

Article

Transferable Principles for Managing the Nexus: Lessons from Historical Global Water Modelling of Central Asia

Joseph H. A. Guillaume ^{1,*}, Matti Kummu ¹, Stephanie Eisner ² and Olli Varis ¹

¹ Water & Development Research Group, Aalto University, Tietotie 1E, Espoo 02150, Finland; E-Mails: matti.kummu@aalto.fi (M.K.); olli.varis@aalto.fi (O.V.)

² Center for Environmental Systems Research, University of Kassel, Kassel 34117, Germany; E-Mail: eisner@usf.uni-kassel.de

* Author to whom correspondence should be addressed; E-Mail: joseph.guillaume@aalto.fi; Tel.: +358-50-407-2906.

Academic Editor: Miklas Scholz

Received: 26 May 2015 / Accepted: 24 July 2015 / Published: 31 July 2015

Abstract: The complex relationships within the water-energy-food security nexus tend to be place-specific, increasing the importance of identifying transferable principles to facilitate implementation of a nexus approach. This paper aims to contribute transferable principles by using global model data and concepts to illustrate and analyze the water history of Central Asia. This approach builds on extensive literature about Central Asia and global change as well as recent advances in global water modeling. Decadal water availability and sectorial water consumption time series are presented for the whole 20th century, along with monthly changes in discharge attributable to human influences. Concepts from resilience and socio-ecological system theory are used to interpret the results and identify five principles relevant to managing the transboundary nexus: (1) the subsystems included/excluded from the nexus are case-specific and should be consciously scrutinized; (2) consensus is needed on what boundaries can acceptably be crossed within the nexus; (3) there is a need to understand how reducing trade-offs will modify system dependencies; (4) global stakeholders have both a responsibility and right to contribute to the shaping of the nexus; (5) combining data with global and local perspectives can help to enhance transferability and understanding of shared problems in our globalized world.

Keywords: Central Asia; nexus; WaterGAP; resilience

1. Introduction

A nexus approach is one that “reduces trade-offs and builds synergies across sectors” [1], notably between the management of water, energy, and food security. Practical implementation of a nexus approach involves understanding inter-relationships between sectors and seeking suitable governance and management options [2]. Those relationships are naturally quite case-specific. From a water perspective, interactions will be very different in regions with snow or glacial melt, monsoon, groundwater, mountains, and deserts. Interactions involving the energy sector might differ depending on the importance and availability of fossil fuels, biomass, hydropower, nuclear, wind, tidal energy, *etc.* Relationships with food notably vary depending on energy intensiveness, labor- and land-productivity [3], as well as the importance of trade [4], irrigation [5], non-food agriculture (e.g., cotton) [2], and non-agricultural food production (e.g., freshwater or marine fisheries) [6]. The nexus is readily acknowledged as unique in every place. This is even more noticeably the case in transboundary nexus situations, where negotiations are often focused on a particular issue, for example, on a specific transboundary watercourse and its specific competing uses.

Learning about the management of the nexus globally therefore depends on our ability to identify and share transferable principles that appear to apply across scales around the world. One approach is to develop a theory about processes, including transferable methodologies (e.g., [7,8]). Another is to use case studies to contribute to the growing checklist-style body of knowledge about relationships to look out for and corresponding governance arrangements (e.g., [2,9,10]). The key aim in each case is to cross scales, linking the local implementation-scale situation to a broader global understanding.

Considering Central Asia as a case study, there is already a solid foundation of research on which to build, including the use of the nexus approach and global data. Water in Central Asia has been extensively discussed, particularly focusing on the history and future of the Aral Sea basin. Notable publications include several books (e.g., [11,12]), policy reports [13,14], as well as special issues on “Water and Security in Central Asia: Solving the Rubik’s cube” [15], “Water in Central Asia—Perspectives under global change” [16], and (this year) “Sustainable Water Management in Central Asia” [17].

This existing work has included nexus approaches. This has included analyses of historical and ongoing multilateral cooperation and benefit sharing, for example, at basin scale with regard to energy and water [18] and at regional scale with regard to water, energy, food, and agriculture [2,19]. Other analyses focused on international influences on management of the nexus in Central Asia and the need for capacity-building [20], economic analyses of energy supply and irrigation [18], and the need for economic reform as a means of addressing nexus challenges [21]. Stucki and Sojamo [22] notably give a useful introductory overview of the “nouns and numbers” of the nexus in Central Asia through definitions, indicators, and data. The special issue that this article is a part of focuses on transboundary nexus issues in Asian river basins, including other case studies focused on Central Asia (e.g., [23,24]).

Global data has also been used in multiple ways in assessments of Central Asia. Varis and Kummu [25] produced vulnerability profiles of basins. Porkka *et al.* [26] investigated the effect of changes in import and export on water stress and shortage based on data in the year 2000. Aus der Beek *et al.* [27] applied a global model (WaterGAP3) to differentiate the impact of climate and water use on flows in the Aral Sea basin. Malsy *et al.* [28] used the same model to analyze the potential impact of climate change on Central Asian water resources.

More generally, recent developments in global water modeling and global change literature have provided new means of looking at local issues. Global water models, such as in the Water and Global Change (WATCH) project [29,30], provide widely applicable datasets for water availability and multi-sectorial water consumption. Their growing maturity, particularly in estimation of water use (e.g., [31]), has led to broad application across many scales (e.g., [4,5,26–28,32]). Simultaneously, literature on global change, socio-ecological systems, and resilience has developed descriptive and normative theory regarding planetary boundaries [33] specifically, and has taken a resilience-based perspective to water sustainability [34] more generally. These concepts have aims similar to the nexus [1,35], and can be expected to yield useful principles regarding its management.

This paper aims to contribute transferable principles that could be applicable across scales around the world. The approach taken is to begin with global model data and concepts and apply them to a local case study. This helps to identify possible generalizable implications for the implementation of a nexus approach. We look at the nexus through a water lens, where food and energy are users of the resource [7]. Specifically, we use output from the WaterGAP global water model, based on a new 100-year input dataset of irrigated areas [36], to illustrate the history of the nexus in Central Asia from 1900 to 2000. This history is described through a series of spatiotemporal assessments of blue water availability and consumption combining powerful visualizations and their interpretation using literature about Central Asia. Central Asia has been selected for its particular history and wealth of prior analyses. Discussion of the analysis then makes use of globally applicable concepts from resilience theory and socio-ecological systems, notably boundaries and system dependencies, in order to uncover transferable principles for implementation of a nexus approach. This paper does not aim to provide specific recommendations regarding management of the nexus in Central Asia.

The structure of this article follows. Section 2 (Method and Data) describes the global water model used and the assessments performed. Section 3 (Results and Interpretation) presents the results and their interpretation in the form of a history of the nexus in Central Asia. Section 4 (Discussion) delves deeper into concepts underlying this history in order to identify implications for management of the nexus, as well as possible extensions to this analysis. Section 5 (Conclusion) summarizes key conclusions about the history of the nexus in Central Asia as well as transferable principles for management of the nexus.

2. Method and Data

2.1. Global, Spatially Distributed Estimates of Water Availability and Consumption

The analysis uses monthly time series of blue water availability and consumption for the 20th century, produced using a preliminary version of WaterGAP2.2 [37]. Blue water availability is calculated by a daily water balance model for each 0.5° grid cell based on meteorological forcing and landscape factors. Blue water corresponds to “liquid water in rivers and aquifers”, as opposed to green water, which refers to “naturally infiltrated rain, attached to soil particles and accessible to roots” [38]. Blue water is of particular interest in Central Asia, notably due to the highly publicized effects of irrigation water use on the Aral Sea, as discussed further in Section 3.

Spatially explicit estimates of water consumption are provided by the WaterGAP water use models for five sectors: households and small businesses (domestic sector), thermal power plant cooling (electricity sector), irrigated agriculture, livestock farming, and manufacturing industries [31]. Water consumption refers to water that is “evaporated or incorporated into products” [37]. Key drivers include water use intensities, consumptive water use coefficients, and structural or technological change factors.

