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*Review*

# Consideration of the Environment in Water-Energy-Food Nexus Research in the Aral Sea Basin

**Mohammad Assem Mayar [1,*], Ahmad Hamidov [1,2], Akmal Akramkhanov [3] and Katharina Helming [1,4]**

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany; ahmad.hamidov@zalf.de (A.H.); helming@zalf.de (K.H.)
[2] "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers", National Research University ("TIIAME" NRU), Kary-Niyaziy 39, Tashkent 100000, Uzbekistan
[3] International Center for Agricultural Research in Dry Area (ICARDA), Osiyo Street 6-107, Tashkent 100000, Uzbekistan
[4] Faculty of Landscape Management and Nature Conservation, Eberswalde University for Sustainable Development (HNEE), Schicklerstr. 5, 16225 Eberswalde, Germany
* Correspondence: assem.mayar@zalf.de

**Abstract:** The water-energy-food (WEF) nexus is a holistic concept used to understand the synergies and trade-offs of interdependent water, energy, and food resources. Despite its widespread use, this concept often overlooks environmental concerns. In addition, the lack of a systemic approach in the Aral Sea Basin (ASB) has resulted in serious environmental degradation. For instance, the Aral Sea, situated at the terminus of the basin, is steadily shrinking, yet researchers studying the WEF nexus tend to overlook the upstream tributaries of the basin. This study aims to determine the extent to which research on the WEF nexus in the ASB in Central Asia has considered the environment through a systematic review of the literature published between 2012 and 2022. The results indicate that the number of WEF publications regarding the ASB has seen an upward trend, with a primary focus on the transboundary level and less research available on the local and national levels. This confirms the strong reliance of Central Asian states on one another for food, energy, and water resources. Furthermore, the results show that the majority of published studies either do not consider environmental concerns in their analyses at all or do so with little precision. Therefore, to achieve precise and sustainable outcomes, this study recommends the inclusion of environmental concerns along with basin-wide coverage in future WEF analyses. Finally, the WEF concept should be downscaled to the national and local levels in order to facilitate its implementation.

**Keywords:** systematic review; transboundary; sustainability; Central Asia; trends



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## 1. Introduction

The concept of the water-energy-food (WEF) nexus focuses on the balanced governance of these highly interconnected resources, emphasizing the link between the production and use of water, energy, and food [1]. It compels users to consider the consequences of a decision not only on one sector but also on others connected to it. Therefore, the WEF nexus has become a significant topic in both academic research and practice [2]. This concept was first introduced by the World Economic Forum in 2011 [3]. Since then, researchers and practitioners have applied the WEF nexus concept at local [4], national [5], and international or transboundary [6,7] levels in various parts of the world.

The transboundary Aral Sea Basin (ASB) is among the regions that have attracted increasing attention regarding WEF nexus research. Studies have attempted to unravel the intricate interdependencies between water, energy, and food systems, acknowledging their critical interconnections and the implications of this interconnection for sustainable development in this region [8–10]. These investigations have emphasized the multifaceted challenges stemming from climate change, anthropogenic activities, and the shrinking of

the Aral Sea and their repercussions on water availability, agricultural productivity, and energy dynamics in the basin.

The WEF nexus, a concept dedicated to the sustainable utilization of water, energy, and food resources, inherently requires the incorporation of all three (social, economic, and environmental) dimensions of sustainability. However, some WEF studies, many of which cover the ASB, focus solely on the economic and social aspects of WEF resources (Hao et al. [11] and Karatayev et al. [12]), and do not consider environmental concerns in their analyses. Conversely, other studies focusing on Central Asia, while incorporating environmental factors in their analyses [13–16], neglect the upstream tributaries of the Aral Sea or Amu Darya river basins, which serve as the primary water source for the ASB. Additionally, future development plans for these upper tributaries significantly affect water flow toward downstream riparian zones. This scenario exacerbates the environmental crisis in the ASB, where the shrinking of the Aral Sea, located at the end of this endorheic basin, has become an environmental disaster [17]. The steadily declining water levels and rising salinity of the Aral Sea have resulted in the extinction of numerous unique aquatic species that once only existed in this ecosystem [18]. Moreover, the desiccation of the Aral Sea has caused saline soil to be transported by winds onto arable lands, undermining the agricultural system [19]. Therefore, environmental concerns are at their highest level in this region. Excluding the upstream catchments from WEF analyses not only compromises the accuracy and sustainability of the environmental analyses but also undermines the integrity of WEF analyses in this key area of interest.

Furthermore, the inclusion of certain environmental aspects, particularly those related to water flow, water quality, ecology, and ecosystems, is crucial, as they are closely tied to water resources. Ensuring the sustainability of water resources based on an integrated water resource management paradigm necessitates basin-wide consideration. Therefore, to achieve a thorough assessment of the environment within the WEF analyses, the following two indicators should be applied: (1) consideration of the environment in addition to social and economic perspectives and (2) basin-wide coverage. Local- and small-scale WEF analyses, which provide the basis for secondary WEF research, may not address the environment or only cover environmental aspects that do not require basin-wide consideration. These studies can be integrated into the subsequent level of analyses in order to support WEF decisions at the upper levels of analysis.

To gain a thorough understanding of the current status of publications on the WEF nexus and contribute to the implementation of WEF nexus research, this study aims to assess to what extent publications on the WEF nexus in the ASB address the environment using the two aforementioned indicators. Additionally, this study summarizes and synthesizes existing WEF research and identifies gaps and inconsistencies in the literature. As a result, for the first time, we are able to comprehensively assess the research on the WEF nexus in the ASB and propose directions for future WEF nexus studies in the region.

