can be in place, but it does not mean that cooperation can be enforced) [83,84], the exercise of power [76,85] or power distribution among local actors [86]. Based on the work of Mirumachi and Allan (2007), Mirumachi (2015), and Zeitoun and Mirumachi (2008), five intensities of cooperation (from low to high) can be identified [80,81,73]:

(1) Confrontation over an issue. States acknowledge water issues but make no towards joint action. Instead, they act individually and without the intention of cooperation.

(2) Ad hoc cooperation. States undertake joint actions coincidentally, without sharing goals – for example, State A wants to reduce water pollution to protect a fishery, while State B wants to improve the quality of shared waters to promote ecotourism.

(3) Technical cooperation. States have compatible goals but do not agree on how to achieve them – for example, while State A improves water infrastructure to promote water transportation, State B proposes new traffic regulations, contributing to the same goal by a different pathway.

(4) Risk-averting cooperation. States know what they want and how to achieve shared goals, but they lack consensus on what responsibilities and guarantees would safeguard their

collective actions. For example, both countries might agree on a sustainable water flow regime, but rising water demand may motivate the upstream country to divert water to other destinations, reducing the benefits that are shared with other states.

(5) Risk-taking cooperation. States synchronize national interests along with domestic policy and absorb the associated costs without demanding reciprocity. For example, State A might provide hydrological data for free to State B even though this adds a substantial cost for data collection and translation into standardized formats.

Four intensities of conflict from low to high are therefore represented by:

(1) Non-politicized conflict. States are not concerned about water issues, or water issues are not part of the public domain. Issues like decreasing water levels due to dams' operation may lead to complaints to local authorities, but do not reach higher political circles [86].

(2) Politicized conflict. Water issues become part of the political agenda, and states calculate their willingness to solve the clash of interests. For example, downstream states negotiate with upstream countries to divert more water from the mainstream. Downstream states may then consider building their own multipurpose dams to store more water or negotiate with upstream countries to set up some win-win provisions for ensuring sustainable water flow.

(3) Securitized conflict. States undertake emergency measures to justify specific actions, or legitimize certain actions in an extraordinary way, outside regular political procedure, to gain more benefits from existing situations [81]. For example, an upstream state may build a hydropower dam to boost its domestic economy. The dam's socio-environmental impacts on downstream countries may prompt various kinds of retaliation.

(4) Violent conflict. States step beyond the realm of normal politics and adopt any sort of measure to gain control over the shared waters. So far, this has only included acts of water terrorism [87] or violence at the domestic rather than the interstate level [88].

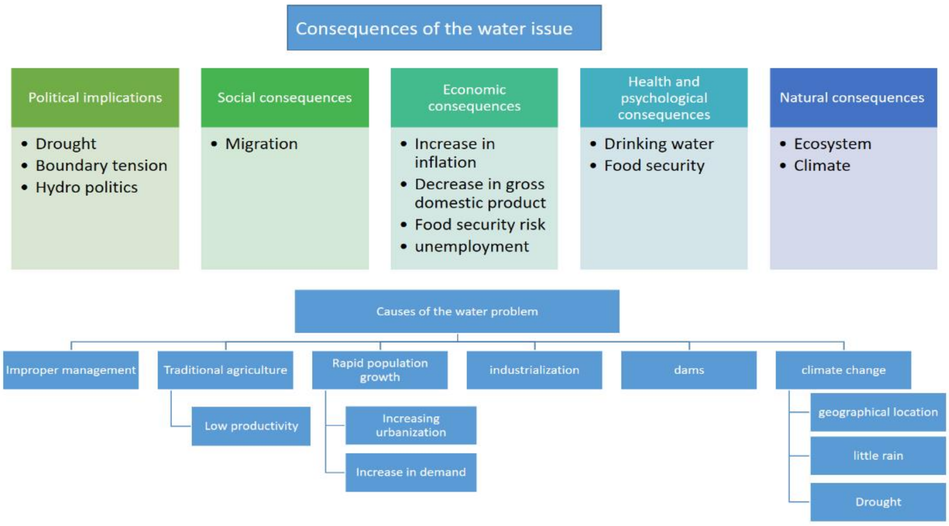

**Figure 5.** The causes and consequences of the water problem at the global level

### 2.4.Transboundary water treaties

Oregon State University’s Transboundary Freshwater Dispute Database (TFDD) provides comprehensive datasets on water resources and recently identified more than 310 international transboundary river basins globally (2018), which are shared between at least two countries (Fig. 6a). Also, the International Groundwater Resources Assessment Centre (2015) has identified 592 transboundary aquifers in the world (Fig. 6b). The world’s transboundary river basins span 151 countries, include more than 2.8 billion people (around 42% of the world’s population), cover 62 million km2 (42% of the total land area of the Earth), and produce around 22,000 km3 of river discharge each year (roughly 54% of the global river discharge) [89]. The existing 310 transboundary lake and river basins cover almost one half of the globe’s land surface and 60% of global water flow and are also home to 40% of the world’s population (TFDD) [89]. The socioeconomic and environmental costs of challenges in transboundary waters, unpredictable future (including regional peace, security and prosperity), and long term reactions for rehabilitation disturbed relations between countries are essential parameters which persuade governments to establish robust transboundary water treaties.

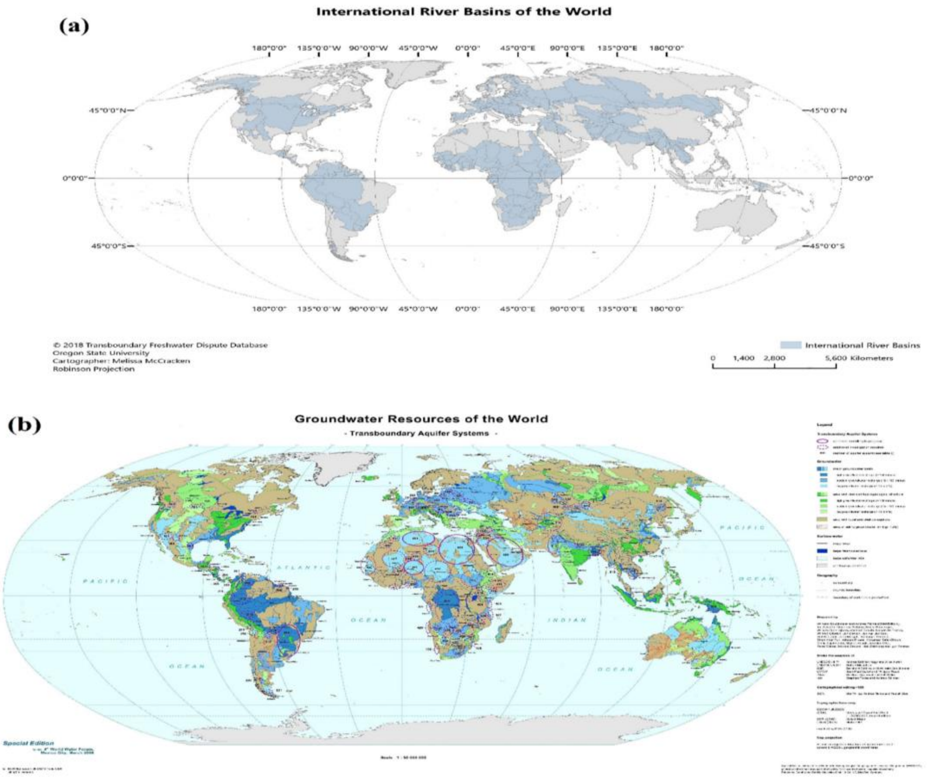

**Figure 6.** a) Transboundary river basins and b) Transboundary groundwater resources (Source: www.twap-rivers.org-2023 and www.un-igrac.org-2023).

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### *2.5.The importance of Iran's position in the Middle East*

Despite of relatively advanced water management system than other Middle Eastern countries, Iran is experiencing a serious water crisis [90]. For example, water scarcity was intensified by growing demand in different sectors which has created environmental, social, and economic challenges in the Urmia Lake Basin [91]. The government blames the current crisis on climate changes, frequent droughts, and international sanctions, believing water shortages are periodic, but Iran is mainly suffering from a socio-economic drought which is named water bankruptcy, where water demand exceeds the natural water supply. Madani et al. explained the current status of water resources in Iran and introduced three major troublemakers for the current water crisis: (1) rapid population growth and inappropriate spatial population distribution, (2) inefficient agriculture sector, and (3) mismanagement and thirst for development [92]. In theory, this problem can be resolved by reestablishing the balance between water supply–demand through developing additional sources of water supply and implementing aggressive water demand reduction plans [93].

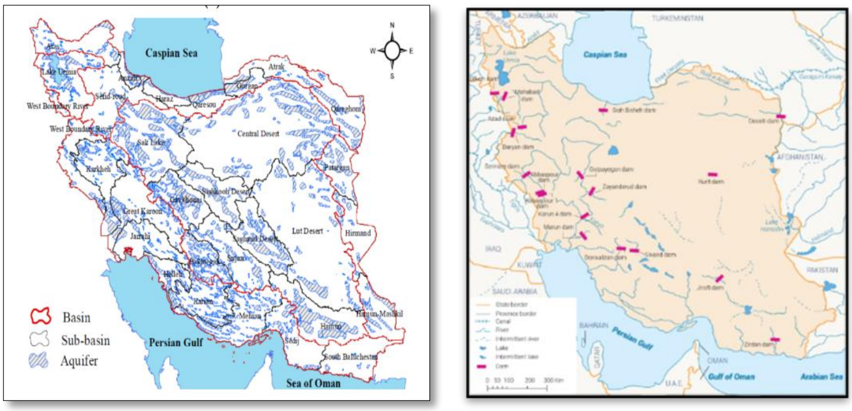

**Figure 7.** Distribution of aqueducts and underground water tables and aquifers in Iran

**Table 1.** Long-term monthly values of groundwater storage in different sub-basins in Iran

| Sub-Basins | Code | Trend (Mm$^3$/yr) | Sub-Basins | Code | Trend (Mm$^3$/yr) |
|---|---|---|---|---|---|
| Aras | 11 | −63.107 | Urmieh | 30 | −535.362 |
| Anzali | 12 | −13.873 | Daryache Namak | 41 | −2881.360 |
| Sefidrood Bozorg | 13 | −281.418 | Gav khooni | 42 | −465.545 |
| Sefidrood-Haraz | 14 | −31.955 | Tashtak | 43 | −695.810 |
| Gharasoo-Haraz | 15 | −16.708 | Abarghoo | 44 | −1521.080 |
| Gharasoo-Gorganrood | 16 | −50.125 | Hamoon | 45 | −1039.140 |
| Atrak | 17 | −3867 | Kavir loot | 46 | −1399.170 |
| Marzi-e-Gharb | 21 | −240.328 | Kavir Markazi | 47 | −4502.970 |
| Karkheh | 22 | −591.728 | Kavir Siahkooh | 48 | −185.784 |
| Karoon | 23 | 34.798 | Kavir Daranjir | 49 | −933.010 |
| Hendijan-Jarahi | 24 | −247.809 | Khaf | 51 | −368.318 |
| Hele | 25 | −100.770 | Hirmand | 52 | 7.842 |
| Mand | 26 | −567.042 | Mashkil | 53 | −209.970 |
| Mehran | 27 | −830.647 | Ghareghome | 60 | −2178.660 |
| Bandar Abbas | 28 | −441.877 | | | |
| Baloochestan Jonubi | 29 | −20.909 | | | |

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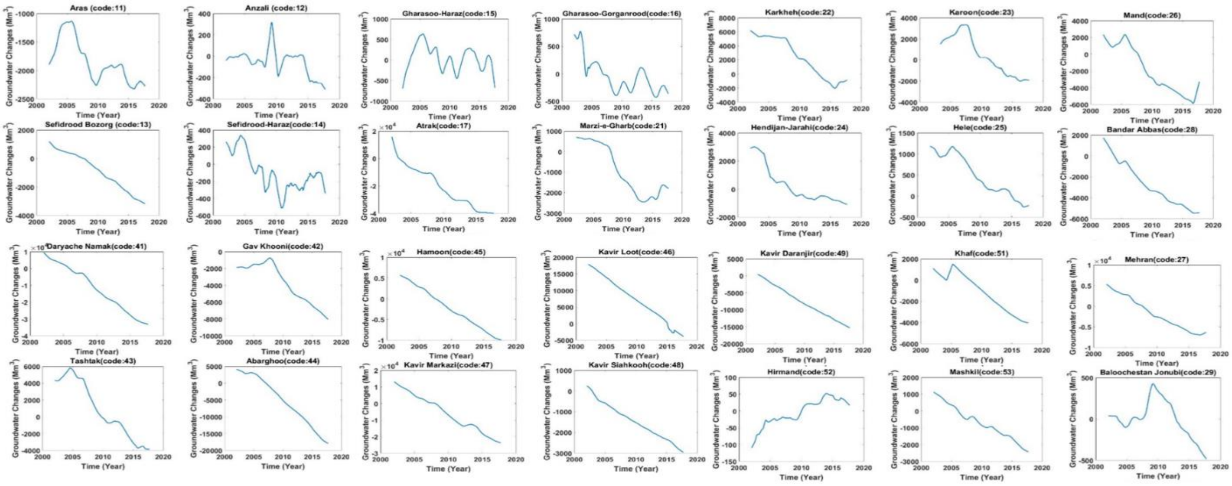

**Figure 8.** Long-term monthly values of groundwater storage in different sub-basins in Iran

### *2.6.The shape of the future*

According a report by Munia et al., water stress was already high when considering only local water usage, affecting 0.95– 1.44 billion people or 33%–51% of the population in transboundary river basins. After accounting for upstream water use, stress level increased by at least 1% for 30–65 sub-basins, affecting 0.29–1.13 billion people. Altogether 288 out of 298 middle-stream and downstream sub-basin regions experienced changes in stress level. The conflicts and cooperation events originated from a combination of different drivers. While it is well recognized that upstream water use in transboundary river basins increased the water scarcity in downstream parts of the basin, this had not been quantified in the global scale. Water stress was already high even when considering only local water use. When including upstream water use, the population under water stress increased slightly, but stress levels intensified considerably in many areas. Therefore, it was observed that cooperation and conflict were not directly dependent only on water stress or water use and there were other different drivers which were important [94]. The inequities (e.g., political and financial) which derived from unequal resources were shared between several states, caused threatening and weakening of their effectiveness [95]. Treaties toward transboundary cooperation can be more resilient to conflicts through the involvement of third parties (A third-party, is a person who may have the right to sue on a contract, despite not having originally been an active party to the contract). Third-party involvement is a concept which can describe diplomatic, economic or virtual engagement on a shared water resource. Also, third-party involvement indicates a level of influence from an outside party on the decisions and agreements made between riparian countries on shared waters. Transboundary water resources of Iran are shown that neighbor countries have improved their transboundary water cooperation, but some important challenges exist. The lack of appropriate management structures in common exploitation and the

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management of surface and underground waters can turn the exploitation of these resources into a crisis and tension between countries. Wars like the Iran-Iraq war and the silent regional wars over cross-border resources which lead to irreparable damage are the result of this type of approaches. Therefore, decision-makers should consider the long-term solutions which can control short-term conflicts, too. Nowadays, hydro politics is more focused on the regional and local scale which deal with the policies of countries on the distribution, control and quality of water resources. These issues can also lead to tensions among countries. To study the relationship between water and politics at the regional level, water resources are discussed on both sides of the border, and the main disagreements from the boundary water resources come about exploitation of water resources and river basin management. Climate change, excessive exploitation, consumption of water resources, centrality of agriculture in the national economy, traditional methods of irrigation, and the loss of a significant portion of resources are also the most important causes of water scarcity among the Persian Gulf and the West Asia countries. Due to the implementation of socio-economic development programs, the demand for water is increasing sharply. Resolving disputes and crisis which arise between countries is difficult in two aspects. First, there is no clear and decisive international law to protect and divide water between beneficiary countries and communities, and one-third of the world's rivers, such as the Danube in Europe, are subject to the special local and regional contracts, and the Helsinki agreement on the use of international rivers in 1966 emphasizes that every country within its borders has fair right to access to international waters. Therefore, the lack of certainty and transparency of international law prevents an agreement between countries. Second, water scarcity is considered to be geopolitical crisis which is long-standing and cannot easily be resolved, in contrast to the political crisis which can be easily resolved at meetings. Geographic values in one country are also considered as national interests, and governments cannot easily bargain over national interests.