Monthly time series of blue water availability are simulated in two model setups: (1) including human interference on the natural regime through water abstraction and reservoir operation, and (2) under naturalized conditions, *i.e.*, excluding any human interference. The model setup was nearly identical to the WATCH project [30], but it differs in a few important aspects. While the WATCH precipitation and temperature forcing datasets were used [29], irrigation water use is additionally based on a new dataset of irrigated land from 1900–2005 compiled from a variety of subnational sources [36]. Secondly, spin-up of the model allows data to be used from the year 1901, whereas the WATCH dataset treats the 1901–1905 period as model spin-up, such that these cannot be used for analysis.

The data used naturally has limitations (discussed throughout the article), and needs to be interpreted with care. The data itself has therefore not been made available, and our conclusions regarding the nexus and Central Asia have been additionally supported with references to previous research. An interested reader can nevertheless find similar publically available datasets from the WATCH or Inter-sectoral Impact Model Intercomparison Project (ISI-MIP) projects [30,39].

2.2. Construction of Historical Assessments in Central Asia

Water availability and consumptions were aggregated to Food Production Units (FPUs), which are a combination of river basin and economic regions used by a number of previous studies [4,40–42]. Other units of analysis may yield some variation in quantitative results [32]. FPUs are a hydro-politically relevant scale of analysis [40], and the conclusions drawn with this unit of analysis were found to be consistent with existing literature about Central Asia.

This paper focuses on a subset of FPUs within Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Afghanistan (Figure 1). FPUs that are part of larger river basins (e.g., the Volga and Ob) have been omitted, as have some small, sparsely populated endorheic basins with little water use. The study area is shown in Figure 1, including mean water availability, country borders, basin borders, key rivers, and boundaries of the FPUs.

For the majority of the analysis, the monthly data have been aggregated to obtain decadal water availability and consumption time series. This allows a focus on broad temporal patterns, and reduces the impact of error at shorter time scales. The use of decadal scales lessens the importance of inter-annual storage variation, such that inaccuracies in reservoir operations, snowmelt, and groundwater have less effect.

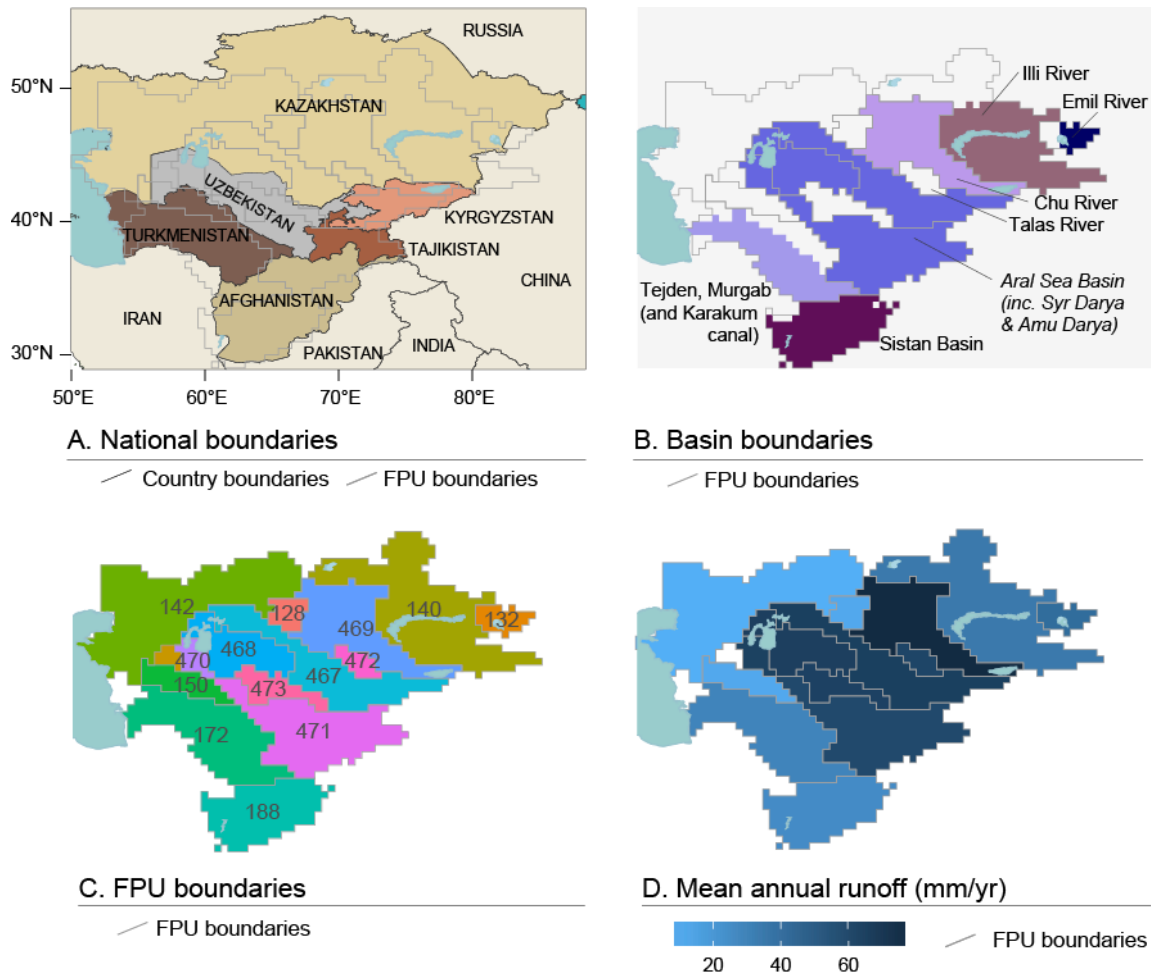


Figure 1. Map of study area: (A) national boundaries; (B) basin boundaries; (C) FPU boundaries; (D) mean decadal water availability for each food production unit (FPU); overlain with a selection of lakes [43,44].

FPU were split into clusters based on the similarity of their decadal water availability time series. Hierarchical clustering (the *hclust* function in R [45]) was used to identify four clusters using positive Kendall correlations as measure of similarity.

In interpreting the results, we treat consumptive uses as different pathways by which water becomes inaccessible to humans, notably through evaporation by which water returns to the atmosphere. In this paper, we focus on blue water in particular. If there were no human uses, then blue water would eventually evaporate from rivers, lakes, or from the sea. Given that the catchments in Central Asia are endorheic, this means that, for example, any water that reaches the Aral Sea or Lake Balkhash will ultimately evaporate from there. This environmental water is available to aquatic ecosystems, and is therefore key to maintaining healthy waterways and ecosystem services. Reflecting the importance of sharing water between society and ecosystems [46], we include total environmental water as a consumptive use, and calculate it as the difference between availability and total human consumption of blue water.

Per capita consumption and decadal stress and shortage were also calculated. The latter two are common indicators of water scarcity [47–49], respectively calculated as the ratio of human water consumption and availability and per capita availability of water. Their interpretation is discussed in

Section 3.3 when they are used. Population data for each decade was obtained from the spatially explicit History Database of the Global Environment (HYDE) dataset [50].

To complement the high-level decadal view, we also calculated the monthly difference between natural discharge and human-influenced discharge, *i.e.*, with flow regulation and water abstraction. Errors may be more significant when using global scale modeling of shorter time scales. Models may be able to estimate relative changes even if absolute values are not quite right. We therefore avoid examining availability and consumption data directly and instead focus on the change in seasonal flows that has occurred due to human water use.

3. Results and Interpretation: History of the Nexus in Central Asia through a Global Water Lens

This section illustrates the 20th century history of the water-energy-food nexus in Central Asia through a water lens. Assessment of decadal blue water availability is followed by decadal water consumption and human-induced seasonal changes in discharge.

3.1. Decadal Water Availability

Physical water availability is a key factor influencing the water-energy-food security nexus. Figure 1 shows mean decadal blue water availability in the study region while Figure 2B shows time series of decadal blue water availability. Decadal water availability is an indicator of the size of the resource and its variation in the long-term. Across Central Asia, most basins are endorheic and transboundary. Mean water available is relatively low (Figure 1). There is still significant variation spatially, such that the FPU clusters can be split into clusters according to the similarity of the variation over time (Figure 2A). Summaries of these clusters follow.