## 2. Materials and Methods

### *2.1. The Aral Sea Basin*

The ASB is the largest basin in Central Asia. This basin's catchment crosses political divisions and spans the seven countries of Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and a small portion of Iran (Table 1, Figure 1). This basin is formed by the following three river basins: Syr Darya, Amu Darya, and Murghab. Amu Darya is the largest river of the ASB; it receives water from Afghanistan, Tajikistan, and Kyrgyzstan and flows through Uzbekistan and Turkmenistan, eventually draining into the Aral Sea. The Syr Darya River basin spans Kyrgyzstan, Tajikistan, Uzbekistan, and Kazakhstan. This river receives water from the Tien Shan mountains in Kyrgyzstan and Uzbekistan and streams into the northern part of the Aral Sea, known as the small Aral Sea [20]. Murghab is the third river basin, and its water flows from the northwestern parts of Afghanistan and the eastern part of Iran to Turkmenistan. The water from this basin dries in the Karakum desert and does not drain into the Aral Sea. Therefore, some studies,

i.e., [21–26] and the World Meteorological Organization (WMO), do not consider it as a part of the ASB (the WMO's river basin layer is depicted in Figure 1). However, the Karakum Canal, which annually transfers 13 billion cubic meters of water from the Amu Darya River to Turkmenistan, links this basin to the ASB. Thus, some studies, i.e., Micklin [27,28] and Burr et al. [29], have included the Murghab River basin in the catchment of the ASB. This study analyses the Murghab River basin within the ASB context. The authors remain neutral concerning the river basin division and its legality. The Iranian portion of the Murghab River basin is called the Sarakhs watershed. Some characteristics of the countries located in the ASB are mentioned in Table 1.

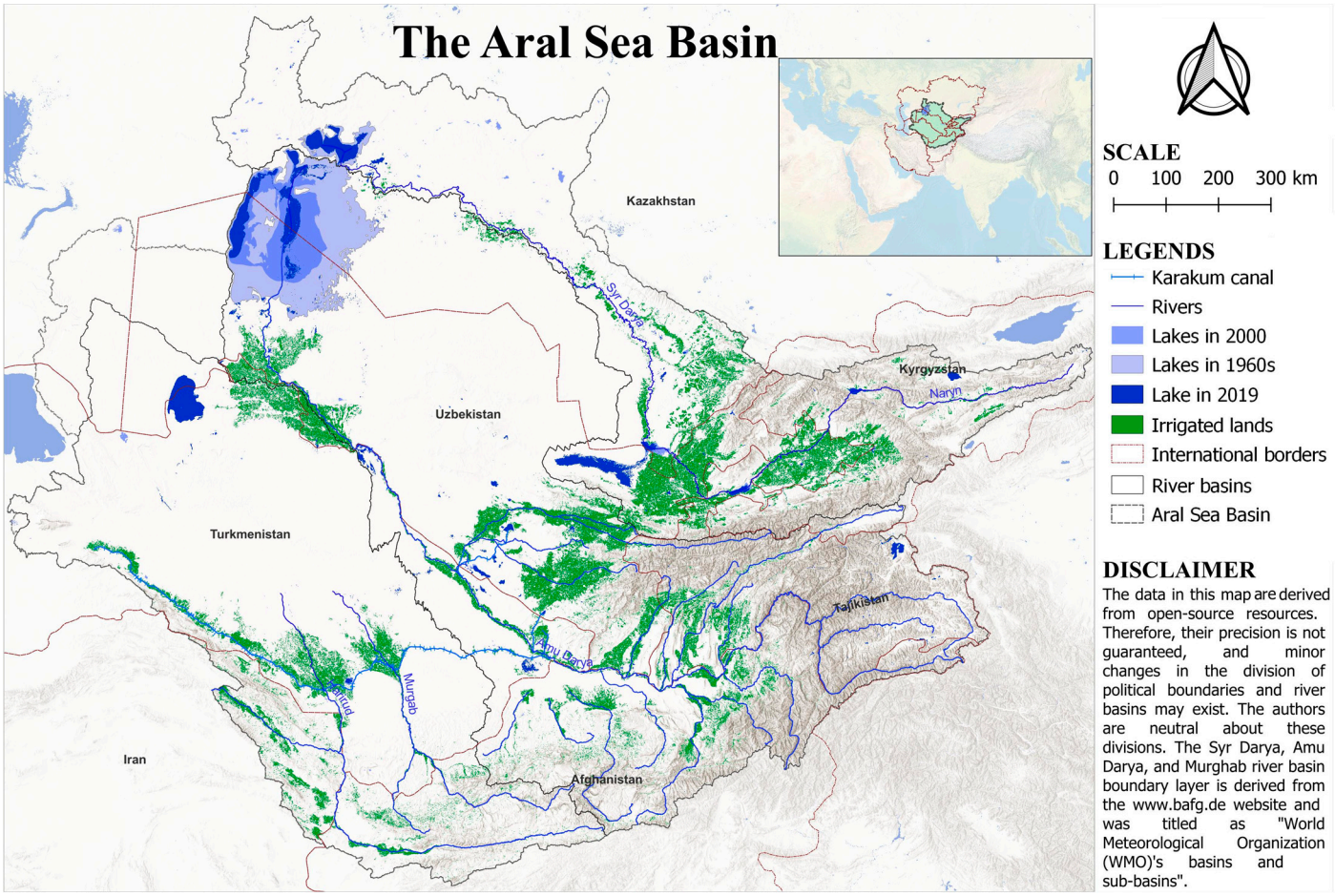


**Figure 1.** Map of the Aral Sea Basin depicting the highlands that feed the rivers, the distribution of irrigated land, and the drying of the Aral Sea.