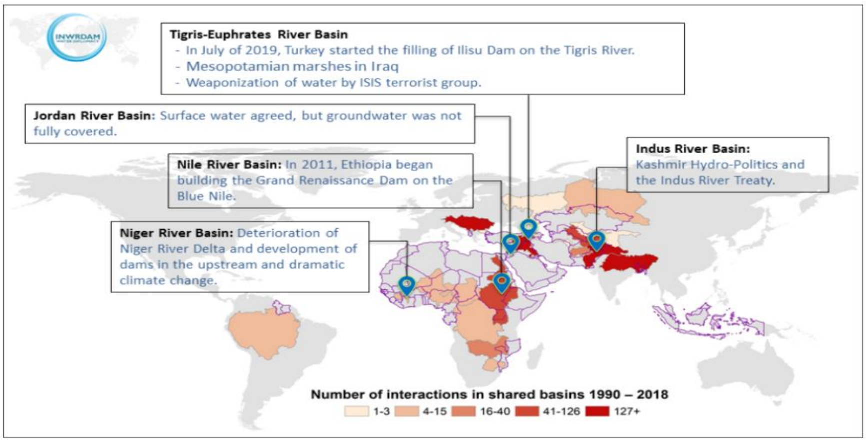

**Figure 9.** Investigating the problem of hydro politics in the rivers of the Middle East region (www.inwrdam.net )

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### *2.7.International water law*

International water law regulates the usage of international watercourses which are located partly in different countries. The 1997 UN Convention on the Law of the Non-navigational uses of International Watercourses (UN Watercourses Convention) [96] and the 1992 United Nations Economic Commission for Europe (UNECE) Convention on the Protection and use of Transboundary Watercourses and International Lakes (ECE Water Convention) are two conventions which covering this field. These two conventions have general principles, such as cooperation, equitable, reasonable utilization, and the no-harm rule [97]. In the framework of international water law, cooperation between countries which have shared water basin is difficult because of water scarcity. Based on international water law, basin conditions (e.g., geographical, hydrographical, ecological, and hydrological features, climate, type of drought, politics, economy, culture) need to be identified and evaluated for analysis of key sectors and indicators, due to the benefits and costs of stakeholders, assessment of intersectional issues, and decision-making based on the nexus dialogue [98].

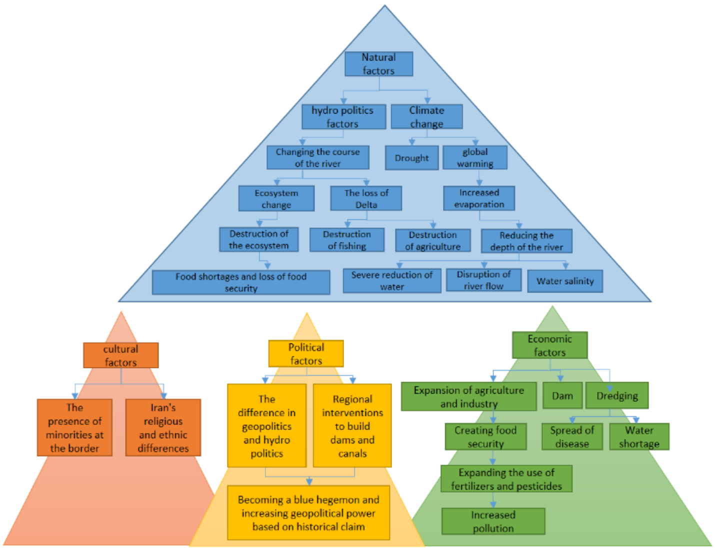

**Figure 10.** Factors affecting the creation and escalation of disputes in the Middle East

### *2.8.Water governance*

The water governance refers to social, economic, administrative, and political systems influencing the transboundary water use and management. Dinar et al. described water governance means ‘‘who gets what water, when and how much, and who has the right to water related benefits” and it can minimize water conflicts and enhance cooperation between upper and lower riparian states [99]. In one study, Kalair et al. conducted research on Indus Water Treaty (IWT), which is cited to be one of the few efficient settlements of boundary water basin

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conflicts that has stood the test of times since last decades. According to IWT, India has gained control of three eastern rivers (Ravi, Beas and Sutlej) and Pakistan has obtained control of three western rivers (Indus, Jhelum and Chenab). As a successful example for presenting water governance principles, upper and lower riparian states of IWT have bonded by WEF nexus [100]. A major challenge of collaborative governance is deciding on the appropriate scale, by defining regulation boundaries and identifying catchment areas and river basin dimensions [101-103]. Also, Dai et al. believe we need to improve our ability for better classification of existing approaches which help us to compare the capacities, strengths and weaknesses between them. Thus, a wider group of stakeholders and scientific community can utilize their existing knowledge to improve their effective management by focusing on ‘‘governing” and ‘‘implementing” the nexus [104].

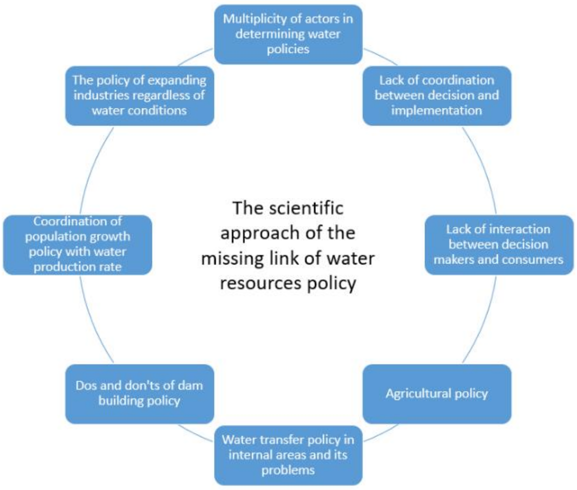

**Figure 11.** The scientific approach of the missing link of water resources policy

Transboundary water conflict resolution mechanisms Transboundary conflict resolution process is defined as a complex multi-dimensional process which needs a process-based approach to analyze. As an analytical framework, a mechanism provides holistic analysis of process with it’s different components, such as, riparian states and stakeholders goals, initial and terminal conditions, and environment constraints. These mechanisms consist of game theory, static and dynamic systems engineering models, social planner, water market, and negotiation analyses, which have same characteristic features in some cases. Engineering literature has covered prediction and planning, economics analysis focused on explanation and planning in transboundary water conflict resolution mechanisms, political studies explain the political limitations in transboundary water conflicts, management decisions have concentrated on some studies that related transboundary water conflicts [74]. In this case, Tayia addressed the gap between theory and practice in the field of transboundary water conflict resolution.

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Therefore, many of these mechanisms can be combined together to shape a paradigm with strong analytical capacity by more collaboration and cooperation [74].

### *2.9.Integrated water resources management*

Integrated water resources management (IWRM) as an approach could improve benefits for all riparian states and has been implemented through international, national, and regional water management guidelines. According the principles of IWRM, cooperation of riparian states and stakeholders is needed for any improvement in the basin especially in transboundary basins. Water, energy, and food issues are often strongly interlinked in the international water resources [105]. Therefore, possible frictions between the riparian countries and different interests make the nexus approach even more challenging than national level [106,107]. In this case, implementation of zero-sum approach for all parties generates more conflicts. Middle East has many challenges for easy access of riparian states to freshwater resources which induced severe disputes in shared water basins. The IWRM could be a paradigm for Middle East countries to promote their treaty implementation on transboundary waters [108].

### *2.10. Water-energy-food nexus*

As a general definition, the process of linking different stakeholders' ideas and activities under various conditions and circumstances to attain sustainable evolution and development is called ‘‘Nexus” concept. First, the WEF nexus has introduced at the Stockholm Environment Institute in the Bonn 2011 Nexus Conference. Also, water-energy-land (WEL) nexus was proposed by European Report on Development in the 2011–2012. Recently, more complex linkages have been introduced to interact with more core sectors, such as, climate, land, energy and water (CLEW) nexus [109]. The interdependencies among water, energy, and food are dynamic, numerous and multidimensional [34,110,111] which has emerged as a multi-centric lens for assessing integrated resources management and sustainable development. The discourse on food, water, and energy security is driven by growing pressure on natural resources [112,113]. It is not yet clearly understood how the concept can be applied to ensure food, water, and energy security. Although understanding the different interfaces in the WEF nexus will be critical for taking action. Actions in one sector usually induce impacts on the others, with economic, environmental, political, and social implications. Indeed, the security of one sector often cannot be achieved without undermining another sector [114-116]. Human security is in the core of triangle of this nexus which depends on availability of water, food, and energy resources. Developing countries face a serious challenge in meeting the growing demands for food, water, and energy. Although the concept of WEF nexus is gaining international currency, and adaptation to climate change has become an urgent need [117]. Nexus approach means that when governments and industries determine policies in one sector whether it is energy, agriculture, food or water, they take into account the implications in other

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sectors. Nexus thinking emerged from an understanding that natural resources are beginning to limit [116]. Smajgl and his coworkers described the WEF nexus which emerged as a new perspective in debates concerned with energy, water or food security. Current frameworks are partial as they largely represent a water-centric perspective. Our hypothesis is a dynamic nexus framework which attempts to equally weight sectoral objectives to provide a new paradigm for diagnosis and investigation [118]. Nexus policies are being enabled at different spatial extents from regional, transboundary, and national scale to an urban level. In this case, appropriate mechanisms and decision support tools to achieve integrated nexus planning are evolving. Simpson and Jewitt reported, there are several motivations for applying the WEF nexus as a multi-centric framework. First, is the security of resources, with the extreme weather events, natural disasters, the failure of climate change mitigation, and water crisis as four of the top risks in the Global Risks Report 2018 [119]. Also, they addressed the trade-offs between the sectors which need to be managed and optimized as a second motivation. The nexus must be considered to be a framework, not a recipe, because it is a mechanism for achieving the relevant sector related SDGs [119]. Further, the lack of a supporting integrated framework and the clear lack of agreement on the definition of the WEF nexus are problematic [120]. Agriculture is the largest consumer of the world’s freshwater resources, and more than one-quarter of the energy used globally is expended on food production and supply. The inextricable linkages between these critical domains require a suitably integrated approach to ensuring WEF security, sustainable agriculture, and energy production. Due to especial situation of Iran we need an approach which reduces conflict and brings cooperation instead of competition among parties. In this case, nexus approach is really helpful because of the flexibility and efficiency.

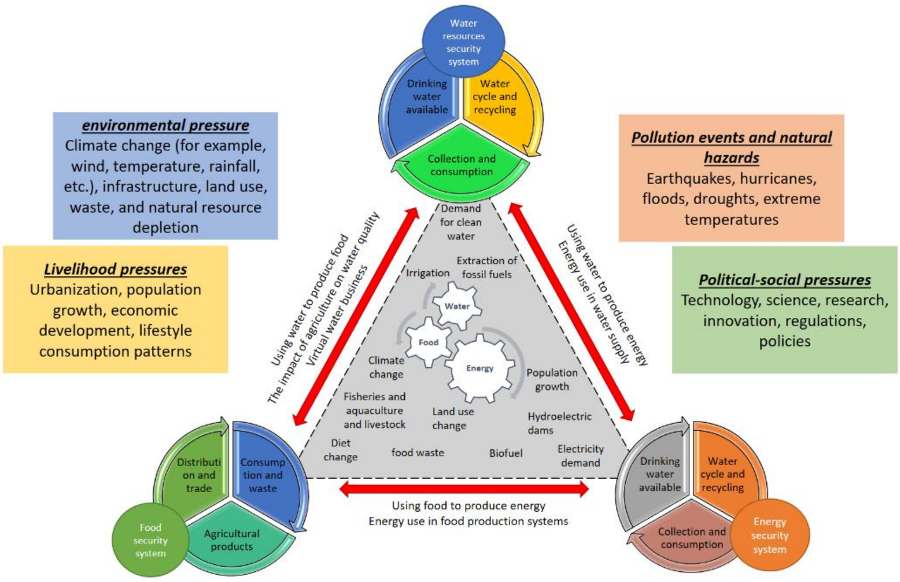

**Figure 12.** Conceptual framework of water-energy-food Nexus factors

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### *2.11. Quantitative assessment of WEF nexus*

To address WEF security, adopting novel WEF production technologies in innovative way is necessary. Clarification of the status and the influence of any proposed WEF nexus policy option or scenario, needs the quantitative assessment of WEF nexus as an important tool. In this case, the quantitative nexus models require a significant number of inter-sectoral data, e.g., quantities of water used in energy production, energy used in water production, and water and energy used in food production, etc., which are generally lacked or difficult to access and collect. Karnib and Alameh claimed, to overcome WEF data availability and to improve quantitative WEF nexus analysis, adopting a technology-oriented framework for WEF nexus offers a vital opportunity, which can advise stakeholders and policy makers about the direct and indirect water and energy quantities needed for any proposed policy setting [121]. Several nexus studies have been recently conducted in the Middle East. For example, Dubreuil et al. proposed an assessment optimized model for WE nexus in the Middle East region, considering unconventional water resources, such as, desalination and wastewater [122]. The main environmental degradation drivers in the MENA region had studied by Al-Mulali and Ozturk and they discovered that trade openness, ecological footprint, urbanization, energy consumption, industrial development and political stability are the critical contributors of environmental degradation in the [123]. Further, the carbon dioxide emissions, economic growth, and energy nexus for a total of ten Middle Eastern countries for the period of 1971–2006 was investigated by Magazzino [124]. WEF security is an obvious issue in the Middle East. Hameed et al. through an extensive research, provided drivers impacting the WEF security in the Middle East in the 21st century including water scarcity, extreme events (e.g., droughts, floods, storm surges, and dust storms), economic growth, urbanization, population growth, poverty and political stability. It is crucial to investigate the dynamics behind the WEF security concerns in this region. As a chain circumstances, increasing population along with water scarcity and natural hazards like drought, precipitation extremes, and heat waves contribute to the stress on water resources and energy sector in the region. Also, food production in the Middle East may affected by energy production which cause climate change, due to the greenhouse gases (GHGs) emission. Hameed et al. classified the WEF security in the Middle East into two major categories of WE security and WF security. Also, they proved WE security is directly affected by water scarcity, drought, and economic growth. Therefore, WF security is directly impacted by water scarcity, drought, population growth, political unrest, and urbanization. In their research, they considered poverty and migration as the possible consequences of unsustainable WEF management. There is strong connection among these parameters, and any change of WEF can involve each one of them. [125]. The results showed that most countries in the Middle East are facing WEF resource insecurity owing to weak

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planning or management strategies. Also, the climatic and socioeconomic factors have contributed to the harsh stress on WEF resources, specifically on the water sector [125].