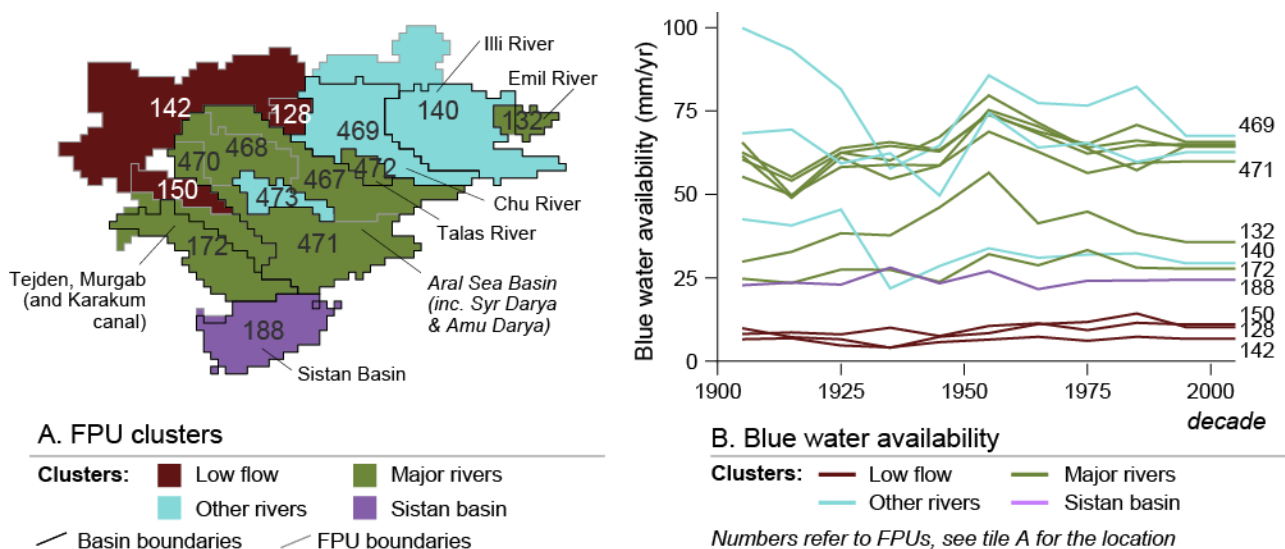


Figure 2. Decadal water availability: (A) Map of food production units (FPUs) showing clusters based on correlation of their time series, along with major basins; (B) water availability time series for each FPU, colored according to the same clusters.

In general, the “major rivers” cluster is characterized by high water availability, driven by glacial and snow melt from the Pamir and Tien Shan mountains to the east [51]. This is a dominant feature of

the region, as the arid downstream areas depend on the continental climate of these headwaters and the relative reliability of glacier flows [52]. The time series in Figure 2 does, however, show lower water availability at the start of the century, a peak in the middle of the century, followed by a return to lower levels, consistent with the strong role of observed climatic variation [51] and a cold, wet period in the 1950s [53]. There is, however, no clear trend of water availability, consistent with studies showing that climate change effects on runoff vary substantially between catchments, though increased temperature, evaporation, and glacier melt are generally accepted to be playing a major role [51]. Note that the model used here does not explicitly represent glacier melt, though it is still considered to have acceptable performance in Central Asia [27,28], at least for the purpose of this paper.

This “major rivers” cluster most notably includes the Aral Sea drainage basin (FPU 468, see Figures 1 and 2), including the Amu Darya (FPU 470, 471) and Syr Darya main stream (FPU 467). The Talas river (FPU 472) has similar flow patterns. It also descends from the mountains in Kyrgyzstan and disappears in the desert in Kazakhstan [54]. FPU 132 and 172 were identified as having relatively similar temporal patterns but lower water availability. FPU 132 includes the catchment of the saline Lake Alakul, including the Emin (Emel or Emil) river, which flows from the mountains in China into eastern Kazakhstan [55]. FPU 172 includes the Tedjen (or Hari) and Murghab rivers flowing from the mountains of Afghanistan. While the model does not include the Kara-kum canal, which contributes significantly to irrigation in Turkmenistan by carrying water from the Amu Darya [56], the data still sufficiently demonstrates key features of the region’s water consumption history.

The “other rivers” cluster spans very different river systems, some of which are characterized by sometimes quite high but highly variable water availability (Figure 2). The cluster includes important transboundary river basins such as the Chu river (FPU 469) and the Illi river, which flows into Lake Balkash (FPU 140). The same FPUs include smaller basins such as the endorheic lake Issyk Kul and Sary su River (FPU 469) and the Ramsar-listed Tengiz-Korgalzhyn Lake System (FPU 140), as well as other smaller endorheic basins. FPU 473 provides another contrast, with the anthropogenic Aydar-Arnasay system of lakes in Uzbekistan and nearby irrigation areas [57], as well as the city of Zarafshan in the Kyzylkum desert. The area makes use of water from both the Syr Darya and Amu Darya rivers.

In the “low flows” cluster, FPU 150 includes extensive irrigation areas in Turkmenistan and Uzbekistan near the Amu Darya. FPUs 142 and 128 cover large parts of Kazakhstan. While FPU 142 does include some endorheic rivers (including the Emba River, which leads to the Caspian Sea), water availability is generally much lower than in the other regions. The climate is predominantly cold, arid desert and steppe.

In the cluster “Sistan basin”, FPU 188 has been singled out as uncorrelated with others. The largest river in the basin is the Helmand (Hirmand), which is notably fed by snowmelt from mountains to the northeast of the region, and is used for irrigation in both Afghanistan and Iran [58]. Blue water availability is also relatively low.

3.2. Decadal Blue Water Consumption

From a nexus point of view, the key is how the available water is used. In this section, we focus on different consumptive uses of water (Figure 3). As discussed in Section 2.2, consumptive uses can be

considered as different pathways by which water becomes inaccessible to us, notably through evaporation by which water returns to the atmosphere. This includes both human uses and water that is available to aquatic ecosystems (referred to as environmental water). When water is consumed (evaporated or transpired), it returns to the atmosphere and, hence, the global water circulation system. The analysis of van der Ent *et al.* [59] indicates that in Central Asia, a large proportion of water available comes from its consumption (*i.e.*, evaporation) on the European and Asian continents to the west, and when it is consumed (*i.e.*, evaporates) in the study area, the majority will return as precipitation on the Asian continent to the east. The water is not lost, but can no longer be easily reused in its previous location.