Water, energy, and food resources have been unevenly distributed in the ASB. The highlands of upstream countries, i.e., Afghanistan, Tajikistan, and Kyrgyzstan, contribute 16.64%, 47.86%, and 23.07% of the ASB's total water, respectively (Table 1). Meanwhile, downstream countries, i.e., Kazakhstan, Uzbekistan, and Turkmenistan, have significant water utilization in the form of irrigation for food production (according to Table 1, these countries account for 10.15%, 41.95%, and 18.75% of the total irrigation in the ASB, respectively). In addition, Kyrgyzstan and Tajikistan use river flows for hydropower production. These countries produce 68.88% and 15.84% of the total hydropower generated in the ASB, respectively (Table 1). The downstream countries of Uzbekistan, Turkmenistan, and Iran use fossil energy to meet their energy demands. Kyrgyzstan, Kazakhstan, and Uzbekistan have maintained a barter agreement, exchanging water and energy on the Syr Darya River since 1998 [30]. Based on this agreement, Kyrgyzstan releases water during the summer to fulfill the irrigation demand of the downstream countries. In return, the downstream

countries supply fossil energy to Kyrgyzstan during the winter. This agreement has been breached several times in recent years due to the growing price of energy, which has created tensions between these countries. Therefore, Uzbekistan recently announced plans to build reservoirs to take control of water for its agricultural needs. Agriculture contributes significantly to the gross domestic product (GDP) of the countries located in the ASB [31]. The share of agriculture in the GDP of Kazakhstan, Turkmenistan, Kyrgyzstan, Tajikistan, Uzbekistan, and Afghanistan is 5.0%, 10.8%, 14.7%, 24.0%, 25.0%, and 33.5%, respectively [32]. These numbers indicate the dependence of these countries on this sector. Considering the GDP per capita (Table 1), Afghanistan is the poorest nation in the ASB.

**Table 1.** Characteristics of the countries located in the Aral Sea Basin (ASB).

| Countries | Area Share of the Country in the Basin (%) | Extent of Share in the Basin (%) | Mean Annual Water Resources [1] (%) | Water Withdrawal from the Basin [2] (%) | Irrigated Area Share in the Basin [3] (%) | Hydropower Production Share in the Basin [4] (%) | Population Share in the Basin [5] (%) | GDP per Capita [6] (USD) |
|---|---|---|---|---|---|---|---|---|
| Afghanistan | 37.40 | 13.70 | 16.64 | 6.95 [2a] | 11.97 | 0.82 [4a] | 17.34 | 368.8 |
| Iran | 2.60 | 2.00 | 0.42 [1a] | 2.09 [2a] | 4.56 | 0.11 [4b] | 6.71 | 4091.2 |
| Kazakhstan | 12.70 | 19.50 | 1.92 | 1.49 | 10.15 | 1.32 | 5.60 | 10373.8 |
| Kyrgyzstan | 59.20 | 6.70 | 23.07 | 0.32 | 4.39 | 15.84 | 4.88 | 1276.7 |
| Tajikistan | 99.00 | 7.98 | 47.86 | 8.88 | 8.22 | 68.88 | 12.92 | 897.0 |
| Turkmenistan | 94.60 | 26.10 | 1.22 | 16.40 | 18.75 | 0.17 | 7.84 | 7344.6 |
| Uzbekistan | 95.00 | 24.02 | 8.87 | 36.03 | 41.95 | 12.86 | 44.71 | 1983.1 |

Notes: [1] [33]; [1a] [34] Values presented as a percentage of the entire ASB. [2] [35]; [2a] [34] Values presented as a percentage of the entire ASB. The remaining amount of water is either lost or drained into the Aral Sea. [3] [36] Global cropland database. Northeast region in 2019 with a pixel size of 0.00025 × 0.00025 degrees. Values presented as a percentage of the entire ASB. [4] [37] Values represent hydropower production as a percentage of the total hydropower generated in the ASB. [4a] Sum of the electricity generated in the Afghan-India Friendship Dam, Pol-e-Khumri I, II hydropower stations, and Shorabak micro-hydropower plant in the Badakhshan province of Afghanistan. The Shorabak 7.5 megawatt micro-HPP has not been commissioned to date. [4b] Iran and Turkmenistan have agreed to use water and electricity of the Iran-Turkmen Friendship Dam equally. [5] [38] The values represent the population residing in the portion of the country that is part of the ASB as a percentage of the ASB's total population. [6] [39].

Within the former Soviet Union, the core element of the WEF nexus, water, was governed through a centralized system in Central Asia. Following the independence of the five Central Asian states, Kyrgyzstan, Kazakhstan, Tajikistan, Uzbekistan, and Turkmenistan signed the Almaty agreement in 1992 to maintain the existing water management mechanism. The upstream state of Afghanistan was excluded from this water-sharing agreement due to the regional legal and institutional framework governing the Amu Darya River [40,41]. Furthermore, this agreement also did not include Iran because of the Sarakhs' watershed, which drains to the Harirud River and then to Turkmenistan. However, Iran (then known as Persia) signed an agreement with the former Soviet Union (Turkmenistan) concerning the equal utilization of the Harirud River's water in 1926. Therefore, these two countries built the Iran-Turkmenistan Friendship Dam and the Shirtapa diversion dam over the Harirud River on the Iran-Turkmenistan border [42]. The Iran-Turkmenistan Friendship Dam stores 1.25 billion cubic meters of water and is used for irrigation and domestic use in Iran and Turkmenistan. For instance, Iran transfers 50% of Mashhad's drinking water (0.15 billion cubic meters) from this reservoir through a series of pumps [43]. However, the water-sharing agreements in Central Asia failed to generate a consensus about water utilization. Thus, disputes are still lingering among the Central Asian states [44].

Similarly, the distribution of food resources (agriculture) is diverse in the ASB. Uzbekistan, Turkmenistan, and Iran have significantly expanded their irrigable lands over the past half-century. This expansion of arable lands has had multiple environmental consequences, including the shrinking of the Aral Sea, which is referred to as the greatest environmental disaster of the twentieth century [17]. While the irrigable land of upstream countries,

particularly Afghanistan, has remained constant since the 1960s [45], its population has tripled. Therefore, Afghanistan imports both food and energy (electricity, fuel, and gas) from the Central Asian states and Iran.