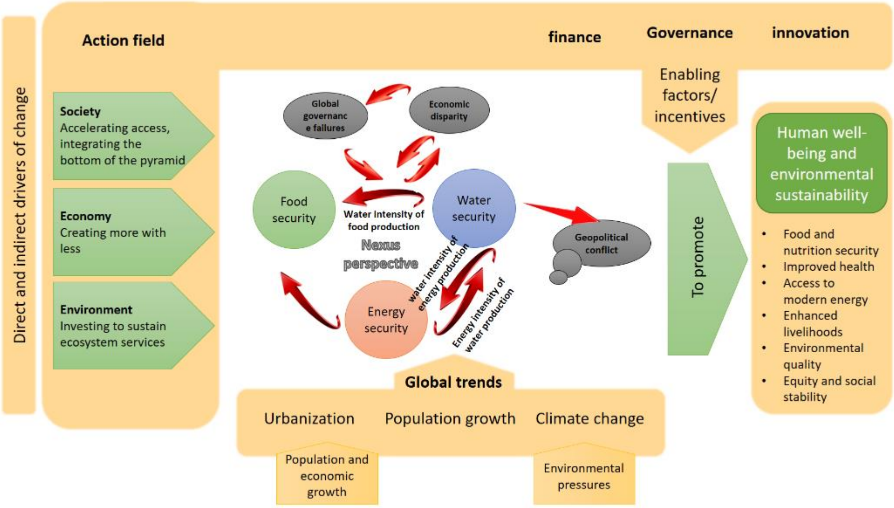

**Figure 12.** Summary of nexus approach for resource security, drivers and outcomes

## 3. Materials and Methods

This Technical Summary describes the global assessment of transboundary river basins, as detailed in the Transboundary River Basins Report (available on http://twap-rivers.org/ ). This is the first truly global and comprehensive assessment of the world’s 286 transboundary river basins covering a broad spectrum of issues (natural and social sciences) and scales (from large to very small basins and Basin Country Units (BCUs)). It is the work of a consortium of nine partners, coordinated by the UNEP-DHI Partnership, Denmark. Partners include: Center for Environmental Systems Research, University of Kassel, Germany; Center for International Earth Science Information Network, Columbia University, USA; City University of New York, Environmental Crossroads Initiative, USA; International Union for the Conservation of Nature; International Geosphere-Biosphere Program; Oregon State University, USA; Stockholm International Water Institute, Sweden, and Delta Alliance. Each partner contributed expertise, datasets, models and assessment tools to undertake this broad global assessment. The aims of the TWAP River Basins component are to: i) undertake a baseline comparative assessment of all of the world’s transboundary river basins, and a selection of deltas, which will enable the identification of priority issues and hotspots at risk from a variety of stressors; ii) establish a sustainable institutional framework to undertake the baseline assessment as well as periodic assessments to track changes over time. The assessment uses indicators of ‘stressors’ which are listed in Table 2 below. They fall under five key themes (water quantity, water quality, ecosystems, governance and socioeconomics) to provide a comprehensive picture of the state

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of transboundary river basins today. Using the same five thematic groups, the report also provides projections for 2030 and 2050, providing some estimates of the state of transboundary river systems for us and the next generation. The assessment strives to address both human and ecosystem vulnerability to stresses since these are closely linked. The baseline and global nature of the assessment limits the extent to which specific causal links between human ecosystem interactions can be established, since these vary from basin to basin and in most cases warrant detailed case investigations.

**Table 2.** Overview of TWAP River Basins Assessment Thematic Groups and Indicators. There are five thematic groups, and 15 core indicators. Five indicators are projected for 2030 and 2050 (According to www.twap-rivers.org ,2023).

| **THEMATIC GROUP** | **INDICATORS** | |
|---|---|---|
| | **Baseline (2010)** | **Projected (2030/2050)** |
| **Water Quantity** | 1. Environmental water stress<br>2. Human water stress<br>3. Agricultural water stress | Environmental water stress<br>Human water stress |
| **Water Quality** | 4. Nutrient pollution<br>5. Wastewater pollution | Nutrient pollution |
| **Ecosystems** | 6. Wetland disconnectivity<br>7. Ecosystem impacts from dams<br>8. Threat to fish<br>9. Extinction risk | [Environmental water stress] |
| **Governance** | 10. Legal framework<br>11. Hydro political tension<br>12. Enabling environment | Exacerbating factors to hydro political tension |
| **Socioeconomics** | 13. Economic dependence on water resources<br>14. Societal well-being<br>15. Exposure to floods and droughts | Change in population density |

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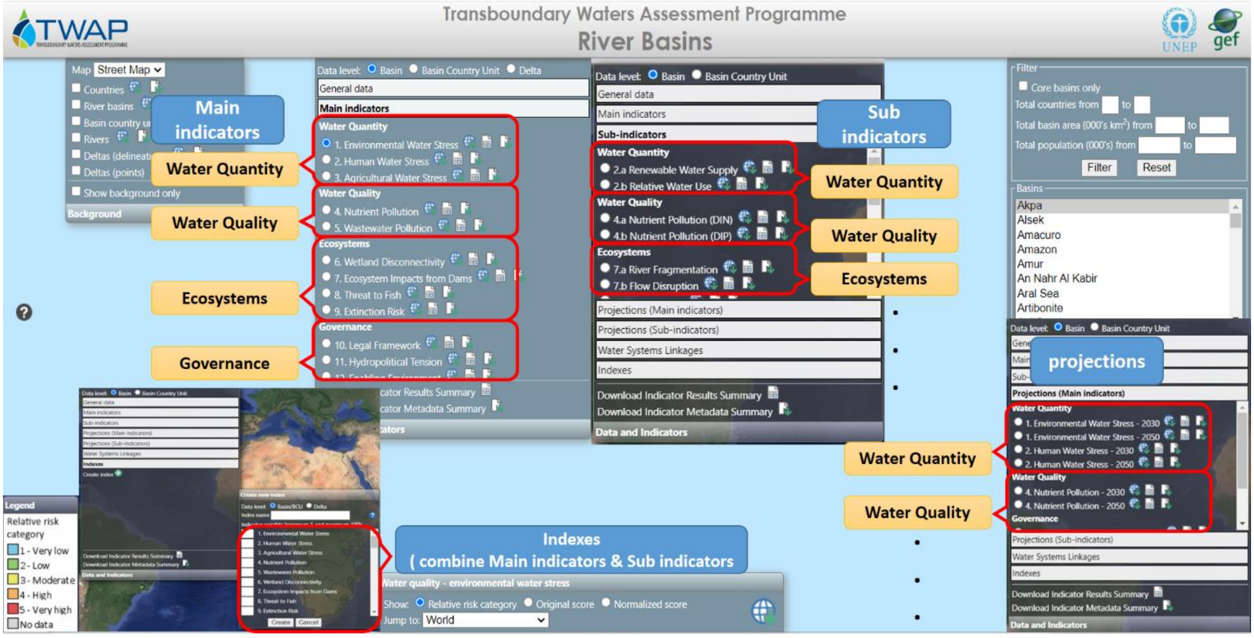

**Figure 13.** Measurable parameters and discussion in the TWAP program (source: www.twap-rivers.org ,2023)

Simulated projections for 2030 and 2050 were generated based on a 'business-as-usual' socio-economic scenario with associated high greenhouse gas (GHG) emissions. These affect future temperature and rainfall patterns, which in turn affect water availability, reliability and variability. The following indicators were considered: environmental stress induced by flow regime alteration, human water stress, nutrient pollution, potential exacerbating factors to hydro political tension, and change in population density. Four future risk hotspots for transboundary river systems were identified. Environmental and human (E&H) water stress is anticipated to increase in all four:

- Orange and Limpopo basins, Southern Africa: increased Environment and Human (E&H) water stress due mainly to increasing water withdrawals, and nutrient pollution due mainly to increased human sewage. Countries affected: Botswana, Lesotho, Mozambique, Namibia, South Africa, Zimbabwe.
- Selected Central Asia basins: range of factors differing between basins, including increased E&H water stress due to combination of projected increases and decreases in water availability, increasing water withdrawal and population density, increased nutrient pollution and hydro political tensions. Basins: Tarim, Indus, Aral Sea, Helmand, Murgab, Hari, Talas, Shu and Ili. Countries affected: Afghanistan, China, India, Iran, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Tajikistan, Turkmenistan, Uzbekistan.
- Ganges-Brahmaputra-Meghan basin: increased E&H water stress due mainly to increased (>50%) water demand driven by population growth. Nutrient pollution remains high, with

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agriculture sources (fertilizer and animal manure) being major contributors and sewage becoming increasingly important, and there is increased risk of hydro political tension associated with new water infrastructure. Countries affected: Bangladesh, Bhutan, China, India, Myanmar, Nepal.

- Selected Middle East basins: continuing high to very high risk of E&H water stress due to decrease in renewable freshwater resources and higher water demand from increased population and irrigation. Nutrient pollution increases or remains in the highest risk category; increased risk of hydro political tension due to political context. Basins: Orontes, Jordan River, Euphrates and Tigris. Countries affected: Egypt, Iraq, Iran, Israel, Jordan, Lebanon, Palestine, Saudi Arabia, Syria, Turkey.

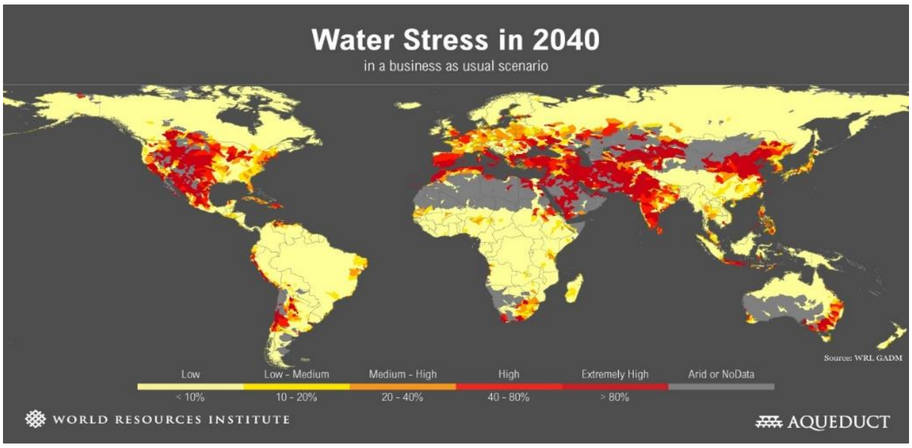

**Figure 13.** water stress in 2040 in a business as usual scenario(Source: world resources institute, www.wri.org )

*3.1.How to choose the areas examined in this article?*

The graphs of long-term monthly values of underground water storage in Iran in different water basins are as follows:

According to the obtained values, it seems that this survey should be done at the global level because the origin of many rivers is not inside the country and originates from outside Iran (the Middle East and Iran's neighboring countries). In addition, according to the historical expansion of transboundary aqueducts and the connection of rivers and water tables at the global level, it is determined which regions of the world should be discussed and compared.

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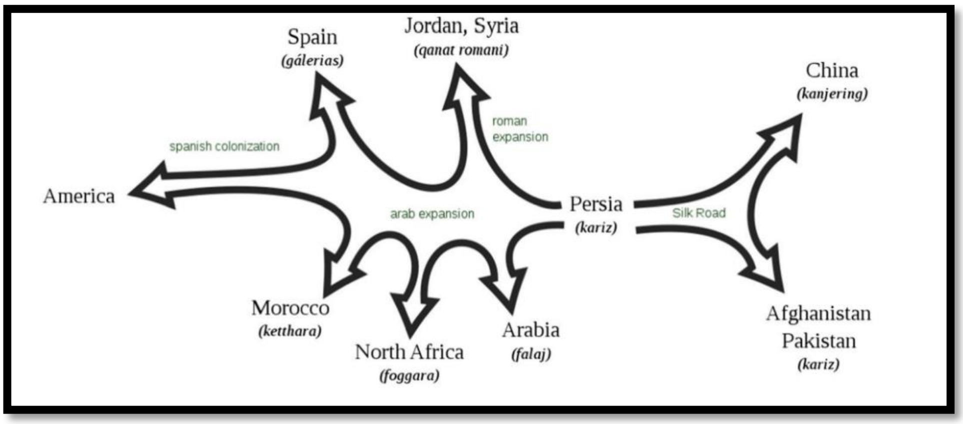
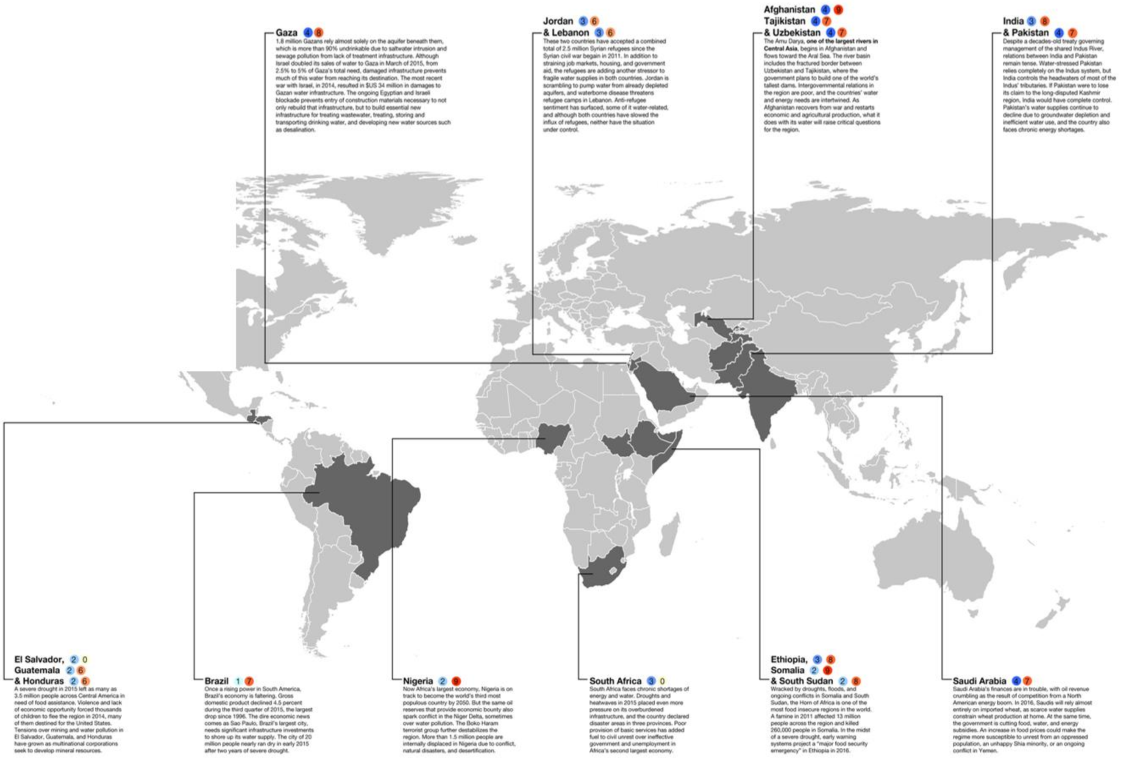


**Figure 14.** Historical expansion of overseas aqueducts



**Gaza** ④ ⑧
1.8 million Gazans rely almost solely on the aquifer beneath them, which is more than 90% undrinkable due to saltwater intrusion and sewage pollution from lack of treatment infrastructure. Although Israel doubled its sales of water to Gaza in March of 2015, from 2.5% to 5% of Gaza's total need, damaged infrastructure prevents much of this water from reaching its destination. The most recent war with Israel, in 2014, resulted in $US 34 million in damages to Gazan water infrastructure. The ongoing Egyptian and Israeli blockade prevents entry of construction materials necessary to not only rebuild that infrastructure, but to build essential new infrastructure for treating wastewater, treating, storing and transporting drinking water, and developing new water sources such as desalination.