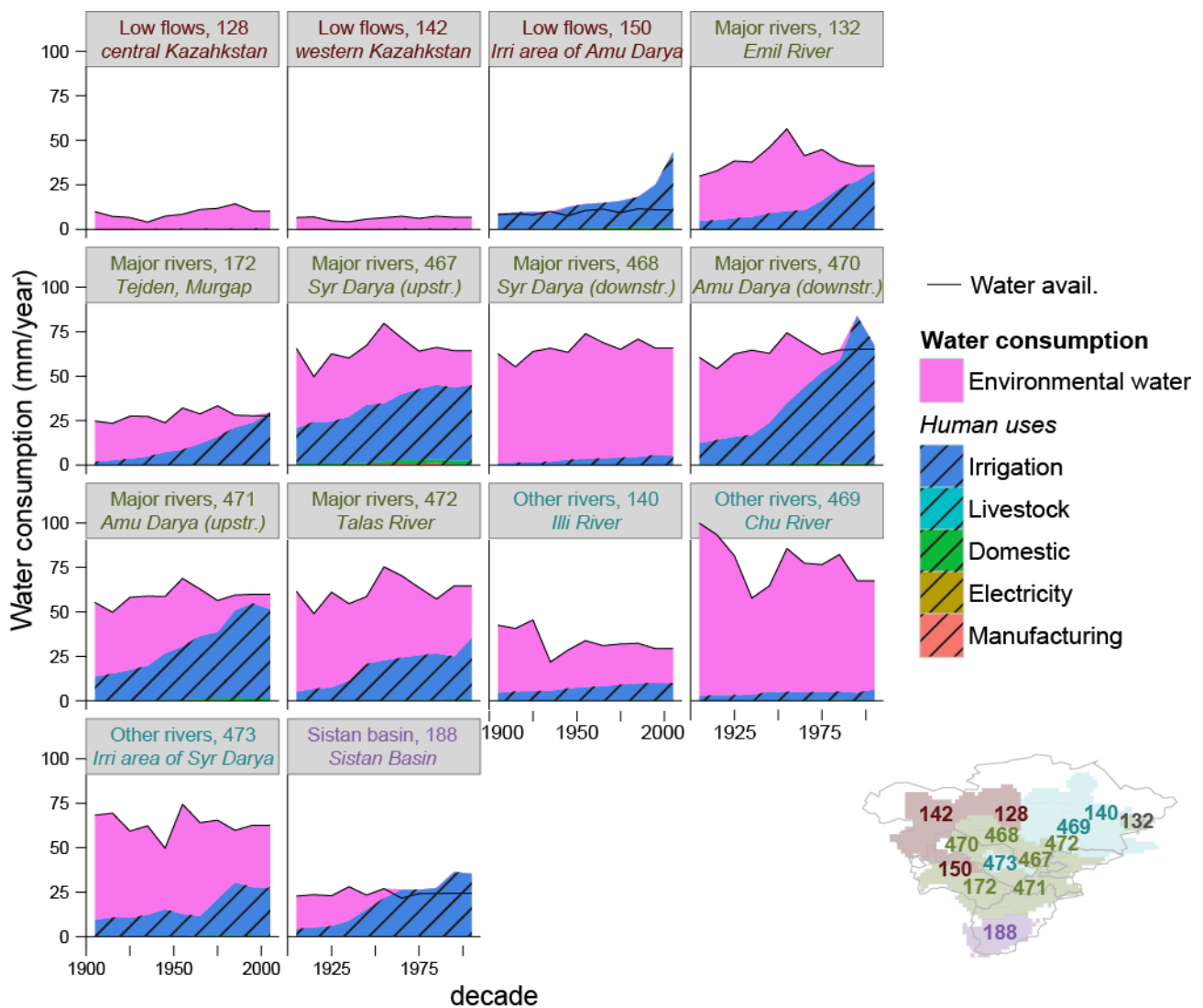


Figure 3. Total blue water use split by end-use of water (*i.e.*, pathway in which it evaporates) for each food production unit (FPU) for 1905–2005, overlain with total water availability. Environmental water is defined here as the water that is available to aquatic ecosystems, calculated as the difference between availability and total human use [46]. Water use sectors other than irrigation and environmental water are so small that they are not visible on this figure.

3.2.1. Partitioning between Human Use and Environmental Water

In our findings (Figure 3), two consumptive uses (*i.e.*, evaporation pathways) stand out: environmental water and irrigation. Other uses are very small by comparison, e.g., at the bottom of the plot for FPU 467. At the start of the 20th century, the majority of water was environmental water in all but one FPU. This means that the water evaporates in a pathway that provides environmental flows [60] and maintains natural ecosystem services.

In some FPUs, environmental water has not changed much. This is predominantly the case in FPUs with low water availability (FPUs 128, 142). In these areas, it is possible that there is not enough water to maintain a large water-dependent population and economy. In FPU 142, oil and gas production is instead particularly prominent, with associated problems with water quality [61]. FPUs 468 and 469 have also seen only relatively small decreases in environmental water. An exception is FPU 150, which is fed by irrigation channels from the Amu Darya [27].

In many other FPUs, environmental water has diminished over time, and human use (notably irrigation) has increased. As the population increases and water-consuming economic activity grows, the use of water becomes determined by humans rather than natural processes [62]. Existing ecosystems have evolved to suit local water availability, such that when tolerable human blue water consumption is exceeded, it can lead to changes in the way the socio-ecological system operates [63] and a “high probability of (possibly abrupt) water-induced changes with large detrimental impacts on human societies” [64].

In some FPUs, human use has even exceeded available water (FPUs 150, 470, 188). In the context of the model, this likely indicates the use of long-term stored water, such as the non-sustainable use of groundwater and unaccounted physical water transfers.

The case of the Aral Sea is a high-profile example of the effect of increasing human water use (and diminishing environmental water) [65]. The Amu Darya (FPUs 471 and 470) and Syr Darya (FPUs 467, 468) are the main rivers feeding the Aral Sea. Irrigation expansion (visible in Figure 3) reduced inflows, resulting in reduced lake area and increased salinity, loss of fish species, desertification, dust storms, and climate change along the shoreline [65]. These changes to the ecological system led to changes in the associated social system, including the collapse of fishing industries, high unemployment, the loss of irrigated land to salinization, poorer diets, and health problems [65].

3.2.2. Distribution of Human Water Consumption per Capita

Human water use is not distributed equally per capita. Societies have different needs and wants and, hence, different water footprints. Figure 4 shows per capita human water use over time. Some FPUs have much larger per capita consumption than others, which reflects intensive use of water within the economy rather than high consumption by individuals. As already noted, the human use of water is dominated by irrigation. The large changes in per capita consumption (e.g., in FPU 468) can therefore be explained by the expansion and contraction of irrigation water in relation to the population. Some declines (e.g., FPUs 140 and 469) are, however, more likely to be explained by improvements in the efficiency of water use or increases in the population. The population grew throughout the 20th

century for all but a few smaller FPU's in Central Asia (results not shown). If population increases and water-dependent industries do not grow, then per capita consumption falls.

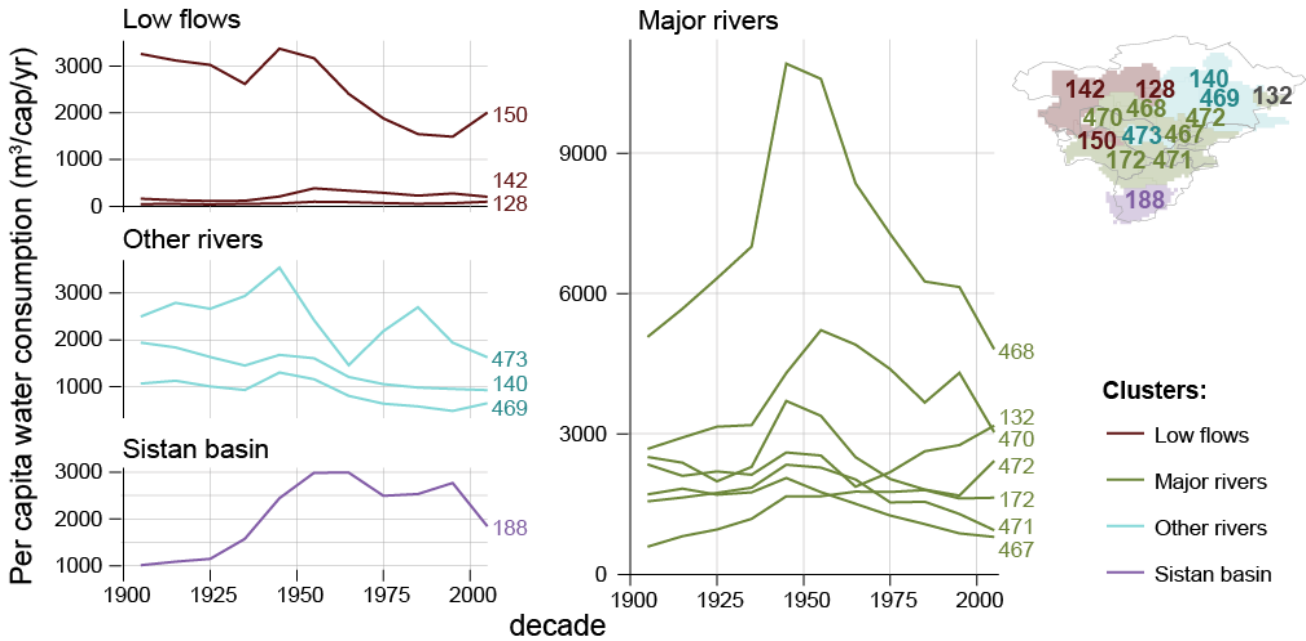


Figure 4. Human blue water consumption per capita.