### *2.2. Methods*

In this study, scientific publications related to the WEF nexus in the ASB were collected from the "Web of Science" and "Scopus" databases and analyzed. We conducted a search of the literature for English language publications in June 2023. Due to language barriers and inaccessibility reasons, articles in their local and regional languages, as well as grey literature, were not included in the analyses. The study period covered 2012–2022. From the indexed publications, the "Note", "Meeting Abstract", "Book Review", "Correction", "Retraction", "News Item", and "Letter" categories were excluded in order to only consider high-quality peer-reviewed publications. To avoid repetition, the indexed abstracts of books were also obtained from the library. However, the relevant book chapters were considered in the analyses. The methodology of this study consisted of three phases, which are depicted in Figure 2.

The literature search phase was repeated four times. First, to capture all publications related to the WEF nexus in the ASB, the terms of water–energy–food, the basins' names (Aral, Amu, Syr, Murghab/Harirud/Tejan, Sarakhs), as well as the political divisions in the study area (such, e.g., Central Asia, Afghanistan, Tajikistan, Kyrgyzstan, Kazakhstan, Uzbekistan, and Turkmenistan) were searched with multiple combinations in the titles, abstracts, and keywords of the publications. The search syntax's general structure was as follows: ("water-energy-food" OR "energy-food-water" OR "food-energy-water" OR "water-food-energy" OR "food-water-energy" OR "energy-food-water" OR "water, energy, food" OR "energy, water, food" OR "food, energy, water" OR "water, food, energy" OR "food, water, energy" OR "energy, food, water" OR "water, energy, and food" OR "energy, water, and food" OR "food, energy, and water" OR "water, food, and energy" OR "food, water, and energy" OR "energy, food, and water") AND ("Aral" OR "Amu" OR "Syr" OR "Murghab" OR "Harirud" OR "Tejen" OR "Sarakhs" OR "Central Asia" OR "Afghanistan" OR "Kyrgyzstan" OR "Kazakhstan" OR "Tajikistan" OR "Uzbekistan" OR "Turkmenistan"). The search syntax also included "Tejen", another name for the Harirud River in Turkmenistan. Furthermore, Iran was not mentioned in the search syntax because its inclusion resulted in several publications that focused on parts of this country that are outside of the ASB. Therefore, for greater precision, the name of the Iranian watershed located in the ASB, Sarakhs, which encompasses the second largest city of the country, Mashhad, was included in the search syntax. The first section of the search syntax focused on the topic, while the second section geographically determined the study area.

Second, the geographical section of the search syntax was set for each geographical unit listed in the above-mentioned search syntax, while the first section of the search syntax remained unchanged. This was chosen in order to evaluate the spatial distribution of WEF nexus publications across relevant basins and political divisions.

Third, to find articles that investigated both the WEF nexus and its influencing parameters, such as irrigation or agriculture, climate change, land, ecology, or the environment and soil, these items were individually included in the first section of the search syntax. This is because agriculture plays a pivotal role in the WEF nexus as it has significant impacts on water and energy resources and is a major contributor to global food security [31]. Climate change poses significant threats to agriculture and, accordingly, to the WEF nexus by altering precipitation patterns, exacerbating water scarcity, and affecting the productivity and quality of crops. The competition of land use for agriculture, forests, human settlements, and infrastructure is another challenge affecting the WEF nexus [1]. Ecology supports sustainable food production by providing essential ecosystem services such as soil fertility, pollination, and pest control. In addition, soil provides a medium for plant growth, stores water and nutrients, and regulates the availability and quality of water resources. Furthermore, researchers around the world have investigated these parameters within the

WEF nexus framework [1]. The second section of the search syntax, which determines the study area, remains unchanged. Subsequently, the second step in the literature search was repeated for this search category as well to identify the number of publications for the entire study area and for each geographical division.

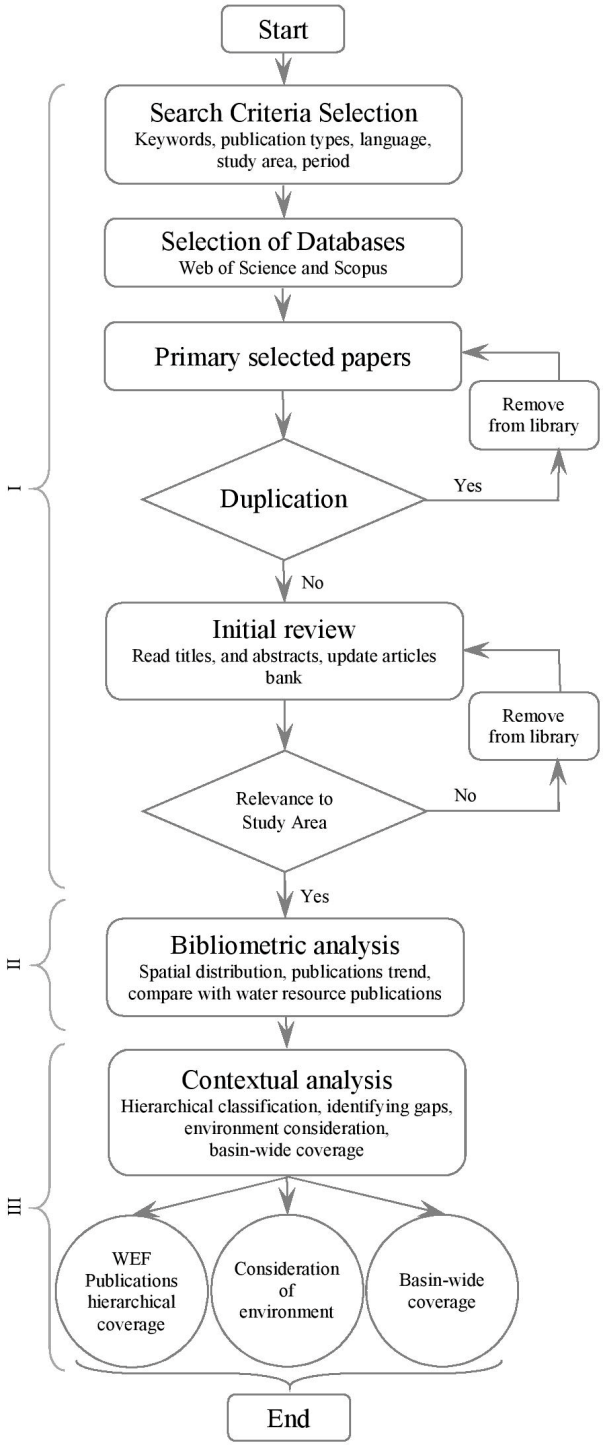


**Figure 2.** Flowchart for the methodology of this study.

Fourth, to compare the number of WEF publications with the published article about water resources in Central Asia, the WEF terms in the first section of the search syntax were replaced with "water resource", and the second section of the search syntax was kept as it was.