**Jordan** ③ ⑥
**& Lebanon** ③ ⑥
These two countries have accepted a combined total of 2.5 million Syrian refugees since the Syrian civil war begain in 2011. In addition to straining job markets, housing, and government aid, the refugees are adding another stressor to fragile water supplies in both countries. Jordan is scrambling to pump water from already depleted aquifers, and waterborne disease threatens refugee camps in Lebanon. Anti-refugee sentiment has surfaced, some of it water-related, and although both countries have slowed the influx of refugees, neither have the situation under control.

**Afghanistan** ④ ⑨
**Tajikistan** ④ ⑦
**& Uzbekistan** ④ ⑦
The Amu Darya, **one of the largest rivers in Central Asia**, begins in Afghanistan and flows toward the Aral Sea. The river basin includes the fractured border between Uzbekistan and Tajikistan, where the government plans to build one of the world's tallest dams. Intergovernmental relations in the region are poor, and the countries' water and energy needs are intertwined. As Afghanistan recovers from war and restarts economic and agricultural production, what it does with its water will raise critical questions for the region.

**India** ③ ⑧
**& Pakistan** ④ ⑦
Despite a decades-old treaty governing management of the shared Indus River, relations between India and Pakistan remain tense. Water-stressed Pakistan relies completely on the Indus system, but India controls the headwaters of most of the Indus' tributaries. If Pakistan were to lose its claim to the long-disputed Kashmir region, India would have complete control. Pakistan's water supplies continue to decline due to groundwater depletion and inefficient water use, and the country also faces chronic energy shortages.

**El Salvador,** ② ⓪
**Guatemala** ② ⑥
**& Honduras** ② ⑥
A severe drought in 2015 left as many as 3.5 million people across Central America in need of food assistance. Violence and lack of economic opportunity forced thousands of children to flee the region in 2014, many of them destined for the United States. Tensions over mining and water pollution in El Salvador, Guatemala, and Honduras have grown as multinational corporations seek to develop mineral resources.

**Brazil** ① ⑦
Once a rising power in South America, Brazil's economy is faltering. Gross domestic product declined 4.5 percent during the third quarter of 2015, the largest drop since 1996. The dire economic news comes as Sao Paulo, Brazil's largest city, needs significant infrastructure investments to shore up its water supply. The city of 20 million people nearly ran dry in early 2015 after two years of severe drought.

**Nigeria** ② ⑨
Now Africa's largest economy, Nigeria is on track to become the world's third most populous country by 2050. But the same oil reserves that provide economic bounty also spark conflict in the Niger Delta, sometimes over water pollution. The Boko Haram terrorist group further destabilizes the region. More than 1.5 million people are internally displaced in Nigeria due to conflict, natural disasters, and desertification.

**South Africa** ③ ⓪
South Africa faces chronic shortages of energy and water. Droughts and heatwaves in 2015 placed even more pressure on its overburdened infrastructure, and the country declared disaster areas in three provinces. Poor provision of basic services has added fuel to civil unrest over ineffective government and unemployment in Africa's second largest economy.

**Ethiopia,** ③ ⑧
**Somalia** ② ⑨
**& South Sudan** ② ⑧
Wracked by droughts, floods, and ongoing conflicts in Somalia and South Sudan, the Horn of Africa is one of the most food insecure regions in the world. A famine in 2011 affected 13 million people across the region and killed 260,000 people in Somalia. In the midst of a severe drought, early warning systems project a "major food security emergency" in Ethiopia in 2016.

**Saudi Arabia** ④ ⑦
Saudi Arabia's finances are in trouble, with oil revenue crumbling as the result of competition from a North American energy boom. In 2016, Saudis will rely almost entirely on imported wheat, as scarce water supplies constrain wheat production at home. At the same time, the government is cutting food, water, and energy subsidies. An increase in food prices could make the regime more susceptible to unrest from an oppressed population, an unhappy Shia minority, or an ongoing conflict in Yemen.

**Figure 15.** Global high-risk points in terms of water resources and border rive(Source: www.twap-rivers.org-2023 and www.un-igrac.org-2023).

According to the map below, which has introduced the vulnerability of resources at the global level and high-risk points, we will select 7 groups of high-risk areas, which we will further analyze and investigate with the cluster analysis method in TWAP program.

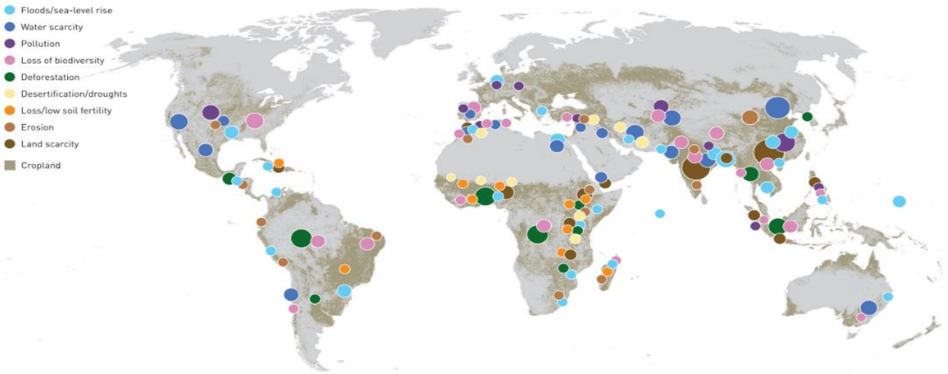


**Figure 16.** Distribution map of the effective factors in reducing the water level of rivers and dealing with the water crisis (Source: www.twap-rivers.org-2023 and www.un-igrac.org-2023).

The need to pay attention to the country of Iran in the Middle East regions, in addition to the size of the area, is the number of main rivers inside the country and borders with neighboring countries. In order to ensure the connection of the hydroelectric problem in the Middle East, especially Iran and its neighboring countries, with the nexus of water, energy and food, an overview was carried out by VOS Viewer software, and according to the results obtained, Iran and the border rivers in the Middle East are also connected with the nexus of water, energy and food. They were close and had the same color (being in a cluster). In addition, some external factors such as agriculture, climate and water extraction systems were also prominent, all of which are a sub-branch of Nexus.

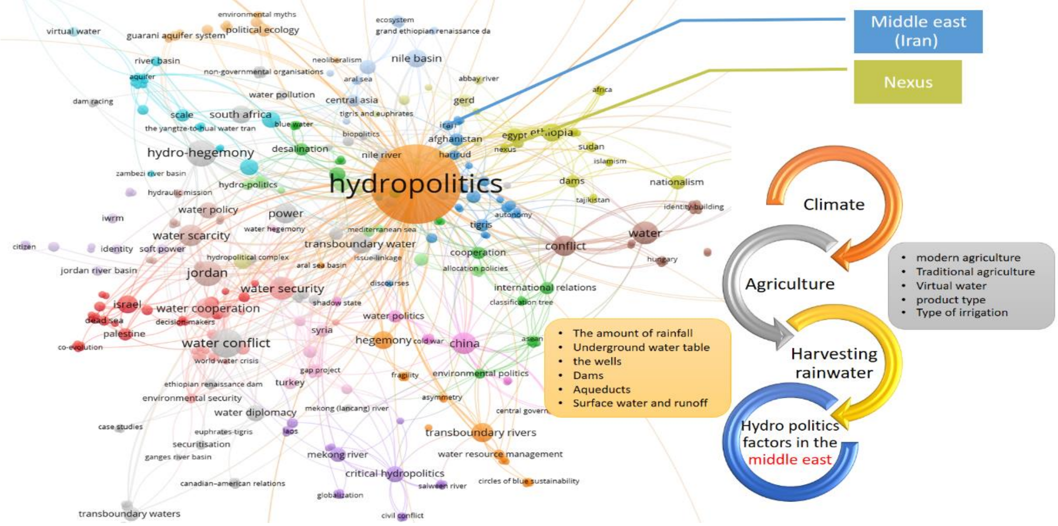


**Figure 17.** Understanding the way of network communication with the keywords of hydroelectric, nexus and middle east in VOS Viewer software

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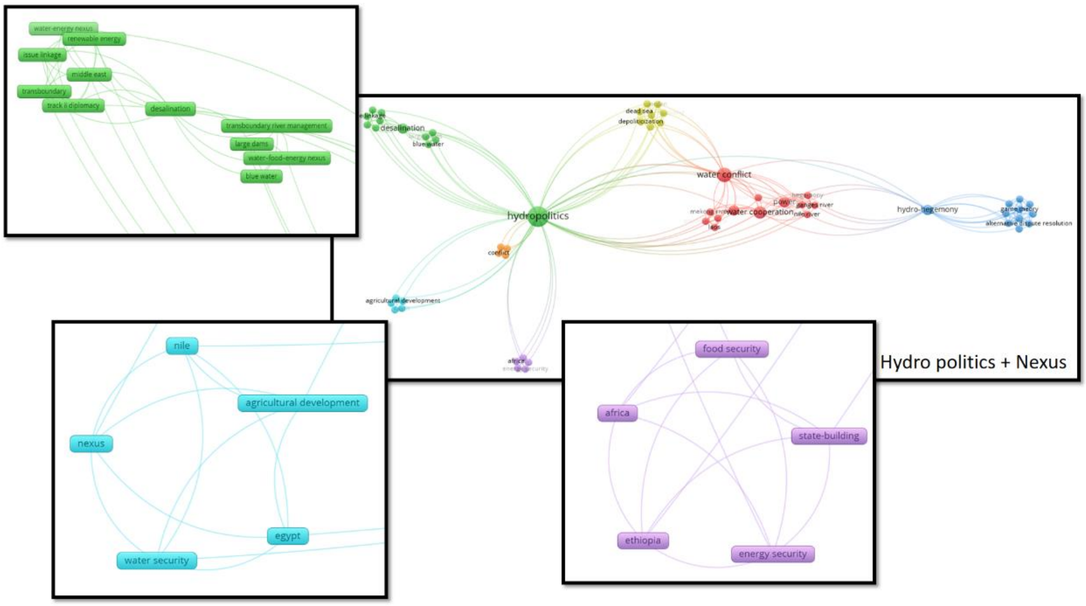

**Figure 18.** Searching for the word hydro politic and nexus and understanding the regional and thematic network

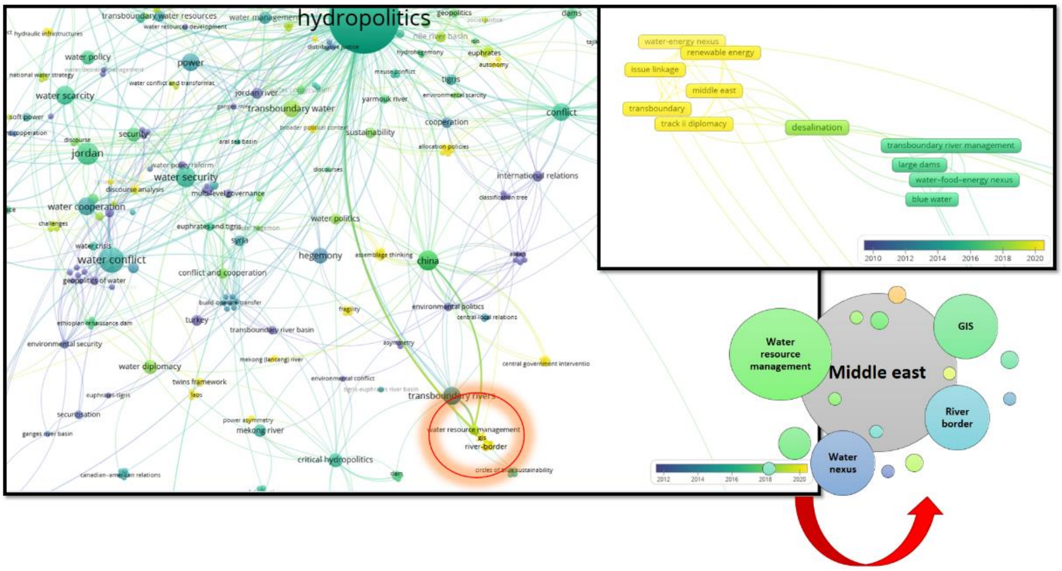

**Figure 19.** Understanding the importance of hydro political issues in the Middle East and solving the problem through the nexus of water, energy and food

### *3.2.. Introduction and General Methodology*

Summarizing and integrating the information from multiple indicators can be a difficult task with many potential pitfalls along the way. Defining a single composite score that integrates the data from a large number of indicators is often conceptually appealing; however,

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it can mask some of the nuances that exist in datasets such as that assembled for the TWAP River Basins analysis.

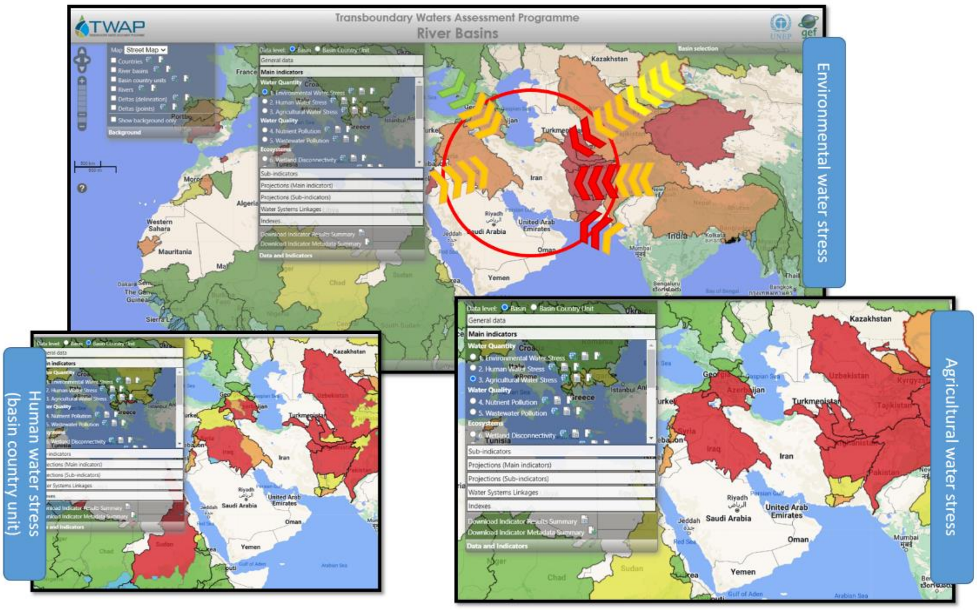

**Figure 20.** TWAP River Basins analysis with focusing on the Middle East region (Iran) (source: www.twap-rivers.org ,2023)

A statistical analysis may not have the conceptual appeal of a single integrative score, however, it can help elucidate interesting patterns that exist in the dataset and provide a more statistical summary of the basins and the indicators themselves. The purpose of this annex is to report the results of such an analysis. The goals of this integrated analysis are to explore the relationships between the indicators and river basins included in the TWAP River Basins component. In addition to summarizing the patterns between the indicators, a goal is to identify groups of basins with similar risk profiles. To quantify the relationships between the indicators as fully as possible, we used the continuous indicator data rather than the risk categories presented in the main body of the TWAP report. Additionally, we used a mix of sub-indicators and indicators to explore the relationships between all available variables in the raw dataset. This provided additional information about each basin which would be lost if uncorrelated sub-indicators such as two human water stress indicators were combined as their average. Based on an assessment of the correlation structure of the data, we used indicators except in a few cases as follows: we separated the two human water stress sub-indicators, grouped the first four of the societal wellbeing sub-indicators as “societal wellbeing” and the last one as “income inequality”, and separated sub-indicators for exposure to floods and droughts. The approach to analysis involved a bivariate and multivariate analysis. Bivariate analyses involve the analysis and comparison of two variables to quantify the nature of the relationship between them. In

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contrast, multivariate analysis considers more than two variables at a time and is commonly used to decompose complex multi-variable datasets into the dominant underlying gradients of variation between the variables or to identify distinct groups of objects, in this case river basins. The first stage of the analysis was to generate a complete correlation matrix to compare the correlation between all pairs of indicators and sub-indicators in this analysis (Section 3). We used Pearson's correlation coefficient, denoted by r, which has a scale of -1 to 1. Two variables with a correlation coefficient of -1 are perfectly negatively correlated with each other, a coefficient of 1 indicates complete positive correlation and a coefficient of 0 indicates the two variables are completely uncorrelated. Subsequent to the correlation analysis we undertook a Principal Components Analysis (PCA), which is a multivariate technique used to explore the relationships between the variables further, and examine the basins in terms of the dominant gradients of variation within the data. Finally, we used cluster analysis to group the basins into categories based on their similarity across all indicators.