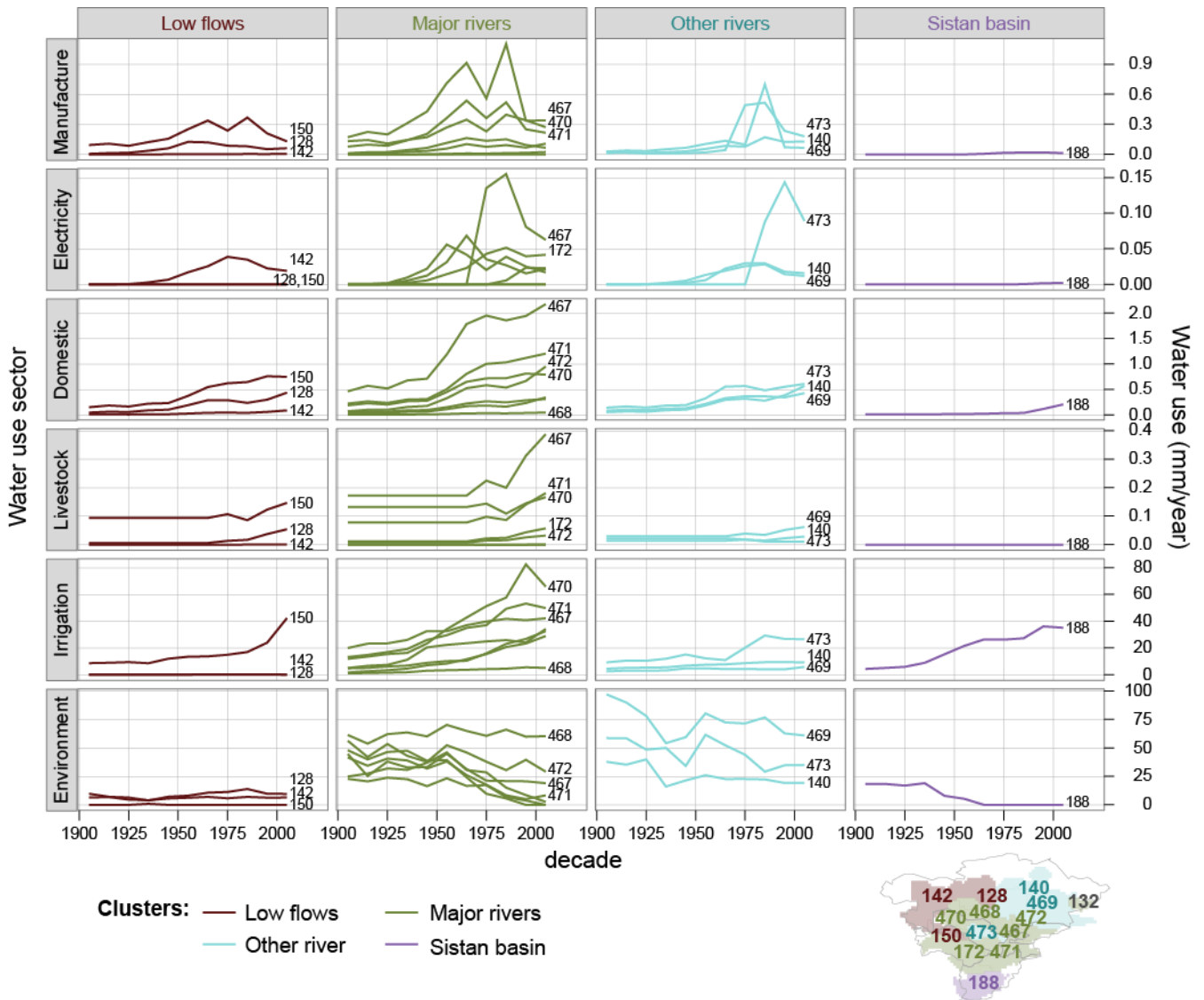
3.2.3. Distribution of Water by Activity

A core issue of the water-energy-food nexus is the trade-off between water-dependent activities. Time series of consumption for each sector are shown in Figure 5. Before interpreting this figure, it is important to remember that the nexus exists within a broader context. When a water resource is not stressed, all industries take as much as they want (at the increasing expense of environmental water). The environment acts as a buffer, mitigating conflict between uses. Similarly, when the population is small, there is less competition for water than when the population is large [48]. Only when water becomes scarce does meeting all activities' water requirements become an issue. This is the case in some basins in Central Asia, which raises the need to understand the requirements and impacts of particular consumptive pathways.

3.2.4. Irrigation

Irrigation is the predominant human use of water. The importance of irrigation globally and locally is well known [5]. From a water management point of view, it is therefore a key point of interaction in the nexus between water, food, and energy. The history of drivers of irrigation area and intensity in Central Asia has been a focus of research attention, particularly in the Aral Sea basin [56,66]. Irrigation is essential because of the aridity of the area. For water-intensive crops such as cotton, there is insufficient green water (soil moisture derived directly from rainfall), so the growth of plants is water-limited. The Soviet Union played a major role in the expansion of irrigation. Large water projects intended first to allow the Soviet Union to become self-sufficient in cotton, and later enable

export earnings [56]. Rather than just food security, non-food agriculture therefore plays a large role in the nexus in Central Asia.



Until recently, irrigation demand had been rising in most FPUs. This had the effect of shifting evaporation from downstream areas to cropland areas [67], often in locations where intensive cropping would not otherwise have been possible. In addition, there was a decrease in productive water use through an undesirable “vapor shift” [68]. Previously, the water evaporated through an environmental water pathway, meaning that all the water was available to aquatic ecosystems, which in turn provided useful ecosystem services. Afterward, only part of that water contributed to valuable crop transpiration. A significant portion was instead wasted through non-productive evaporation from dams, open irrigation canals (officially 28% of the water in Turkmenistan [69]), and the low productivity of the irrigation of crops grown in poor-quality soils [21]. Excess irrigation flowing to groundwater was not productive either, as the rising water table often contributed to salinization [69]. This situation was aggravated by increases in the irrigation rate rather than just the irrigation area [53]. While this

increased the water available to crops and, hence, cash value, it decreased the total productive water use when taking into account the opportunity costs of other industries and ecosystem services. A narrow focus on agricultural productivity came at the expense of potential broader societal benefits.

Irrigation water use and total human water use did reach a peak or stabilize in several FPU. In some cases, such as the Amu Darya (FPU 470, 471) this does coincide with reaching the limits of water availability. Aus der Beek [27] cites two main reasons of this change: improvements in irrigation efficiency and the conversion of cotton fields to food crop fields. The latter has been caused by falls in the price of cotton, the dissolution of the Soviet Union, and the resulting need to increase food self-sufficiency [70].

The fall in irrigation therefore should probably not be interpreted as a response to increasing water stress. In order to continue the expansion of agricultural land, water was seen as an input to be acquired, rather than a limit on development. Within basins, water was prioritized for agricultural use at the expense of downstream flows. As part of what has been called a “hydraulic mission” [22,71,72], dams were built to store water over time. Between basins, water was transferred through a large number of canals. Though it was later abandoned, some preliminary work had even been done on reversing the flow of rivers in Siberia and European Russia, to flow towards Central Asia, away from the Arctic Ocean [73].

There has been a (perhaps temporary) interruption in this tendency to use physical transfers of water to overcome water availability limits. Firstly, the dissolution of the Soviet Union resulted in decreased or stabilizing irrigation water use, as noted above. Secondly, such water transfers would have now required transboundary negotiations between countries, which is still a difficult political issue today [74]. Finally, it became more widely accepted that water does need to be left for ecosystem services (including intrinsic cultural value) [73].

3.2.5. Energy Production

It is widely known that the provision of energy for heating and water for irrigation have long been intertwined in Central Asia, first through barter arrangements of fuel-for-water and more recently through trade-offs between maximizing hydroelectricity production and irrigation [19]. The impacts are however more closely related to water storage, withdrawals, and water quality impacts rather than consumption, driven by the specific role of water in hydropower (which dominates in Kyrgyzstan and Tajikistan), gas (Turkmenistan and Uzbekistan), or oil and coal (Kazakhstan) [22].

The “electricity” water use in Figure 5 corresponds to the use of cooling water in thermoelectric power plants [75]. This is, in most cases, the smallest of the consumptive water uses in Central Asia. It is estimated based on power production for specific technological plant types and cooling systems. Its trend over time is therefore likely explained by changes in demand for thermo-electric power, corresponding to the expansion and contraction of the economy, and increased reliance on hydro-electric power [74]. While consumptive use is small, fossil fuels and thermoelectric power plants are associated with a number of problems with water, soil, and air pollution [61].