Publications in each search category were separately exported to an EndNote library, including information about the title, authors, publication year, abstract, keywords, journals, publishers, page numbers, and institutional affiliation of the authors. Imported articles from the Web of Science and Scopus databases were merged, and duplicate articles were filtered out. Then, the collected publications were evaluated, and articles irrelevant to the study area were dropped from the library and further analyzed.

In the second phase, the spatial distribution of the remaining publications on the WEF nexus and its influencing parameters for each geographical unit were analyzed. Subsequently, the temporal trends of the publications on the WEF nexus and water resources were obtained by analyzing the number of publications per year collected for each search category in the EndNote library.

In the third phase, the identified publications on the WEF nexus in Central Asia were contextually analyzed. There were three steps to this analysis: (1) As a prerequisite, we sorted publications by research type into qualitative and quantitative categories. Articles with results based on interviews with experts and stakeholders, reviews of the literature, rational analyses, or non-quantitative discussions were classified as qualitative research papers, while publications that used models and statistical analyses were listed as quantitative. (2) The articles were sorted into three hierarchical levels based on their coverage of transboundary, national, or local areas. The transboundary level consisted of articles that covered multiple countries but might not cover an entire river basin. Articles on the national level discussed the WEF nexus within a single country. Articles at the local level encompassed the analysis of the WEF nexus on a local scale, i.e., a specific area of a country. Articles that focused on very specific cases, which might not even require the consideration of the environment in their analyses, were also listed in the local category. (3) Finally, in order to evaluate the considerations of the environment presented in the WEF analyses published on the ASB, articles in the national and transboundary categories were assessed based on the two indicators discussed in the introduction.

## 3. Results and Discussions

This section commences with a bibliometric analysis of existing WEF research in the ASB. Subsequently, through contextual analysis, these publications are categorized into three hierarchical levels to identify potential knowledge gaps. Finally, the publications are evaluated for their proper consideration of the environment.

### *3.1. The WEF Nexus Publication in the ASB*

The search results for WEF nexus publications in the ASB yielded 34 articles (Figure 3). The "Total publications" in this category represents the actual number of WEF publications available for the entire study area. In addition, a number of publications overlapped across geographical divisions, including river basins, because the titles, abstracts, and keywords of some articles consisted of more than one search term. The river basin classification shows that the "Aral Sea Basin" was mentioned the most in the titles, abstracts, and keywords of the articles (15 times). Following that, the Amu Darya (six times) and Syr Darya (four times) river basins were mentioned the most frequently, while the Murghab River basin and its Iranian portion (the Sarakhs watershed) were not mentioned in the title, abstract, or keywords of any article. This means that the Murghab River basin and the Sarakhs watershed have not been individually studied. In contrast, Turkmenistan has often been covered in the analyses that focus on the entire Aral Sea and Amu Darya River basins. Despite the three river basins' importance, articles were classified based on the countries they focused on. This division shows that most publications (23) mention Central Asia rather than individual countries. This demonstrates that the WEF nexus has been predominantly considered at the Central Asian level rather than at the national level. Among the countries in the ASB, Uzbekistan has been the most frequently mentioned (15 times) in the title, abstracts, and keywords of collected publications, while Turkmenistan is the least mentioned country (3 times).