We start with an assessment of the correlation matrix (Section 3), turn to the results of the principal components analysis (PCA) (Section 4), and conclude with a section presenting results of a cluster analysis (Section 5). Note that the correlation analysis and PCA were performed on normalized scores, where the original values were converted to a score ranging from 0-100, where 0 refers to lowest risk and 100 refers to highest risk. While retaining the underlying data distribution, this avoids the issue of interpretation of signs, since high is always considered "bad", whereas in the raw data high values were often "good" (e.g., high values for enabling environment on the raw scale were considered good). All analyses were performed using the R statistical software and contributed packages such as plyr (for joining and aggregating datasets), Hmisc (for correlation analysis), stats (for PCA), and the R script for k-means cluster analysis created by Matthew Peeples.

### *3.3. Correlation analysis*

Table 3 includes the correlation matrix for the themes, and only indicators with significant correlations above the 0.10 level (in italics) and 0.05 levels are shown. Bold type face refers to indicators with higher correlations (Pearson's $r > 0.5$). Indicators with high correlations show similar spatial patterns across the world and do not necessarily provide additional, unique information about the basins. This also identifies the manner in which basins may be statistically associated. The clearest pattern that emerges from the correlation matrix surrounds some of the pollution indicators and those associated with governance and between water stress-related indicators. There is a high positive correlation between wastewater pollution and the enabling environment, which suggests that basins in regions that lack strong governance are associated with high pollution levels. These are generally countries with poor societal wellbeing, as confirmed by high correlation between indicator wastewater pollution and

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societal wellbeing. Among the indicators that are related to water endowments, there is a high positive correlation between environmental water stress, agricultural water stress, and exposure to drought.

### 3.4.Principal Component Analysis

We use principal component analysis (PCA) to reduce the number of indicators to a set of latent components to account for the variance of the original data. The approach uses Eigen analysis to summarize the statistical properties of the indicators simultaneously by identifying a set of n uncorrelated principal components (PCs), (where n = the number of indicators). The PCs are linear combinations of the indicators that are conceptually similar to a line of best fit through the data cloud. The first PC explains the largest amount of variation in the n-dimensional data cloud, and the second PC explains the next largest amount of variation, subject to the constraint that it is orthogonal (or uncorrelated) to the first PC. Because the PCs are uncorrelated, the scores associated with each PC encapsulate a unique aspect of the socio-ecological system (and relative risk factors) represented by the original set of indicators. The number of PCs defined in the analysis equals the number of indicators, however, since each successive PC explains less of the total variation in the data, much of the meaningful variation in the data cloud can be captured by the first few PCs. A common method to determine how many components to retain and interpret is the Keiser criterion, which suggests keeping all components with an eigenvalue higher than 1. Prior to running a PCA, the data were standardized as z-scores by subtracting the mean and dividing by the standard deviation, so that all the variables are presented on the same scale with the standard deviation of each variable equal to 1. Hence, a z-score of 0 would represent the mean across all basins, a z-score of 2 represents a value two standard deviations above the mean, and a z-score of -2 represents two standard deviations below the mean. Each PC, then, can be interpreted as a z-score, though the directionality (whether positive z-scores represent high or low risk) needs to be tested against the underlying data. One advantage of the PCA, as applied here, is that it can help illuminate the statistical relationships between the indicators in a spatial context. Each PC captures spatial correlation between the indicators, and different PCs reflect uncorrelated patterns. A PC can be interpreted conceptually as a reflection of the indicators with the highest loadings (equivalent to correlation coefficients). This approach allows the developer to identify where different aspects of risk are most intensely present. Additionally, each basin has a score for each PC which shows how they are related along the main axes of variation in the data. These scores can be displayed graphically to illustrate how the basins are related along these major gradients. Because PCA requires a complete set of data for each basin across all 18 indicators, some smaller basins with incomplete indicator coverage were omitted from this analysis. As such, a total of 156 out of 286 transboundary basins were retained.

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Only the first six principal components had Eigen values greater than one, suggesting their retention for interpretation (Table 4). The first component accounted for more than a fifth of the variance in the underlying indicators (~22.15%) and the retained components together explain more than 69% of the variance in the overall data set.

**Table 3.** Correlation matrix

| **Indicators** | **1** | **2a** | **2b** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14abcde** | **14e** | **15a** | **15b** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1. Environmental water stress** | | | | | | | | | | | | | | | | | | |
| **2a. Human water stress A** | | | | | | | | | | | | | | | | | | |
| **2b. Human water stress B** | 0.35 | | | | | | | | | | | | | | | | | |
| **3. Agricultural water stress** | **0.71** | | 0.31 | | | | | | | | | | | | | | | |
| **4. Nutrient pollution** | 0.21 | | | 0.23 | | | | | | | | | | | | | | |
| **5. Waste water pollution** | | 0.17 | | | 0.12 | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **6. Wetland disconnectivity** | | | | | | 0.22 | | | | | | | | | | | | |
| **7. Ecosystem impacts from dams** | 0.34 | | | 0.23 | 0.13 | -0.41 | -0.18 | | | | | | | | | | | |
| **8. Threat to fish** | | 0.18 | | 0.14 | 0.37 | -0.26 | | 0.24 | | | | | | | | | | |
| **9. Extinction risk** | 0.12 | | | 0.11 | | | | 0.16 | 0.24 | | | | | | | | | |
| **10. Legal framework** | -0.18 | -0.13 | | -0.11 | | 0.28 | 0.12 | -0.44 | -0.27 | -0.21 | | | | | | | | |
| **11. Hydropolitical tension** | | 0.20 | | | | 0.44 | | -0.16 | | 0.22 | 0.47 | | | | | | | |
| **12. Enabling environment** | -0.11 | 0.14 | | | 0.14 | **0.81** | 0.21 | -0.39 | -0.18 | | 0.32 | 0.43 | | | | | | |
| **13. Economic dependence on water** | 0.13 | 0.12 | | 0.11 | | | | 0.39 | 0.24 | 0.29 | -0.30 | | | | | | | |

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| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **resources** | | | | | | | | | | | | | | | | | | |
| **14abcde. Societal wellbeing** | | 0.13 | | | | **0.63** | 0.21 | -0.29 | -0.19 | -0.12 | 0.19 | 0.25 | **0.58** | | | | | |
| **14e. Income inequality** | | | | | | 0.24 | | | -0.22 | | | | 0.20 | -0.12 | 0.13 | | | |
| **15a. Exposure to flood** | | | | | | 0.16 | 0.15 | | 0.27 | | | 0.13 | | 0.12 | | | | |
| **15b. Exposure to drought** | 0.61 | | 0.28 | 0.43 | | | | 0.18 | -0.13 | | -0.18 | | | 0.12 | 0.21 | 0.13 | | |

**Table 4.** Principal Component Analysis – variance explained

| | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 |
|---|---|---|---|---|---|---|
| **Variance (eigenvalues)** | 3.98 | 2.71 | 2.12 | 1.42 | 1.17 | 1.07 |
| **Percentage of Variance explained** | 22.15 | 15.07 | 11.79 | 7.87 | 6.50 | 5.97 |
| **Cumulative Percentage** | 22.15 | 37.23 | 49.02 | 56.89 | 63.38 | **69.35** |

The factor loadings for each principal component (PC) are found in Table 3. Factor loadings can be interpreted as the correlation coefficient between the indicator/sub-indicator and the overall PC, with higher loadings implying a larger contribution to the overall PC. Indicators for which factor loadings are >0.3 or < -0.3 are colored in blue and red, respectively. Each component captures uncorrelated dimensions of risk. The maps in Figures 1a-e are a spatial representation of the first six principal components. In the maps, the unit of measurement is deciles, and highly positive (brown color) represents high risk. The maps, together with an analysis of the factor loadings, can assist with the interpretation of results.

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### *3.5.Interpreting the principal components*

The first PC can be interpreted as an axis that discriminates between basins based on levels of economic development. The component has positive loadings for wastewater pollution, enabling environment (and to a lesser degree legal framework), and social wellbeing, and negative loadings for the ecosystem impact of dams. Basins in developed regions will typically have low risk for the first set of indicators, and high risk for dam impacts following investments in water resource infrastructure to mitigate pollution and guarantee water supply, while countries in developing regions typically show an inverse pattern. For example, Africa as a whole has a lot fewer dams per kilometer of river than Europe, and also tends to score poorly on wastewater, enabling environment, and societal wellbeing. The second PC loads highest on environmental and agricultural water stress, human water stress, and exposure to droughts. This PC discriminates between drier basins with high variability in river flows and high water stress (e.g., the Colorado Basin in the USA), and those basins that are relatively water-abundant (e.g., a number of basins in Europe). PC3 has highly positive loadings for nutrient pollution, exposure to floods, economic dependence, hydro political tension and threat to fish. One possible interpretation of this PC, which would require more testing, is that this PC discriminates between highly and lightly populated basins. PC4 has high positive loadings on legal framework, high negative loadings on economic dependency on water resources, human water stress and moderately negative loadings on social wellbeing (inequality as reflected in the Gini coefficient). This PC has basins with good legal frameworks (low risk) and higher economic dependency on water in the basin (high risk) and relatively high water stress and income inequality. PC5 appears to be related to ecosystems. Extinction risk has a negative loading on this component and wetland disconnectivity has a high positive loading. Potential reasons for this would need to be investigated at the indicator level. Finally, PC6 has high negative loadings on exposure to floods, wetland loss and income inequality, and positive loading on hydro political tension.

**Table 5**. Factor loadings by principal component

| Indicators | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 |
|---|---|---|---|---|---|---|
| **Water Quantity** | | | | | | |
| 1. Environmental water stress | -0.193 | 0.465 | -0.056 | 0.066 | -0.028 | 0.126 |
| 2a. Human water stress A | -0.056 | 0.137 | 0.275 | -0.292 | 0.271 | 0.195 |
| 2b. Human water stress B | -0.125 | 0.371 | 0.043 | 0.316 | -0.091 | -0.109 |
| 3. Agricultural water stress | -0.18 | 0.472 | 0.031 | 0.267 | -0.137 | 0.026 |
| **Water Quality** | | | | | | |
| 4. Nutrient pollution | -0.221 | -0.161 | 0.347 | 0.119 | 0.283 | 0.232 |
| 5. Wastewater pollution | 0.42 | 0.223 | 0.125 | -0.056 | -0.026 | -0.01 |

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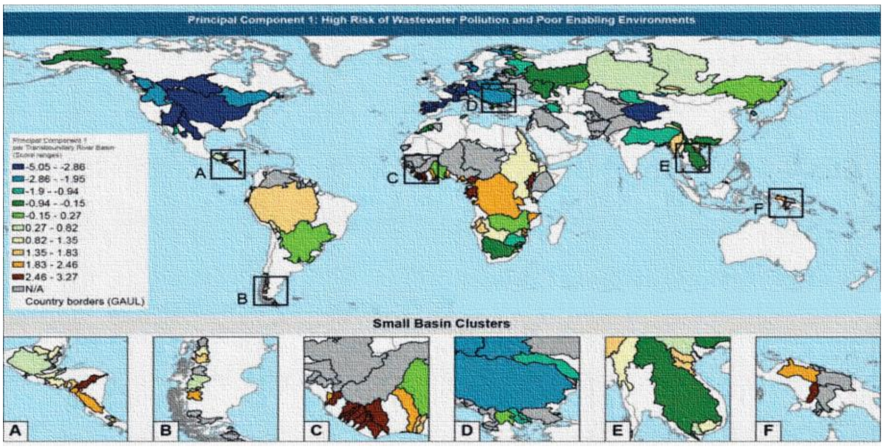
| | | | | | | |
|---|---|---|---|---|---|---|
| **Ecosystems** | | | | | | |
| 6. Wetland disconectivity | 0.09 | 0.085 | 0.254 | -0.043 | 0.403 | -0.443 |
| 7. Ecosystem impacts from dams | -0.349 | 0.082 | 0.125 | -0.198 | 0.259 | 0.149 |
| 8. Threat to fish | -0.212 | -0.056 | 0.37 | 0.094 | -0.143 | -0.295 |
| 9. Extinction risk | -0.057 | 0.03 | 0.259 | -0.285 | -0.684 | -0.047 |
| **Governance** | | | | | | |
| 10. Legal framework | 0.320 | -0.027 | 0.138 | 0.412 | 0.057 | 0.242 |
| 11. Hydro political tension | 0.268 | 0.076 | 0.331 | 0.145 | -0.153 | 0.364 |
| 12. Enabling environment | 0.407 | 0.143 | 0.101 | -0.12 | -0.042 | -0.027 |
| **Socioeconomics** | | | | | | |
| 13. Economic dependence on water | -0.1 | 0.06 | 0.352 | -0.441 | -0.078 | 0.159 |
| 14abcd. Societal wellbeing | 0.372 | 0.155 | 0.058 | -0.186 | 0.198 | 0.049 |
| 14e. Income inequality | 0.118 | 0.179 | -0.229 | -0.309 | 0.003 | -0.355 |
| 15a. Exposure to flood | 0.024 | 0.026 | 0.399 | 0.226 | 0.049 | -0.47 |
| 15b. Exposure to drought | -0.07 | 0.474 | -0.145 | -0.099 | 0.157 | 0.072 |

Maps of each PC are included in Figure 21. A high positive score (orange to red colors) indicates a basin with higher risk for indicators that, according to Table 3, have a high positive loading on the component and a lower risk for those indicators that have a high negative loading on the component. In contrast, a high negative score (green to blue colors) indicates a basin with higher risk for indicators that have a high negative loading on the component and a lower risk for indicators that have a high positive loading on the component.