In this paper, water consumption of hydropower is not estimated. In principle, the storage of water in dams results in higher evaporation [76]. However, in Central Asia, evaporation is much larger in the downstream, arid zone (as high as 2250 mm) than in the upstream, mountainous zone (as low as

500 mm) [56], such that evapotranspiration from downstream uses is much more important than evaporation due to upstream storage of water for hydropower. Additionally, it is difficult to attribute evaporation from these dams to a particular sector. The dams are used for multiple purposes, supplying irrigation water, producing hydropower, and regulating floods [24,74]. There is no reason to attribute consumption to one sector over another from a mass conservation point of view, though it has been suggested that consumption could be allocated based on the ecosystem service benefits produced by each sector [77]. It is therefore of greater interest to focus on the non-consumptive impacts of hydropower, as discussed in Section 4.4.

3.2.6. Other Activities

The trends in other water uses in Figure 5 are best understood through their underlying model assumptions [78]. Domestic water use is estimated based on population and per capita water use intensity. National water use intensity is assumed to depend on income (GDP per capita), consumptive-use-coefficients, and technological change rates. For downscaling, additionally, rural vs. urban setting, and access to safe drinking water are taken into account. All FPU show increases in domestic use over time consistent with increasing population and increasing water use intensities.

Livestock water consumption is estimated based on 10 types of livestock and water consumption per head and per year [78]. Increased livestock water consumption in a number of FPUs therefore primarily reflects increased livestock numbers at a decadal scale, though numbers might have varied from year to year. Note that variations in livestock numbers prior to 1960 are not known, and are therefore kept fixed at the 1960 level.

National time series of manufacturing water use are estimated based on the gross value added (GVA) economic measure, technological change rates, and consumptive-use-coefficients [31]. Country-scale estimates are allocated to grid cells according to the distribution of the urban population. Consistent with Central Asia's turbulent history, manufacturing water use has varied significantly in a number of FPUs, with a dip in the 1970s, followed by a temporary increase in the 1980s, and a fall since the 1990s with the dissolution of the Soviet Union. Manufacturing water consumption is small relative to agriculture, but generally results in the production of higher-value goods. As noted by Stucki and Sojamo [22], manufacturing provides a larger contribution to GDP than agriculture while using far less water.

3.3. Decadal Water Scarcity

The preceding sections discussed the role of decadal water availability and consumption within the history of the nexus in Central Asia. These issues are closely related to the concept of water scarcity, in particular through the water stress and shortage indicators. Figure 6 shows the trajectories of each FPU over time in terms of these two indicators.

Water stress is measured as the ratio of human water consumption and availability. A stress level of 100% means that all available water is used for human purposes. As discussed above, ecosystem services may already be affected at lower stress levels. Falkenmark and Lindh [49] suggest that water supply becomes a limiting factor of economic development when human use exceeds 20% of the

available blue water. A stress level greater than 100% indicates the use of long-term stored water, such as the non-sustainable use of groundwater or unaccounted physical water transfers.

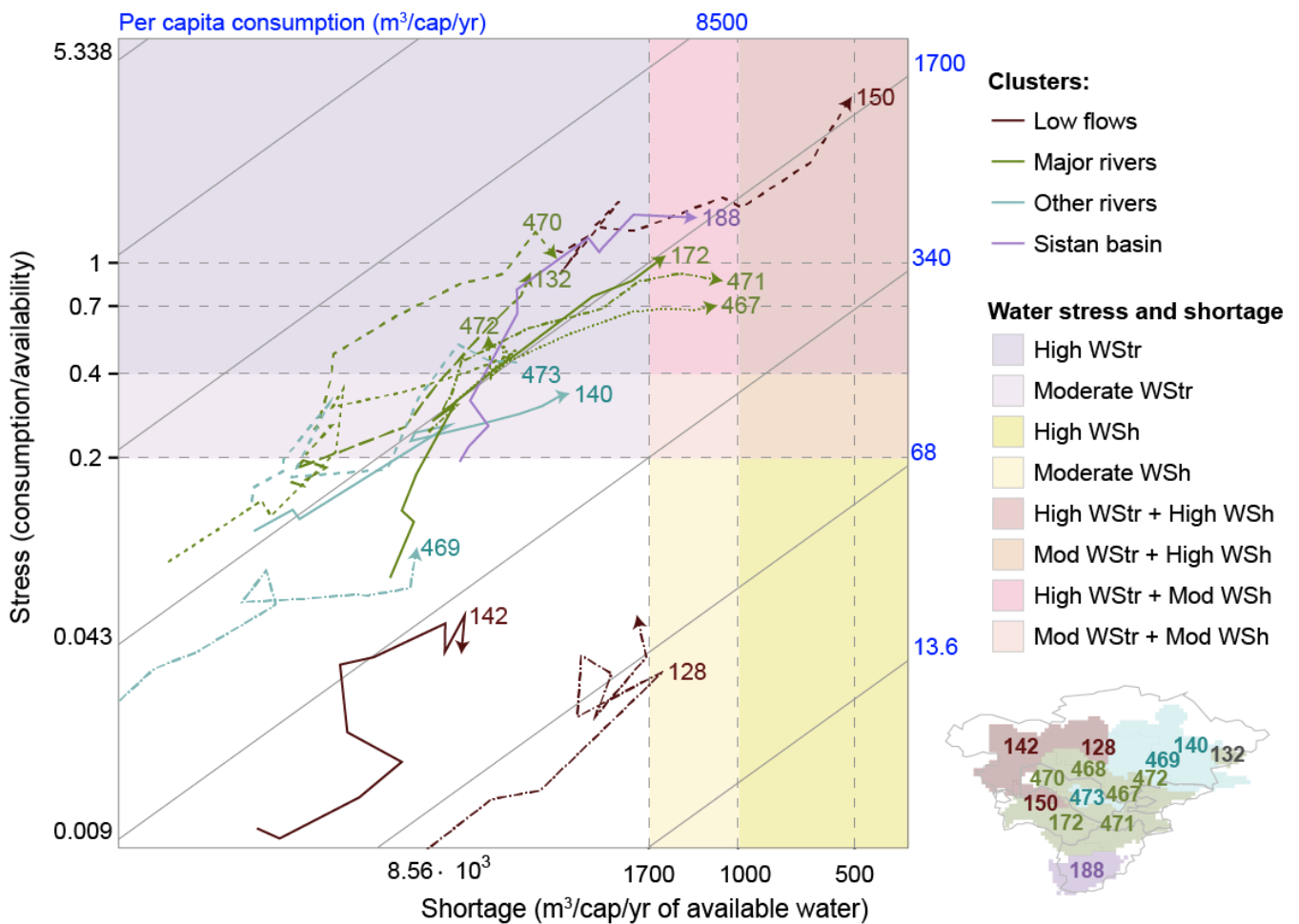


Figure 6. Water scarcity trajectories of each FPU for the 20th century, showing change in shortage, stress, and per capita consumption over time. The diagonal lines refer to per capita consumption isolines. Background colors show existence of moderate and high water stress (consumption respectively >20% and >40% of available water) and moderate and high water shortage (<1700 m³/cap/year and <1000 m³/cap/year), as used in Porkka *et al.* [26].

Water shortage is measured by the per capita availability of water. It is also referred to as water crowding, in which case it is interpreted as an indicator of competition for water [48]. A water shortage of 500 m³ per capita per year corresponds to 2000 people sharing one gigaliter of water per year [47].

A point in the trajectories in Figure 6 represents the average stress and shortage of an FPU for a particular decade, calculated using the data presented in previous sections. Consistent with the preceding results, the overall shape of the trajectories from the bottom-left to the top-right indicates an increase in both stress and shortage over time as human water use and population increases. Per capita consumption is shown with a diagonal grid. The change in position of the trajectories relative to the diagonal grid shows an increase and, in some cases, later decrease consistent with the expansion of irrigation and the dissolution of the Soviet Union. Boundaries indicating multiple levels of water stress and shortage are shown using dashed lines and shading in the background. The trajectories for all the

major rivers cross into regions of the plot, corresponding to some level of water stress, and some are also in regions corresponding to water shortage. Other FPUs appear to be on a trajectory toward stress and shortage as the population increases. In low flow FPUs, small changes have a large effect, as seen by large relative changes in stress or shortage between points.