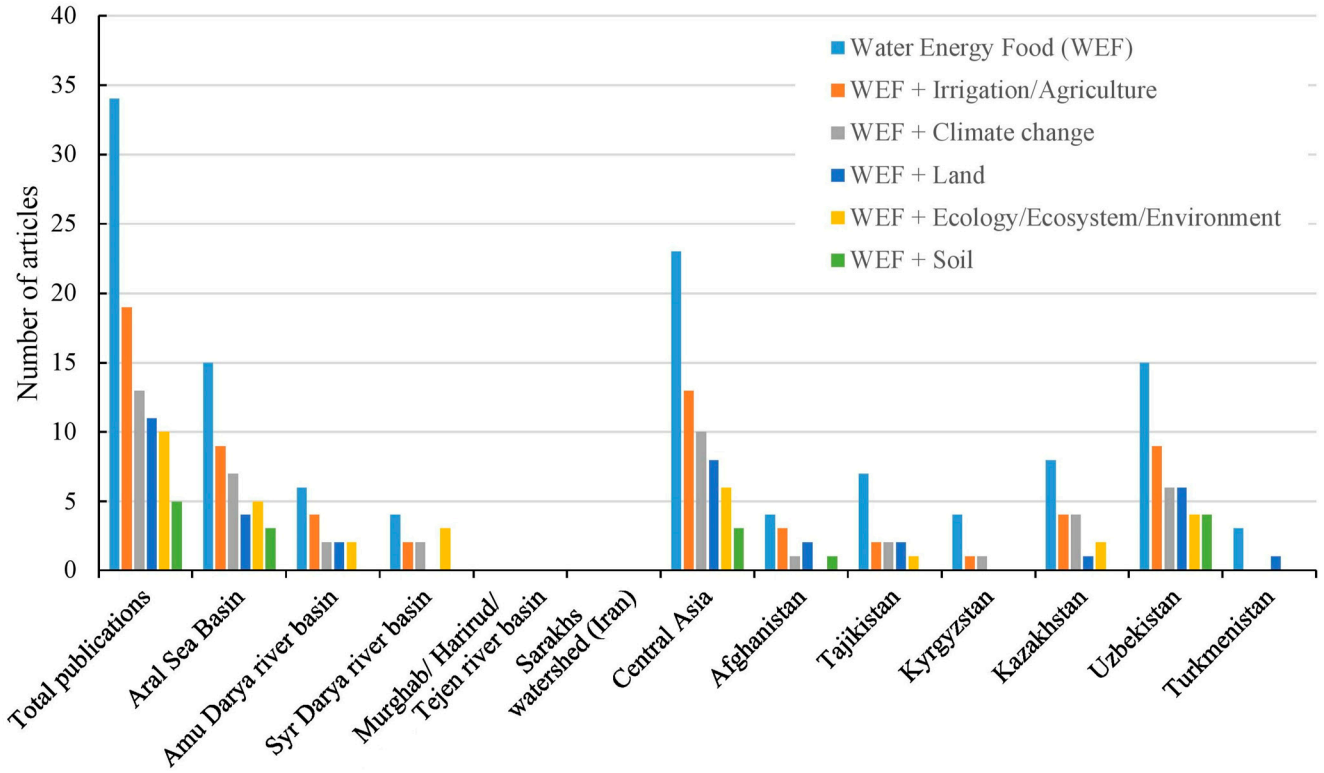


**Figure 3.** The total number of scientific publications on the WEF nexus, their related parameters, and their distribution in the Aral Sea Basin.

Thematically, in addition to studying the WEF nexus in general, it has mostly been studied together with agriculture as follows: "WEF + Irrigation/Agriculture" (Figure 3). Following that, "WEF + Climate change", "WEF + Land", "WEF + Ecology", and "WEF + Soil" were the most studied themes. In total, 19, 13, 11, 10, and 5 articles were collected for each of these categories, respectively (Figure 3). This means that agriculture is an important factor in WEF analyses in the ASB.

The number of WEF nexus publications within the study area showed an upward trend over time (Figure 4). A comparison of this trend with the trend of publications concerning "water resources" shows that the number of WEF nexus publications has a higher rate of increase, but its total number of publications (34) is considerably lower than the total number of publications on "water resources" (1151). Several factors contribute to this upward trend in the number of WEF publications. These encompass the interdependence of the Central Asian states on one another in the water, food, and energy sectors; escalating environmental concerns from the shrinking of the Aral Sea; the growing recognition of the significant role of the WEF nexus; the emergence of interdisciplinary research; and policy relevance. However, the high number of "water resource" publications primarily stems from their monodisciplinary nature (that is, relying on a singular specialization), their relative simplicity compared to the comprehensive analyses within the WEF nexus, the wider data availability, and their narrower scope of research.

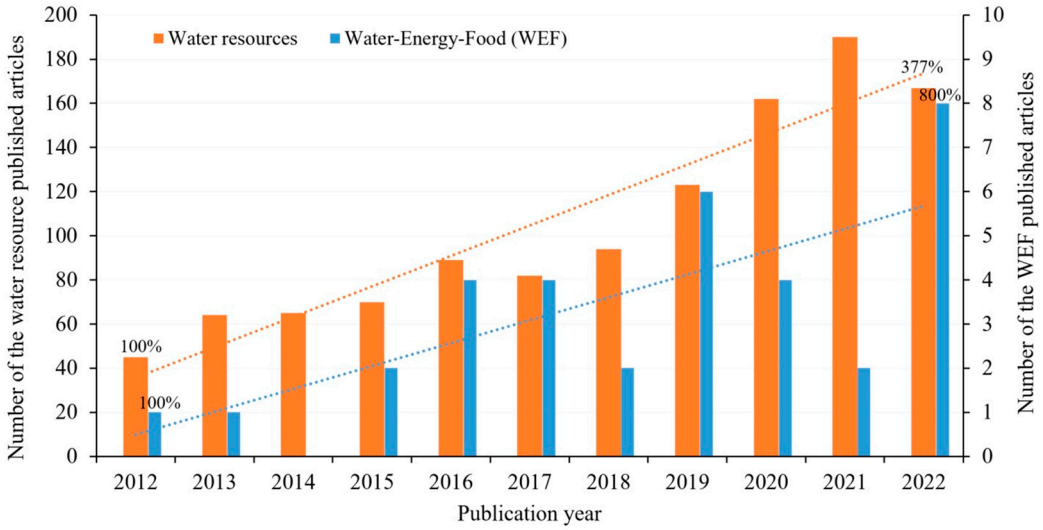


**Figure 4.** Temporal trends and a comparison of the total number of scientific publications on "WEF" and "water resources" in the Aral Sea Basin and Central Asia region.

### *3.2. Consideration of the Environment in the WEF Analyses in the ASB*

The findings of the contextual analyses performed on the WEF nexus publications are presented in Tables 2–4. The number of publications is equivalent in the qualitative and quantitative categories for the study area (Table 2). Qualitative research papers investigated issues such as institutional and policy frameworks for water resource management; the interconnections between water, energy, and food systems [46,47]; the challenges and opportunities of managing these resources in the region [12]; and the role of science in addressing environmental misperceptions. Additionally, Martius [48] proposed science-based management strategies for water resources, while Hamidov et al. [49] explored equitable governance approaches and stakeholder-based assessments of water-related sustainable development. The quantitative research papers examined the gains and losses of new water developments; assessed water and energy use, carbon emissions, and soil salinity changes in the region [50]; and proposed integrative analytical frameworks and optimization models for planning water, food, and energy systems [16,51]. Some papers, e.g., Graham et al. [13], also explored the complex interconnections between water, food, and energy security and confronted the substantial problem of fisheries in Central Asia. Additionally, Shi et al. [14,52] employed Bayesian networks and causal structure-based frameworks for water resource analysis and management.