a) PC1: High risk of wastewater pollution and poor enabling environment



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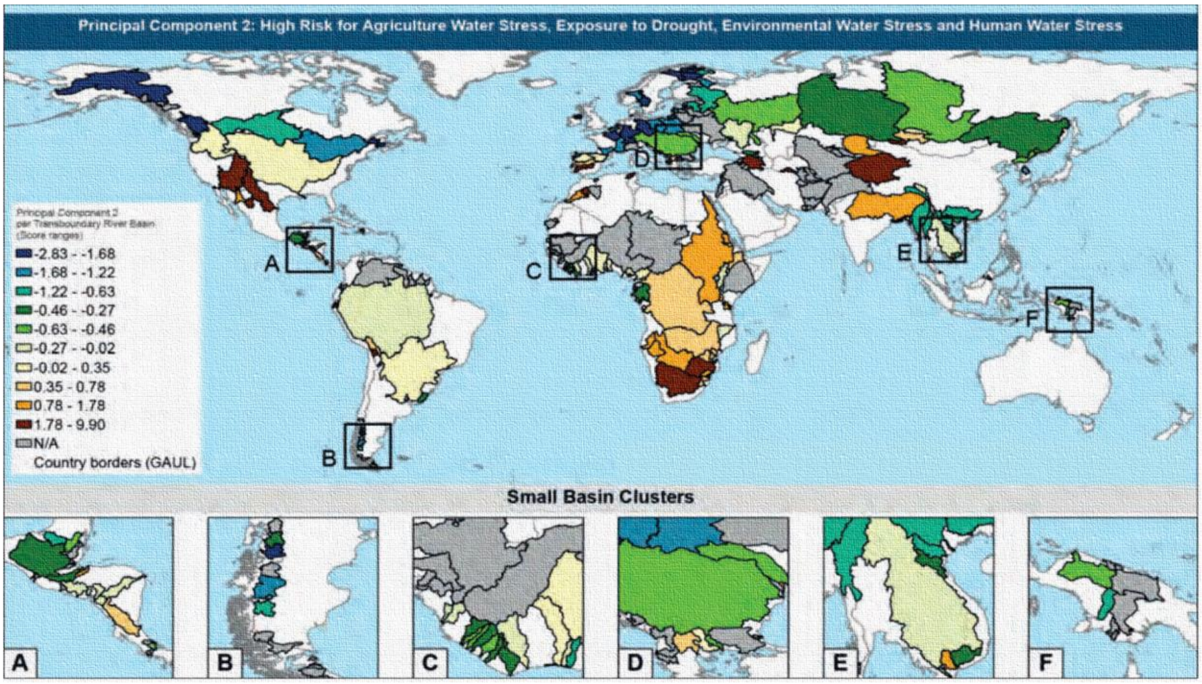
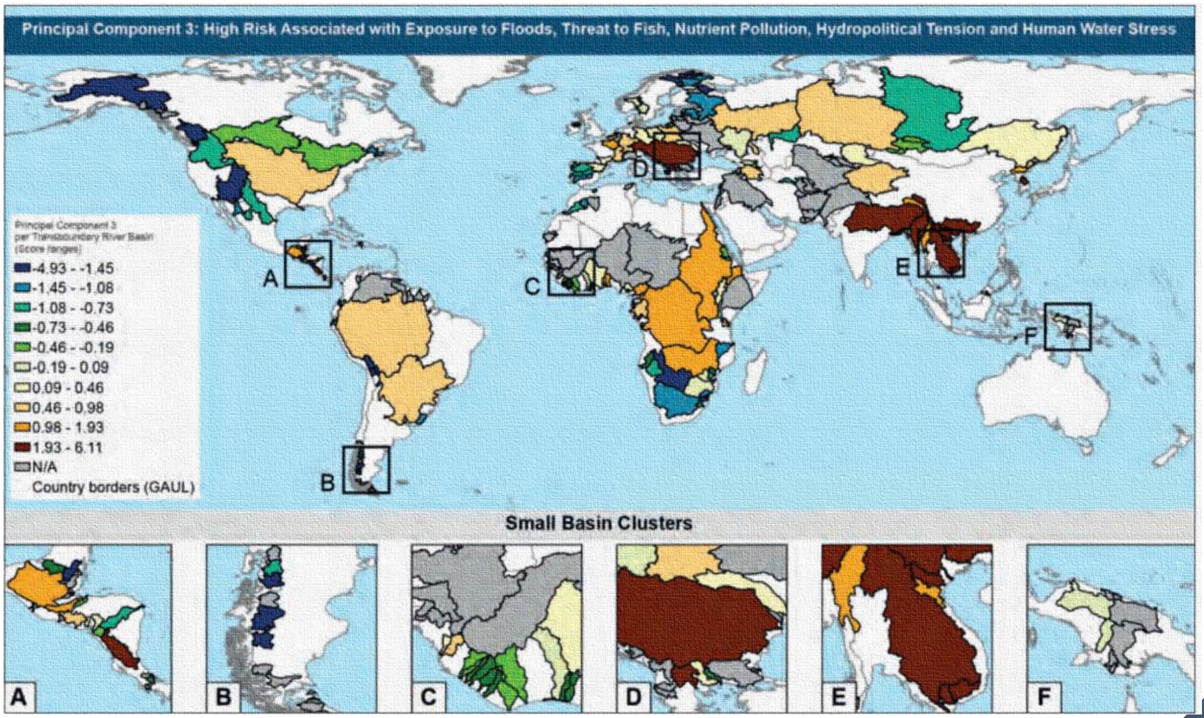
b) PC2: High risk for agriculture water stress, exposure to drought, environmental water stress and human water stress



c) PC3: High risk associated with exposure to floods, threat to fish, nutrient pollution, hydro political tension and human water stress



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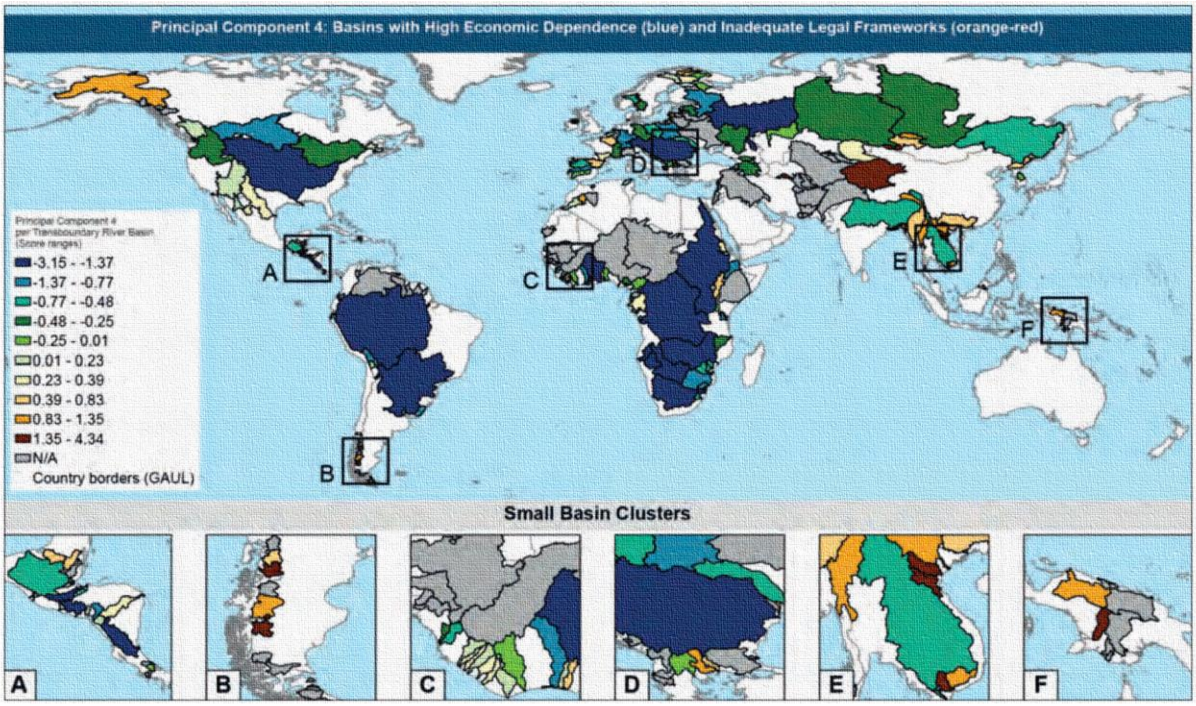
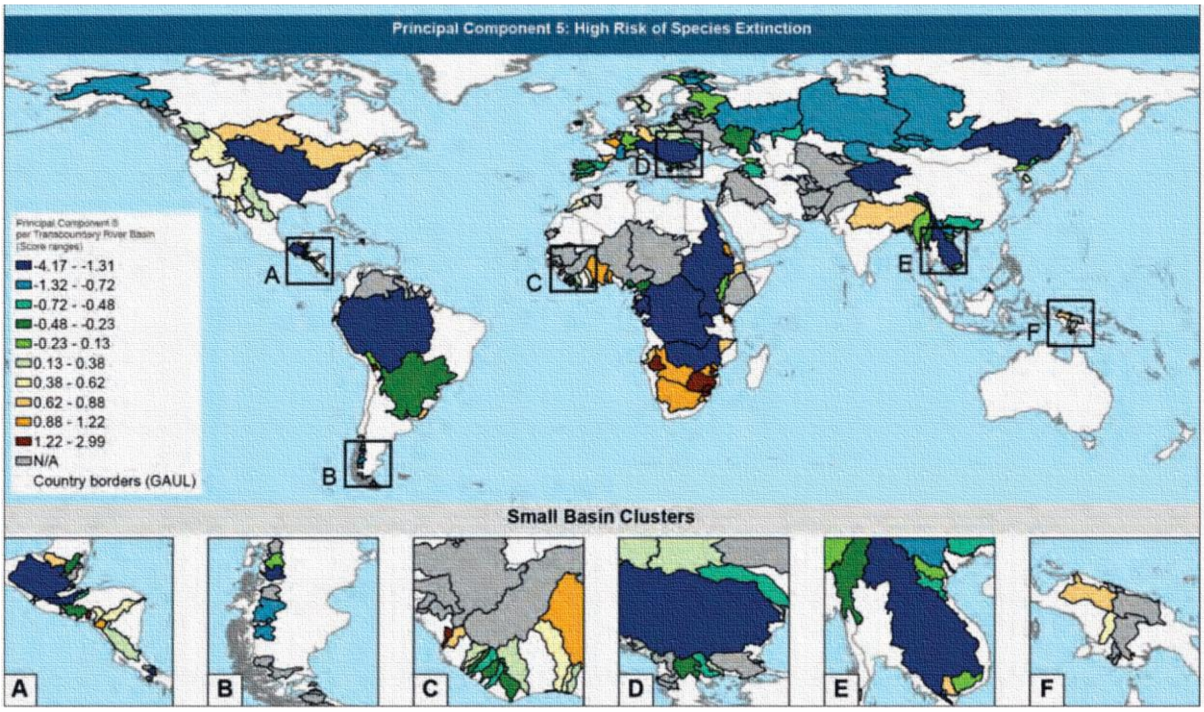
d) PC4: Basins with high economic dependence (blue) and inadequate legal frameworks (orange-red) stress



e) PC5: High risk of species extinction



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f) PC6: High risk of wetland disconnectivity and social inequality

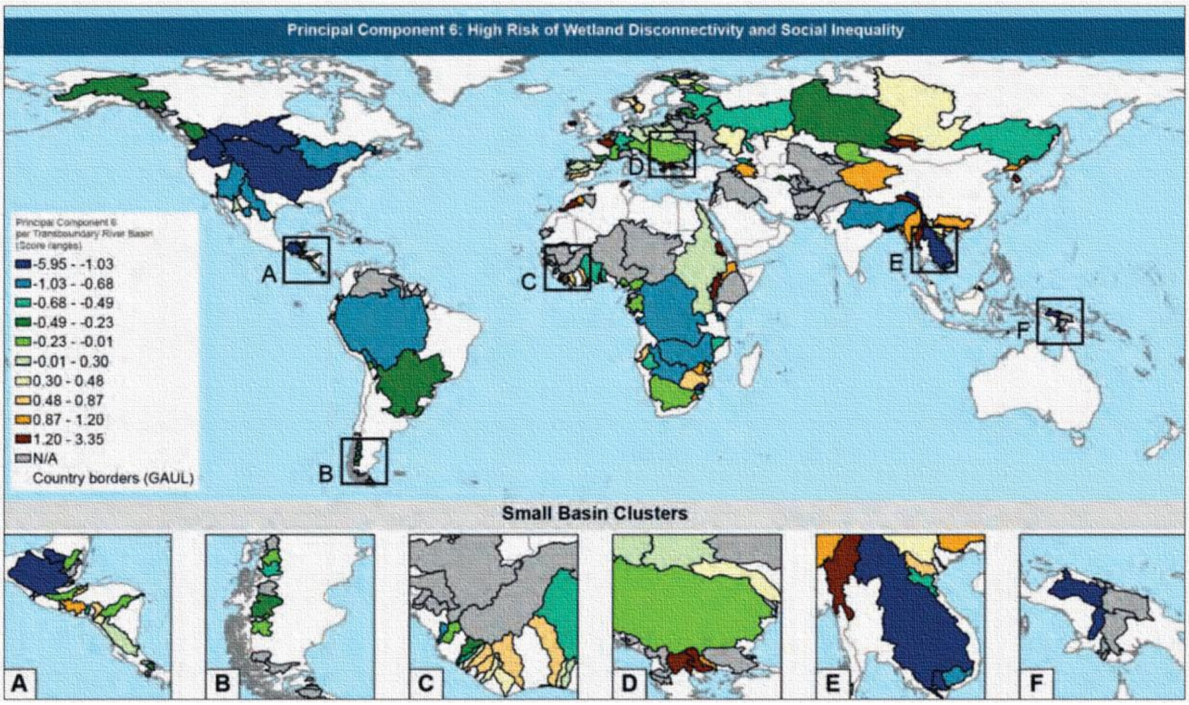

**Figure 21.** Maps of Principal Components with basins colored according to their score along each principal component.

## 4. Results and Discussion

### *4.1.Cluster Analysis*

The purpose of cluster analysis is to find group of similar basins based on the full suite of indicators used in this analysis. Cluster analysis is the natural complement to principal components analysis as it uses Euclidian distance to define the clusters in such a way that variability of basins within the clusters is reduced and the variability between the clusters is maximized. Analysis of the data via calculation of the sum of square errors between clusters (using the actual and 1 000 random generated data) suggested that nine cluster groups was the most optimal solution. This K-Means cluster algorithm is an iterative process (we set the number of iterations to 1000), which means that each basin’s membership to the cluster is re-evaluated at each iteration, according to the center of the clusters calculated at each iteration. A map representing the spatial distribution of clusters is found in Figure 8, while the table including the basin names and cluster location are included in Appendix A. We also calculated average indicator z-scores for each cluster (Table 6), positive values representing high risk, and negative values representing low risk. The results of the cluster analysis provide an opportunity to define broad risk profiles based on the typical values of each indicator in each group. This can be used to identify which basins tend to be of high or low risk across different groups of

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indicators or indeed, most indicators (Figure 22). The range of values for the indicators within each cluster group shows that not all basins in each group are identical, but rather are broadly similar. Basins in cluster groups 1, 2 and 3 tend to show moderate and low water stress for humans, the environment and agriculture, moderately high wastewater pollution but differentiate along governance and societal wellbeing indicators, group 1 being at highest risk in these areas compared with the other two groups. Basins in groups 4 and 6 have low risk for wastewater pollution, and also have comparable scores for human water stress, ecosystem impact from dams and threat to fish (moderate high), yet they differ in terms of nutrient pollution, as group 6 is at highest risk among all cluster groups. Countries included in group 4 also fair better for governance indicators (legal framework, hydro political tension and enabling environment), having the lowest risk among all the clusters. Basins in groups 5 are water scarce and those in group 7 are prone to floods. Although the basins in this group have moderate scores for all other indicators, basins in group 5 score slightly better for governance and societal-well-being indicators, while basins in group 7 do better in terms of inequality, the ecosystem impact from dams and threat to fish. The relationships evident in Figure 5 are also visible when examining the boxplot of the PCA, which shows the basins and indicators arrayed on the first two PCs, identified by cluster group (Figure 23).