These trajectories are suggestive of FPUs' attitude to change and to the crossing of boundaries. One might expect that as an FPU approaches a stress limit, efforts would be made to curb water consumption. Similarly, as an FPU reaches a shortage limit, migration or population control would stabilize water shortage. Instead, what we see is an apparent disregard for boundaries. As discussed in the previous sections, increasing water scarcity has instead been met by physical transfers to increase water availability and engineering works to reduce the impacts of stress. The literature on Central Asia even suggests that the dissolution of the Soviet Union is in fact responsible for the FPUs that do appear to have reached a stress ceiling (FPUs 471, 467, 470), not the response to decreasing water availability. In any case, when stabilization did eventuate, significant changes had already occurred, particularly in the case of the Aral Sea.

Naturally, there were efforts to return or remain within the boundaries and, hence, avoid or mitigate associated impacts [56]. While some plans were halted, such as the reversal of the Northern rivers [73], other changes simply happened too fast and too strongly to avoid crossing at least some boundaries. From a societal point of view, changes could not be controlled or regulated due to problems with the economy, the loss of expertise, the breakdown of cooperation, and social unrest [56]. Unfortunately, in the face of such a fast rate of change, the transformations of natural ecosystems have been quite significant [79]. Humans have become very successful at making changes—expanding our population and impact—but are not always very good at regulating those changes, at least when it comes to water consumption.

3.4. Impact of Human Use on Seasonal Discharge

Previous sections focused on decadal change, which does not show human impacts at shorter time scales. Figure 7 shows the monthly change in discharge between human and natural scenarios, summed for each FPU, and averaged across each decade, obtained using two model setups as described in Section 2.1. Relative changes are expressed as a percentage of natural discharge. This emphasizes changes in environmentally important low flows rather than high flows [60].

As expected, the analysis shows an overall decrease in discharge due to withdrawals for irrigation, which becomes more substantial over time. What is important here is the distribution across months. Most FPUs show greater withdrawals during the irrigation season, which varies in time and by location. For example, in the Syr Darya (FPU 467), decreases in discharge are most prominent from March to July in 1901–1910 and extend from March to November in 1991–2000, with decreases larger than 50% in some months. Historically, some FPUs have seen increases in discharge at other times, corresponding to a seasonal shift in the timing of flows due to reservoir operation [80]. While the model may not fully capture historical reservoir operations, this shift corresponds to the combined effect of multiple uses, most notably irrigation and hydropower generation. The need for irrigation in months with naturally low flows may result in higher discharges, particularly upstream of irrigation areas. More importantly, from the point of view of the nexus, Tajikistan and Kyrgyzstan are highly

dependent on hydropower for winter heating, resulting in releases of stored water that could have been used for irrigation [2,74]. This is notably the focal point of conflict between Uzbekistan and Tajikistan over the Rogun Dam [74,81].

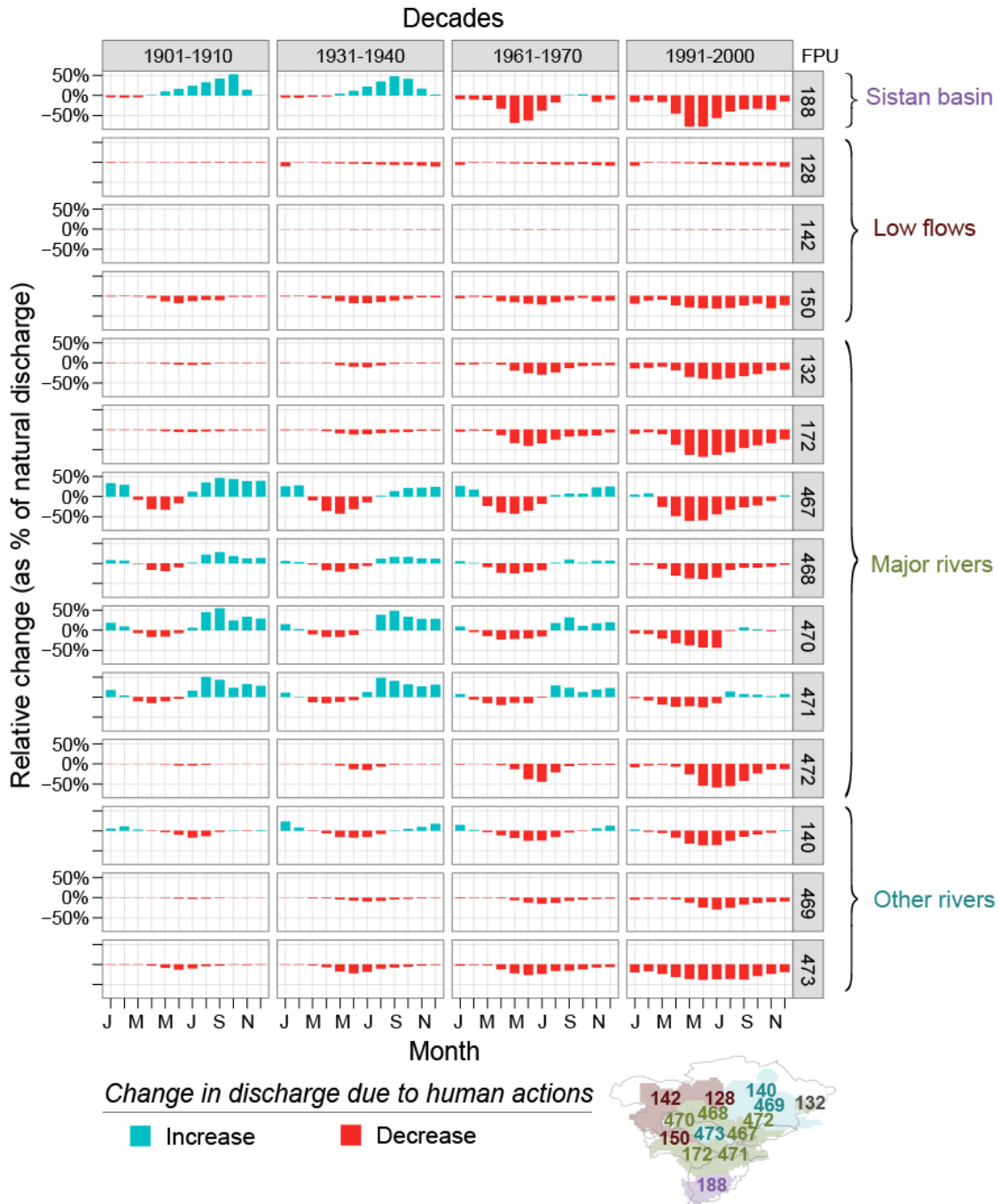


Figure 7. Monthly change in discharge due to human influence, relative to natural discharge, averaged for decades from 1905–2000. Estimated discharge under a natural scenario is subtracted from estimated discharge including human influences, *i.e.*, with flow regulation and water abstraction.

The conflict over seasonal flows raises the broader issue of temporal scales of water availability and use. Fundamentally, different users may have water needs that are continuous, seasonal, or episodic. Water needs may also be essential to survival (“obligate”), or optional (“facultative”) [82]. Basic human

needs must be satisfied (nearly) continuously, but some ecosystems can persist even with occasional floods. In Central Asia, the rise in irrigation, the seasonal shift in discharge, and the conflict with winter hydropower suggest that irrigation and hydropower would be “obligate” needs, as a result of quotas and the lack of economic alternatives [70]. However, the subsequent reduction in water use shows that irrigation and hydropower for winter heating are in fact essentially “facultative” and seasonal. It is technically possible to obtain food, foreign currency, and energy by other means, for example, by emphasizing trade, the development of urban economies, and knowledge-intensive industries [21]. Seasonal irrigation and hydropower can also vary each year depending on water availability and in response to food and energy crises, as is the case with current *ad hoc* annual agreements [74]. In the Soviet era, food security did not depend on local irrigation and winter heating did not depend solely on hydropower [10]. Admittedly, those arrangements also led to increased water consumption and, hence, the loss of the Aral Sea, and have since been destabilized by the dissolution of the Soviet Union. The history of Central Asia does however show that we are not truly locked into a particular path. There is the capacity for change to accommodate multiple, evolving objectives, which is, of course, beneficial in pursuing a nexus approach.

4. Discussion: Implications for the Water-Energy-Food Security Nexus

The intention of this paper was to derive generalizable conclusions regarding the implementation of the nexus by taking a global perspective when illustrating the history of the nexus in Central Asia. We do not aim to make specific recommendations for Central Asia. The use of a global water model put the focus on the basic principles underlying water availability, multi-sector consumption, and their historical changes.