**Table 2.** Qualitative and quantitative classification of scientific publications on the WEF nexus in the Aral Sea Basin.

| Type of Analysis | Total Number of Articles | References |
|---|---|---|
| Qualitative | 18 | Karatayev et al. [12], Soliev et al. [46], Koulouri and Mouraviev [47], Martius [48], Hamidov et al. [49], Granit et al. [53], Keskinen et al. [54], Karthe et al. [55], Yapiyev et al. [56], Rakhmatullaev et al. [57], Cassara et al. [58], Tankibayeva and Adibayeva [59], Murzakulova et al. [60], Baubekova and Kvasha [61], Pueppke et al. [62], Saidmamatov et al. [8], Shams and Muhammad [63], Hamidov et al. [9] |
| Quantitative | 16 | Hao et al. [11], Graham et al. [13], Shi et al. [14], Zhang et al. [16], Qin et al. [15], Guillaume et al. [26], Khamidov et al. [50], Ma et al. [51], Shi et al. [52], Jalilov et al. [10], Bekchanov and Lamers [64], Jalilov et al. [7], Jalilov et al. [6], Djumaboev et al. [65], Ibragimov et al. [66], Zhang et al. [67] |
| Total | 34 | |

**Table 3.** Classification of publications on the WEF nexus into three hierarchical categories. R (#) represents the number of repeated articles.

| Coverage | Total Number of Articles | Quantitative | Qualitative |
|---|---|---|---|
| Transboundary level | 25 | Hao et al. [11], Graham et al. [13], Shi et al. [14], Zhang et al. [16], Qin et al. [15], Guillaume et al. [26], Ma et al. [51], Shi et al. [52], Jalilov et al. [10], Bekchanov and Lamers [64], Jalilov et al. [7], Jalilov et al. [6] | Martius [48], Granit et al. [53], Keskinen et al. [54], Karthe et al. [55], Yapiyev et al. [56], Rakhmatullaev et al. [57], Cassara et al. [58], Tankibayeva and Adibayeva [59], Murzakulova et al. [60], Baubekova and Kvasha [61], Pueppke et al. [62], Saidmamatov et al. [8], Hamidov et al. [9] |
| Sub-total | | 12 | 13 |
| National level | 5 | Zhang et al. [67] | Karatayev et al. [12], Koulouri and Mouraviev [47], Hamidov et al. [49], Rakhmatullaev et al. [57], Cassara et al. [58], Shams and Muhammad [63] |
| Sub-total | | 1 | 4 + R (2) |
| Local level and specific cases | 4 | Khamidov et al. [50], Djumaboev et al. [65], Ibragimov et al. [66] | Soliev et al. [46], Hamidov et al. [9] |
| Sub-total | | 3 | 1 + R (1) |
| Total | 34 | 16 | 18 |

**Table 4.** Consideration of the environment in publications on the WEF nexus in the Aral Sea Basin.

| Indicator | Total Number of Articles | Quantitative | | Qualitative | |
|---|---|---|---|---|---|
| | | Do not Meet Indicators | Meet Indicators | Do not Meet Indicators | Meet Indicators |
| Consideration of environment | 30 | Hao et al. [11], Ma et al. [51], Jalilov et al. [10], Bekchanov and Lamers [64], Jalilov et al. [6], Zhang et al. [67] | Graham et al. [13], Shi et al. [14], Zhang et al. [16], Qin et al. [15], Guillaume et al. [26], Shi et al. [52], Jalilov et al. [7] | Karatayev et al. [12], Koulouri and Mouraviev [47], Granit et al. [53], Yapiyev et al. [56], Cassara et al. [58], Murzakulova et al. [60], Baubekova and Kvasha [61] | Martius [48], Hamidov et al. [49], Keskinen et al. [54], Karthe et al. [55], Rakhmatullaev et al. [57], Tankibayeva and Adibayeva [59], Pueppke et al. [62], Saidmamatov et al. [8], Shams and Muhammad [63], Hamidov et al. [9] |
| Sub-total | | 6 | 7 | 7 | 10 |
| Basin-wide coverage | 25 | Hao et al. [11], Graham et al. [13], Shi et al. [14], Zhang et al. [16], Qin et al. [15], Ma et al. [51], Bekchanov and Lamers [64], | Aral Sea Basin Guillaume et al. [26]<br>Syr River Basin Shi et al. [52]<br>Amu River Basin Jalilov et al. [10], Jalilov et al. [7], Jalilov et al. [6] | Martius [48], Keskinen et al. [54], Karthe et al. [55], Yapiyev et al. [56], Rakhmatullaev et al. [57], Cassara et al. [58], Tankibayeva and Adibayeva [59], Murzakulova et al. [60], Pueppke et al. [62], Hamidov et al. [9] Aral Sea Basin (excluding Sarakhs watershed) Granit et al. [53], Baubekova and Kvasha [61], Saidmamatov et al. [8] | |
| Sub-total | | 7 | 5 | 13 | |

The spatial coverage of the published articles is classified in Table 3 according to the three hierarchical levels (transboundary, national, and local). In both quantitative and qualitative categories (Table 3), most of the papers (73.5%) focused on transboundary-level analyses of the WEF nexus. Seven articles (14.7%), two of which also covered the transboundary level, studied the WEF nexus at the national level. In the last category, five articles (11.7%), including one repeated article, focused on the local-level analyses of the WEF nexus. The main reason for this descending trend in the top-to-bottom classification of articles is the Central Asian states' strong reliance on one another for food, energy, and water resources. This is because the upper tributaries provide water and hydropower, while the lower regions are utilized for agriculture. Furthermore, the ASB and its three river basins (Amu Darya, Syr Darya, and Murghab) cross international borders. Therefore, research focusing on any of these river basins inherently covers transboundary areas. Moreover, the regional division of the five states in Central Asia, the existence of a water utilization agreement among these states (The Almaty 1992 agreement), as well as the consideration of nationally averaged statistics in WEF analyses play a role in the transboundary consideration of this topic in Central Asia.