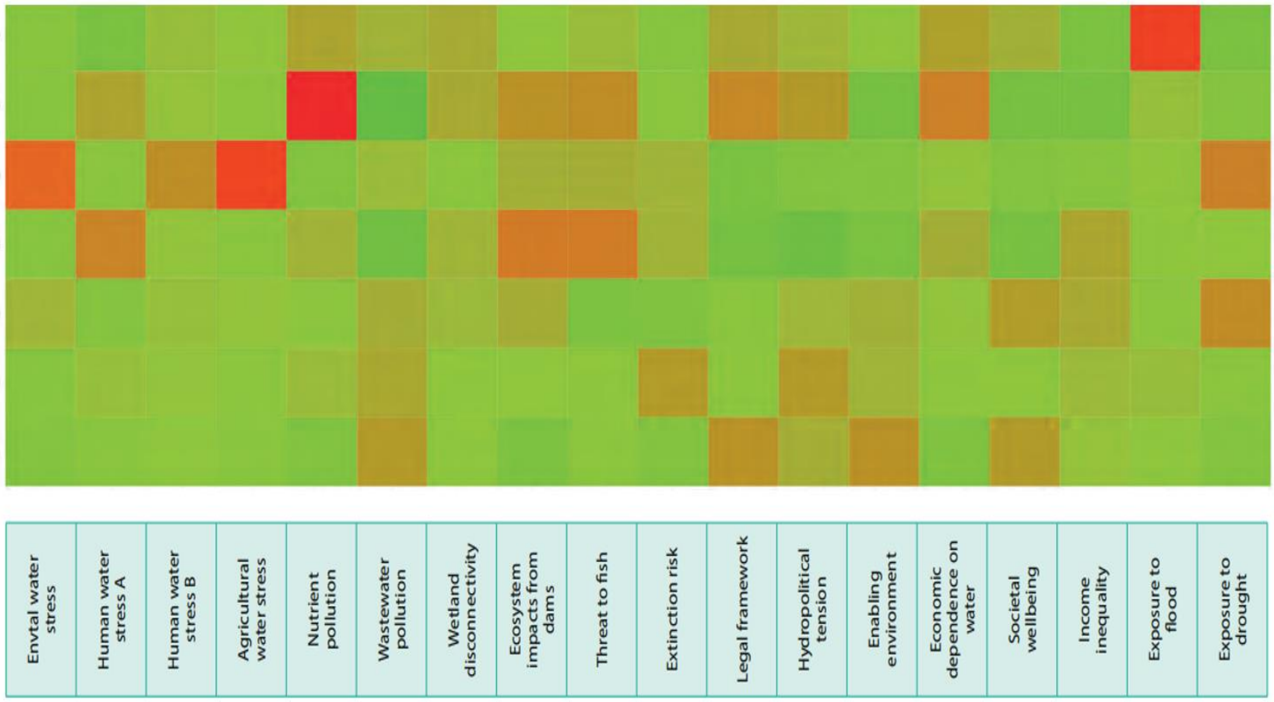

**Figure 22.** Heat map of median scores for each cluster group for each indicator (low risk is displayed in green, high risk in red)

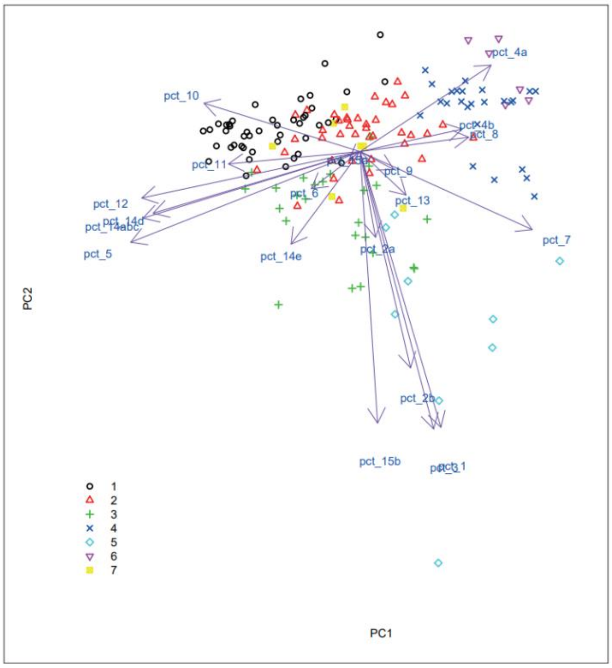

**Figure 23.** Boxplot showing the first two axes of the principal components analysis with basins identified by K-means cluster group Note: This plot is for the K-means

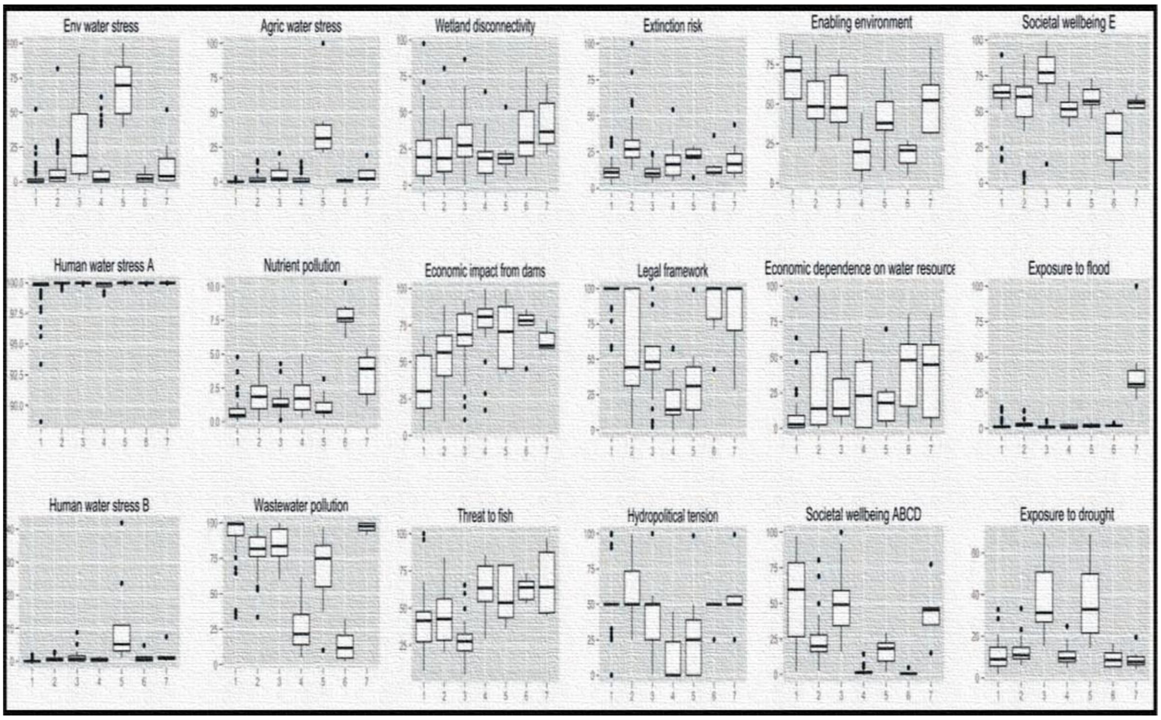

**Figure 24.** Boxplots showing the distribution of values for each cluster group

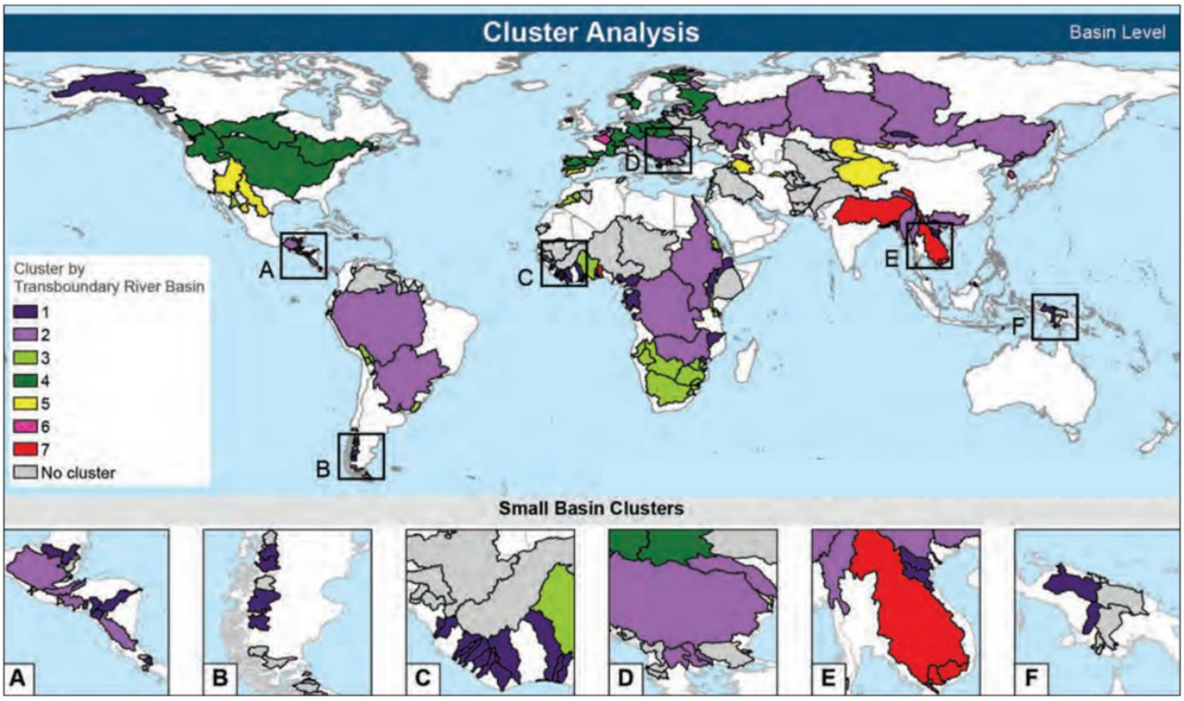

**Figure 25.** Map of the Cluster analysis showing the locations of the basins within each cluster group.

**Table 6.** Mean indicator z-score by cluster

| **Indicators** | **Cluster 1** | **Cluster 2** | **Cluster 3** | **Cluster 4** | **Cluster 5** | **Cluster 6** | **Cluster 7** |
|---|---|---|---|---|---|---|---|
| **Water Quantity** | | | | | | | |
| 1. Environmental water stress | -0.46 | -0.25 | 0.51 | 0.03 | 2.33 | -0.44 | -0.16 |
| 2a. Human water stress A | -0.3 | -0.1 | -0.5 | 1.54 | -0.48 | 0.44 | -0.97 |
| 2b. Human water stress B | -0.29 | -0.15 | 0.02 | -0.13 | 2.32 | 0.08 | 0.04 |
| 3. Agricultural water stress | -0.43 | -0.22 | 0.08 | -0.12 | 3.36 | -0.34 | 0.06 |
| **Water Quality** | | | | | | | |
| 4. Nutrient pollution | -0.55 | 0.01 | -0.28 | 0.44 | -0.37 | 3.52 | 0.42 |
| 5. Wastewater pollution | 0.64 | 0.37 | 0.25 | -1.42 | -0.4 | -2.1 | 0.31 |
| **Ecosystems** | | | | | | | |
| 6. Wetland loss | -0.13 | -0.17 | 0.21 | 0.03 | -0.28 | 0.95 | 0.49 |
| 7. Ecosystem impacts from dams | -0.85 | -0.16 | 0.08 | 1.49 | 0.18 | 0.81 | -0.21 |
| 8. Threat to fish | -0.41 | -0.2 | -0.86 | 1.54 | 0.24 | 0.97 | 0.2 |
| 9. Extinction risk | -0.53 | 0.89 | -0.66 | 0.35 | 0.02 | -0.18 | -0.29 |
| **Governance** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10. Legal framework | 0.92 | -0.16 | -0.43 | -0.93 | -0.91 | 1.04 | 0.11 |
| 11. Hydro political tension | 0.28 | 0.65 | -0.2 | -1.22 | -0.72 | 0.51 | 0.11 |
| 12. Enabling environment | 0.77 | 0.18 | 0.03 | -1.08 | -0.5 | -1.38 | -0.36 |
| **Socioeconomics** | | | | | | | |
| 13. Economic dependence on water | -0.51 | 0.16 | -0.02 | 0.41 | -0.14 | 0.98 | 0.32 |
| 14abcd. Societal wellbeing | 0.75 | -0.29 | 0.62 | -1.06 | -0.66 | -1.15 | 0.21 |
| 14e. Income inequality | -0.02 | -0.19 | 0.42 | 0.59 | -0.36 | -1.31 | -0.85 |
| 15a. Exposure to flood | -0.19 | -0.07 | -0.28 | -0.25 | -0.23 | -0.12 | 3.87 |
| 15b. Exposure to drought | -0.49 | -0.32 | 1.4 | -0.16 | 1.37 | -0.52 | -0.8 |

### *4.2.Perspectives and prospects*

When comes to middle east, we need to create an integrated framework with a holistic view to identify and evaluate potential risk for future and supply technical, and financial resources for cooperation between stakeholders to establish sustainable and efficient management approach. The useful management of transboundary water is critical for social, political and economic stability, as well as for sustainable development [126]. different opinions may be existed among riparian states regarding to the economic development, infrastructure capacity, political orientation and cultural values but they can use opportunities and sharing benefits, despite of the mutual disagreements. For this purpose, the bankruptcy approach was proposed by Madani et al. for resolving transboundary river conflicts in which the total water demand or claim of the riparian parties is more than the available water. Bankruptcy solution methods can allocate the available water to the conflicting parties with respect to their claims [127]. Also, Zeitoun and Warner presented Framework of Hydro-Hegemony. This framework described a political question: who gets how much water, how and why? Hydro-hegemony is hegemony at the river basin level, achieved through water resource control strategies such as resource capture, integration and containment. The strategies are executed through an array of tactics (e.g. treaties, knowledge construction, etc.) that are enabled by the exploitation of existing power asymmetries within a weak international institutional context [128]. In this section, we dis cussed four frameworks for mitigation of transboundary water conflicts which can be utilized in middle east specially Iran.

### *4.3.Management*

The management approach for transboundary water resources is very important, alongside with water scarcity [79]. Also, based on water security definition absence or presence of water is problematic. Therefore, management of water resources is a critical challenge. For a suitable and more effective agreement, all the aspects in the transboundary basins should be considered. For this purposes, a team of different technical, legal and management sections should attend

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on the meeting and sessions between riparian countries of a transboundary basin. Also, institutions capable of overseeing the resources management should be built which providing analytical tools to assess trade-offs management between resources [129].

### *4.4.Cooperation*

Water cooperation assist policy developers, advisors, practitioners, and academics to reduce conflict and increase economic development and growth at a local, national or regional level. The recommendations made are as follows [17,89]: (a) define, elaborate and apply a key set of management attributes for the transboundary basin organization to help promote good management, (b) learn from the experiences of other basin organizations that are in, or have completed, the same development phase, (c) recognize that building confidence and organizational skills is a long-term process for transboundary organizations, and that some results may take decades to achieve, (d) use a combination of governance and technical indicators to provide evidence of outcomes of IWRM, (e) promote the role and potential value of functioning transboundary organizations in order to increase support from riparian states, and (f) promote joint environmental monitoring in order to strengthen the basis for decision making, and promote increased cooperation and the value of ecosystem services.

WEF nexus Future prospects for WEF nexus research are proposed from the perspectives of conceptual development, methodology improvement, and target region extension [130]. A holistic approach for dialogue among middle east and the world should consider the dynamic interdependencies between WEF resources more than traditional approaches which often overlook the interdependencies. In this case, the WEF nexus approach has come to the forefront within scientific and practice communities. Also, conventional engineering and management decision making processes for water and energy resources tend to primarily consider cost and quantity parameters. Therefore, a holistic approach which considers all stakeholders, policy makers and interdependent systems, such as energy costs, footprints of water production and distribution, and tradeoffs of water allocation between sectors is required for long-term and sustainable water management decisions. Kulat et al. recommended the primary objectives of the study for a holistic WEF nexus approach as follows: (a) Identification of Scenarios: including infrastructure interventions which can decrease risk and vulnerability in securities of WEF resources, (b) Development of WEF Nexus Platform: a systems level WEF nexus platform, including a tool for quantification of trade-offs assessment in developed scenarios, (c) Analyzing the Sustainability: development of criteria for obtaining optimal scenarios and analyzing them based on economic, social, and environmental sustainability, and their trade-off implications for WEF resources. Consequently, this study provides water resource planners an opportunity to quantify the trade-offs between primary resources, and bring all stakeholders to a single basis regarding the use of financial and WEF resources while also protecting the natural environment [131].

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*4.5 Key findings for each thematic group*

Socioeconomics

1. Climate-related risk is linked to economic dependence and low wellbeing: Basins with high economic dependence, low levels of societal wellbeing and high exposure to floods and droughts have the highest climate-related risks. These basins are found mostly in Africa and south and southeast Asia. They include, at the highest levels of vulnerability, the Limpopo, the Ganges and the Mekong.

2. Wellbeing and governance capacity to address disasters are linked: In basins where societal wellbeing is low, governance capacity to address vulnerability to floods and droughts is also likely to be low. Women, children and people with disabilities are groups particularly vulnerable to floods and droughts. Attention might be warranted to assess governance needs and increase capacity in these countries and basins.

3. Larger basins have larger economic dependence: Larger basins tend to have higher levels of economic dependence on basin water resources, due mainly to the fact that larger basins are likely to include greater portions of the populations and areas of the countries. The 14 basins with the highest levels of economic dependence collectively comprise a population that is almost 50% of all transboundary basins (almost 1.4 billion people). These larger basins may be harder to manage from a transboundary point of view because of the number of countries and diversity of priorities. Management becomes even more critical to safeguard socioeconomic wellbeing in these countries.

Governance

1. More effort is needed on transboundary agreements: The adoption of international principles associated with the shift of water paradigms toward more sustainable development has been faster in domestic water governance arrangements than in international treaties. Focus is needed on renegotiating and implementing transboundary agreements to incorporate more integrated approaches into basin-level management.

2. Construction of water infrastructure needs a cooperative context: The construction of new water infrastructure is in progress or planned in many transboundary basins, including in areas where international water cooperation instruments are still absent or limited in scope. In such areas, a formal institutional framework for transboundary dialogue could help to assuage potential disputes stemming from unilateral basin development.

3. Capacity building is required within countries to meet transboundary objectives: There have been advances in the development of transboundary institutional capacity to deal with transboundary tensions and the application of integrated approaches to national water management, but capacity building is still work-in-progress in most countries.

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Ecosystems

1. Local-level, tailored solutions are needed to address species extinction risks: Analysis at the BCU level gives a more detailed picture of extinction risks than analysis at the basin level, reflecting higher levels of endemic species or threats in some areas of a river basin such as the upper reaches or in large lake systems. This suggests that responses, too, should be at a more detailed level than basin-wide to address extinction risks. There is therefore an urgent need to continue to identify hotspots from transboundary impacts through basin-specific assessments (including, for example, GEF Transboundary Diagnostic Analyses (TDAs)). Conservation strategies should be focused on ecological importance, not necessarily on scale.
2. Decisions about dam sites and dam design are key to minimizing negative ecosystem impacts: Dam density is often a key driver of impacts on ecosystems, with impacts on flow and fragmentation of river systems. Recognizing the benefits of dams to human development, ongoing commitments are needed to improve guidelines for siting new dams, designing dams for multiple purposes and optimizing the operation of dams to maximize human benefits and minimize negative ecosystem impacts. This is particularly important in a transboundary context, where dams are typically located in upstream countries.

Water quantity

1. Action to address agricultural water stress must not increase environmental water stress: Hotspots of environmental water stress are highly correlated with those of agricultural water stress. Addressing agricultural water stress (for example through increasing large-scale water storage) should be done with careful consideration of environmental water requirements.
2. Human water stress needs to be addressed to mitigate projected environmental and agricultural stress: Actions to counter human water stress should be expedited in river basins that are already prone to water stress to mitigate the increasing stress projected for most of these regions.

Water quality

1. Water quality risks are high in many transboundary river basins: Water quality is severely affected in more than 80% of the basins, either by nutrient over-enrichment (typically in developed regions e.g. North America and Europe) or by pathogens (generally in developing regions, e.g. South America, Africa, and in northern Asian basins with Russia), or in both (e.g. emerging economies in southern and eastern Asia).
2. Water quality risks are projected to increase: The projected scenario for nutrient pollution suggests that the relative risk will increase in around 30% of basins between 2000 and 2030, with the risk in two basins increasing by three categories. Between 2030 and 2050 nutrient pollution risk is projected to increase further in 21 basins, while in six basins the risk decreases

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by one category28. The effects of nutrient pollution are also likely to exacerbate risks across other indicators and water systems (e.g. ecosystem health, coastal areas and aquifers).

3. Mitigation measures are needed in all river basins to reduce risks: In basins with a risk of nutrient and wastewater pollution, improvements to wastewater treatment may help to reduce both risks. Improved nutrient management in agriculture (e.g. crop and livestock) will likely be needed to reduce current risks of nutrient pollution in many basins. Even in basins with relatively low risk, both strategies are likely to become more important as the global population continues to rise, which is likely to increase risks of nutrient and wastewater pollution unless adequate mitigation measures are in place.

### *4.6. individual indicators related*

Determining correlations between indicators across thematic groups can help to identify the strength of the statistical relationships between the links in the conceptual model that underpins this work. The results indicate how the human dimension of transboundary rivers, gauged by socioeconomic and governance indicators, is related to the physical dimension represented by water quality and quantity and ecosystem impacts. For example:

- Wastewater pollution, societal wellbeing and enabling environment (governance at the country level) are strongly related, suggesting that addressing wastewater pollution should occur in parallel with improvements in societal wellbeing and national governance;
- Environmental, human and agricultural water stress, and exposure to drought, which are usually worse in basins with high inter-annual variability of water flows, have high correlation levels. This confirms that in the past dams have been built to address water flow variability to meet high human and agricultural demands, with negative impacts on environmental water flows. There is a negative correlation (although weak) between governance and societal wellbeing indicators, and between ecosystem impacts from dams and threats to fish. This would imply that basins which have been developed to support high levels of societal wellbeing may have done so at the expense of the environment.

Simulated projections for the 2030s and 2050s were generated on the basis of a ‘business-as-usual’ socio-economic scenario and an assumed continued high greenhouse gas (GHG) emissions pathway. The following indicators were considered: environmental stress induced by flow alteration, human water stress, nutrient pollution, hydropolitical tensions, and population density.

Four hotspots were identified; environmental and human (E&H) water stress is projected to increase in all four:

- Orange and Limpopo basins, Southern Africa: increased Environment and Human (E&H) water stress due mainly to increasing water withdrawals, and nutrient pollution due mainly to increased human sewage. Countries affected: Botswana, Lesotho, Mozambique, Namibia, South Africa, Zimbabwe.

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- Selected Central Asia basins: range of factors differing between basins, including increased E&H water stress due to a combination of projected increases and decreases in water availability, increasing water withdrawal and population density; increased nutrient pollution and hydropolitical tensions. Basins: Tarim, Indus, Aral Sea, Helmand, Murgab, Hari, Talas, Shu and Ili. Countries affected: Afghanistan, China, India, Iran, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Tajikistan, Turkmenistan, Uzbekistan.
- Ganges-Brahmaputra-Meghna basin: increased E&H water stress due mainly to increased (>50%) water demand driven by population growth. Nutrient pollution remains high with agricultural sources (fertilizer and animal manure) being major contributors and sewage becoming increasingly important, and there is increased risk of hydropolitical tension associated with new water infrastructure. Countries affected: Bangladesh, Bhutan, China, India, Myanmar, Nepal.
- Selected Middle East basins: continued high to very high risk of E&H water stress due to decrease in renewable freshwater resources and higher water demand from increased population and irrigation. Nutrient pollution increases or remains in the highest risk category; increased risk of hydropolitical tension due to the political context. Basins: Orontes, Jordan River, Euphrates and Tigris. Countries affected: Egypt, Iraq, Iran, Israel, Jordan, Lebanon, Palestine, Saudi Arabia, Syria, Turkey.

## 5. Conclusions

The state of water resources in any location depends on a complex array of natural circumstances, pressures, and management responses. This assessment has attempted to cover a broad spectrum of these factors, with each indicator representing an important aspect in its own right. The results identify basins and regions where there are high and low risks of water stress, pollution, and threats to ecosystems and impacts on them. It also assesses governance capacity at the national and transboundary level to deal with threats, and the likely level of vulnerability of societies trying to cope with these risks, including changes to the hydrological regime.

Water scarcity has increased substantially in the last decades in many parts of the world, and it is expected to further exacerbate in the future driven by increasing water withdrawals and shrinking water availability. A wide range of solution options could be implemented to address this growing water scarcity, including supply side and demand-side management options spanning the water, energy, and agricultural sectors. These sectors are intertwined, and tightly linked also to other important societal objectives such as ecosystem health and climate system. Water is a key feature in nexus system, given that all the other features are affected either directly or indirectly, by water availability. Under such circumstances, future water modeling tools should be able to concurrently integrate the different societal objectives and

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resource constraints to identify a broader solution space for the interconnected resources. This paper suggests addressing this complex problem using a nexus modeling framework that connects inputs and outputs between well-established sectoral-oriented models. The application of this framework to assess water scarcity solutions is currently limited, but promising for future research.

Throughout the TWAP River Basins Report, particularly in the indicator descriptions and the integrated analysis, authors have made suggestions for potential future improvements to the methodology. The more broadly applicable suggestions include:

- A deeper understanding of drivers and impacts, in order to identify cause-effect relationships. This will probably require more in-depth analysis of (selected) basins.
- More analysis into within-basin relationships to gain better understanding of the transboundary aspects of risk. In some cases, this may require more detailed datasets (some of which are currently being developed).
- Investigation of the interactions between and implications behind the water-food-energy nexus in basins, including identification of important trade-offs and opportunities presented by integrated water resource management at the transboundary level.
- A closer look at the performance and implementation of governance arrangements at national and transboundary levels and understanding of outcomes at both levels. This may include consideration of private and private-public actors, possibly illustrated by case studies.
- More ‘ground-truthing’ to compare the global assessment results with realities in the basins. This may involve more detailed studies of smaller, representative sub-sets of basins, and increased engagement with stakeholders in these basins.
- Further consideration (particularly for the integrated assessment) of which basins may be more relevant to consider as transboundary basins, and which may be considered as predominantly ‘national’.
- Consideration of the significance of gender and gender disaggregated information in global transboundary assessments.
- Separate analyses of larger and smaller basins, which may lead to different patterns of risk being identified, and consequently improve information for developing policy and management responses.

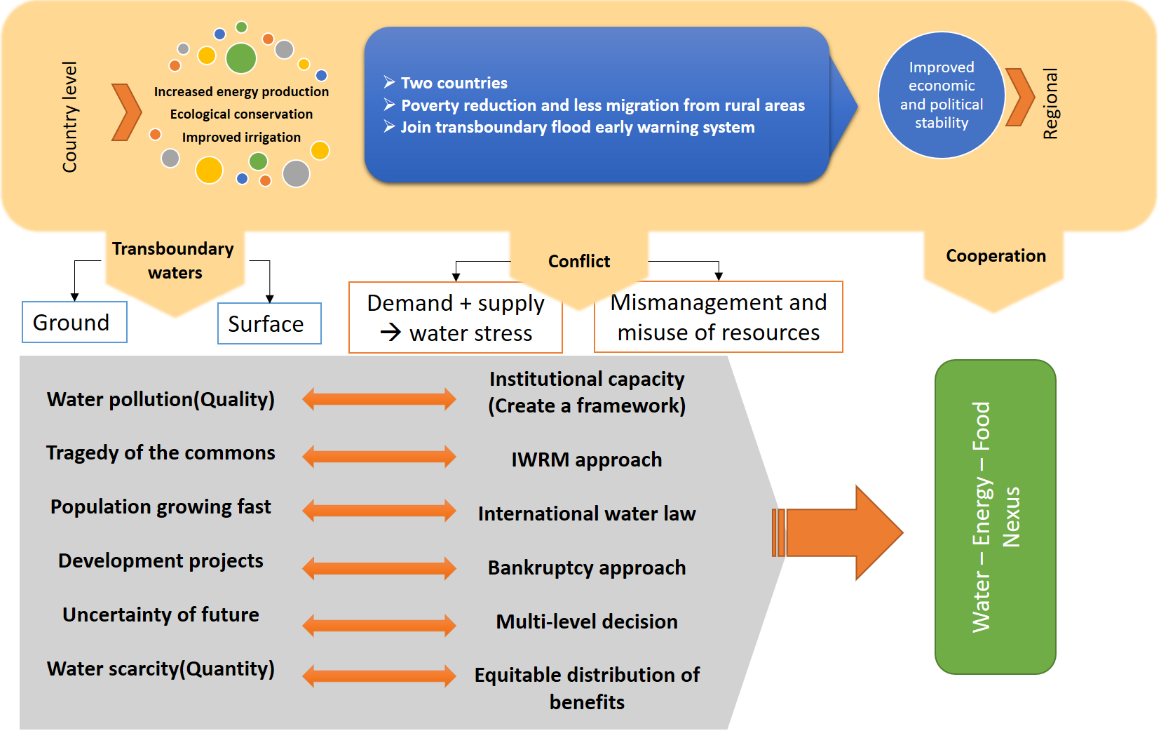

**Figure 26.** The relationship among transboundary water, conflict and cooperation.

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