These findings further indicate that the WEF nexus in the ASB has been investigated less at the national and local levels (Table 3), which is contrary to a bottom-up approach. The top-down order of these analyses lacks local understanding and overlooks the diverse perspectives and experiences of stakeholders at the local level, hindering their participation in decision-making processes. This lack of detail hinders the development of effective WEF policies and practices at the national and local levels and challenges the implementation of the WEF concept at government levels.

The results for the two indicators used to evaluate the studies' consideration of the environment in the WEF research published in Central Asia are organized in Table 4. Around 56% of the published articles met the criteria for the first indicator (the consideration of environment). The quantitative research articles that met this indicator focused on the challenges faced by Central Asia's arid lowland ecosystems with respect to the WEF nexus and the need for the comprehensive management of this interdependent system. Meanwhile, the qualitative research articles that met this indicator emphasized the importance of sustainable development and equitable governance to promote the restoration of the ASB and the conservation of its biodiversity and ecosystem services. The majority of quantitative articles employed the term "ecology", whereas the majority of qualitative articles referred to the more all-encompassing term "environment". One plausible explanation for the neglect of the environment in certain publications may be attributed to the escalating complexity inherent in the analyses stemming from the multidisciplinary expansion of research. The environment, as an all-encompassing term, embodies a spectrum of facets, including ecology, biodiversity, ecosystems, soil salinity, and aquaculture. Integrating these elements with the WEF nexus, which is an already inherently interdisciplinary subject, elevates the analytical intricacy, necessitating collaborative efforts between researchers possessing diverse specializations. Hence, publications meeting the first indicator within the current analysis have predominantly concentrated on examining the interrelation between WEF analyses and a specific environmental theme. For instance, Khamidov et al. [50] investigated the impact of soil salinity, accentuated by climate change, on WEF resources. Likewise, Shi et al. [14,52] and Qin et al. [15] elucidated aspects of the WEF nexus intertwined with ecological considerations. Moreover, the limitations in data availability and its fragmented nature stand as formidable obstacles constraining the breadth of the research scope in the study area.

To evaluate the second indicator (basin-wide coverage), only articles included in the transboundary section of Table 3 were considered. This is because the river basins in the study area span multiple countries, and thus, articles in the national and local categories do not meet this indicator. Therefore, 25 articles covering the total basins were considered. Five articles (20%), all in the quantitative research category, met this indicator. Among these papers, Guillaume et al. [26] covered the entire ASB, Shi et al. [52] focused on the Syr

Darya River basin, and Jalilov et al. [6,7,10] covered the Amu Darya River basin. None of the qualitative articles investigated the entire Aral Sea, Syr Darya, Amu Darya, or Murghab River basins individually.

In light of these findings, it can be stated that the majority of the WEF nexus publications in the ASB do not meet both indicators set for the correct consideration of the environment at the same time. Among these publications, only Guillaume et al. [23], Shi et al. [52], and Jalilov et al. [7], covering the Aral Sea, the Syr Darya River basin, and the Amu Darya River basin, respectively, met both indicators.

The "WEF + irrigation/agriculture", "WEF + Climate change", "WEF + land", "WEF + ecology", and "WEF + soil" categories are the main subsets of the WEF nexus publications in Central Asia. Their contextual analyses are assumed to follow the same pattern as the WEF nexus articles and are, therefore, not considered because of this assumed duplication.

In addition, although soil salinization has been a major constraint to agricultural development in the region, very few papers address soil salinity in the context of the WEF nexus.

To implement the WEF concept at various governmental levels, future WEF nexus research needs to target the local and national levels because addressing the WEF nexus at the local level supports the improvement of the WEF nexus' management at higher levels. Furthermore, engaging local communities and stakeholders in discussions and decision-making processes regarding the WEF nexus can ensure that local concerns and priorities are considered in WEF management strategies. This approach helps to ensure that WEF policies are tailored to the specific needs of different regions. In addition, to obtain accurate and sustainable results from WEF analyses, future studies should consider the environment in their analyses, particularly in the ASB. De Keyser et al. [68] contributed to addressing this data gap through the dissemination of open-source geodata aimed at facilitating WEF research in Central Asia. Basin-wide coverage is required wherever WEF nexus studies do not focus on local-level or small-scale issues.

Finally, the analyses in the current paper only considered publications in English. For a comprehensive overview of the WEF nexus status in the ASB, the literature search should not be limited to the "Web of Science" and "Scopus" databases and should consider the science generated in local and regional languages. Producing knowledge in local languages also enhances the practicality of WEF nexus governance.

## 4. Conclusions

The WEF nexus is a concept that facilitates holistic and multidisciplinary analyses and the management of water, energy, and food resources. However, studies addressing the WEF nexus have not adequately considered the environmental concerns that fall short of meeting sustainability criteria. Therefore, this study analyzed the scientific publications on the WEF nexus of the Aral Sea Basin in Central Asia through a systematic literature review, focusing only on peer-reviewed articles published in English between 2012 and 2022. Due to language barriers and non-standardized archiving, articles written in the local and regional languages, as well as grey literature, were not included in this review. Given these constraints, the results show that the number of WEF nexus publications has seen an upward trend since 2012. Moreover, the analysis of the spatial coverage of these publications showed that the majority of the articles discussed the WEF nexus at a transboundary level rather than at the national and local levels, which is opposite to a bottom-up approach and hinders the practical implementation of the WEF concept across different levels of the government. The implications of these findings suggest a critical need for future WEF research in Central Asia to not only incorporate the two indicators proposed in this study, namely, the consideration of the environment and basin-wide coverage, but to also target the national and local levels. This approach can result in a more resilient environment, facilitating the implementation of the WEF nexus governance and fostering synergies with other sustainable development goals (SDGs) of the United Nations in the

region. By focusing on these aspects, future research can provide valuable insights into the potential perspectives and pathways for advancing sustainable development in the Aral Sea Basin and beyond. Finally, despite soil salinization being a major threat to sustainable agriculture in the region, very few papers discuss soil issues in the context of the WEF nexus. Thus, future research should explore soil health in this region in relation to the WEF nexus.

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