To further help derive generalizable conclusions, we now draw on key concepts from literature on global change, socio-ecological systems, and resilience theory. A resilient socio-ecological system usually operates within a stable regime, compensating for minor disturbances [34,83]. However, if changes to a system are too great, a boundary is crossed, resulting in either the sudden or gradual transformation of the system such that it operates in a new (potentially undesirable) regime. A prominent example is the concept of “planetary boundaries” [33,84], which argues that the Earth system is currently in a regime particularly suited for human life, and that crossing certain boundaries will cause a transformation outside the “safe operating space for humanity”. Boundaries may be social as well as natural, as in the analogous concept of a “just operating space for humanity”, which defines the minimum requirements for social well-being [85,86]. The discussion based on these concepts will cover five key points:

- Firstly, changes in the system do not necessarily occur within the typical nexus sectors of water, energy, and food security. Key changes in Central Asia instead relate to non-food irrigation and the loss of ecosystems. This raises the question: what subsystems should be considered within the nexus?
- Secondly, trade-offs within the nexus (e.g., between water, energy, and food security objectives) are to some extent inevitable (e.g., the use of water by irrigation will always reduce flows). This means that it is important to understand where the boundary is located that determines whether changes are or are not permissible (e.g., a small reduction in flows to the

Aral Sea vs. loss of livelihoods). The question becomes: what boundaries can acceptably be crossed within the nexus?

- Thirdly, crossing boundaries implies that the system is transformed, often resulting in new dependencies being introduced (e.g., on water releases from transboundary reservoirs in other upstream countries). New trade-offs can therefore be created in the process of reducing existing trade-offs within the nexus (e.g., providing water for local food needs vs. cotton export). There is a need to ask: how will managing the nexus change system dependencies?
- Fourthly, these trade-offs, boundaries, and dependencies were historically already influenced by global relationships (e.g., trade of cotton), and this trend is only strengthening as a result of globalization. We discuss: what say should global stakeholders have in managing the water-energy-food security nexus?
- Finally, given that this paper has focused on the use of a global model, we address the question: what role does global data play?

4.1. What Subsystems Should Be Considered within the Nexus?

In the case of Central Asia, key changes in system regimes occurred in non-food industries and ecosystems, neither of which fit within the water, energy, and food security nexus, if taken literally. The increase in the irrigated area was at first related to cotton production, and resulted in the decline of the Aral Sea ecosystems and, hence, the broader socio-ecological system, with the associated loss of livelihoods as well as health impacts. Key issues in a case study do not necessarily relate solely to the security of water, energy, and food supply. If too narrow a scope is used, there is a risk that economic values of energy and food production may be over-emphasized at the expense of other values. This appears to have occurred during the Soviet Era, where comprehensive arrangements were made between republics for the provision of food, energy, and water, as well as export income through cotton. Strictly speaking, a nexus approach was already implemented, but significant problems still emerged because the protection of ecosystems and cultural values was at least partly neglected. Admittedly, this problem has already been recognized by nexus researchers. For example, Hoff [1] explicitly notes that “While not part of most water security definitions yet, availability of and access to water for other human and ecosystem uses is also very important from a nexus perspective” (p. 11). The message is clear: in implementing a nexus approach, it is essential to treat the relevant subsystems (or sectors) as case-specific and to consciously scrutinize what is included in the nexus and what is excluded from it.

4.2. What Boundaries Can Acceptably Be Crossed within the Nexus?

The trade-off between human and environmental water uses highlights the point that some trade-offs within the nexus are inevitable due to the principle of conservation of mass. Water simply cannot be present at two places at the same time. A change in consumptive use (*i.e.*, evaporation pathways) will always result in some degree of change to the system. Even when water is not consumed but returned to the system, a change in the timing of flows will also have some impact elsewhere in the system. Water trade-offs can, of course, be diminished in size by making smaller changes to the water system, or identifying synergies to create more value from the same-sized change.

There is, however, no such thing as a change without impact, and there will always be some degree of trade-off between the sectors of the nexus no matter what synergies are found.

The inevitability of trade-offs does not necessarily imply conflict. We noted that environmental water in particular provides a buffer that delays competition for water (see Figure 3 and Section 3.2.1). However, trade-offs are often problematic when they cross key boundaries, such as upper limits and minimum requirements. Crossing boundaries transforms the identity of the system, modifying the processes that dominate system behavior and the functions that the system provides, as summarized in Table 1. While these boundaries would be difficult to quantify, one could easily see that these types of transformations would be contested and therefore a source of conflict. For example, the irrigated production of cotton is still a point of contention (see transformation for Figure 5 and Section 3.2.4), particularly in light of its effect on the Aral Sea (Figure 3 and Section 3.2.1).

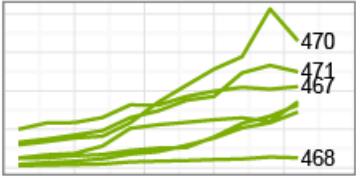
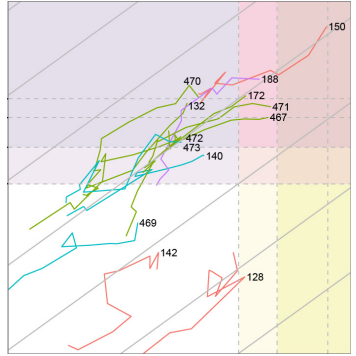

Crossing boundaries (*i.e.*, transformation) may, however, also be necessary. Literature on socio-ecological systems (SES) talks about resilience as “the capacity of a SES to continually change and adapt yet remain within critical thresholds” [87]. At the same time, it highlights that resilient societies need to be able to transform themselves when their conditions become untenable. In particular, transformation at smaller scales helps support the survival of the broader socio-ecological system in the long-term [87]. In Central Asia, physical transfers of irrigation water allow greater human use of land and greater economic wealth (see transformation for Figure 2 and Section 3.2). Achieving certain changes to seasonal discharge associated with hydropower allows greater energy security (Figure 7 and Section 3.4).

The implication is that a key challenge of implementing the nexus is to resolve differences regarding the desired identity of the system: which boundaries are acceptable to cross, and which are not; what changes to processes and functions are permitted, and which are forbidden. The idea is to eliminate what is categorically unacceptable in order to delimit a narrowed negotiation space within which to search for solutions, as has been recommended elsewhere [88,89]. This is naturally of particular importance in a transboundary context, where different boundaries are imposed not just by the water, energy, and food sectors, but also by the interests of different governments and cultures [90]. Negotiations also need to recognize that it is possible that no feasible solution satisfies all of a given set of socio-economic and ecological boundaries, meaning that some boundaries may, in fact, be incompatible. Negotiating a consensus on boundaries raises important issues of power and justice. While these issues are out of scope of the present discussion, they are a key concern in rights-based approaches to development, which similarly emphasize boundaries that should not be crossed, and have been argued to be vital in implementing the water-energy-food security nexus [35,91,92].

Table 1. Key functions and processes illustrated by each assessment in Section 3, and transformations that could occur after boundaries are crossed. Icons refer to Figures 2–7.

Assessment	Relevant Figure	Function	Process to Achieve Function	Transformation after Boundary Is Crossed
Water Availability		Availability of blue water for socio-ecological systems	Partitioning of water flow by location within global water system	Unsustainable reliance on stored water, e.g., fossil groundwater, dependence on energy-intensive physical, or virtual water transfers
Human vs. Environmental Water Consumption		Provision of goods and services by ecosystem and humans	Partitioning of water between human use and environmental water (evaporation pathway)	Reduction in ecosystem services, shift towards dependence on energy-intensive human services
Human per Capita Consumption		Provision of individual human needs and wants, including food and water	Partitioning of water (and its benefits) within population	In extreme cases, starvation, malnutrition, hunger, but also poverty, inequality, and social unrest

Table 1. Cont.

Assessment	Relevant Figure	Function	Process to Achieve Function	Transformation after Boundary Is Crossed
Water by Activity		Provision of human goods and services underpinning human quality of life globally (including energy)	Partitioning of water by activity (reflecting values and power relationships)	Shift in dominant economic power, employment, cultural identity of population, and their diversity
Water Scarcity		Adaptation to cope with external drivers and internal changing needs and wants	Feedback between sub-systems, including water users, governance, and broader environment	Inability of society to adapt to changes; competitive advantage to actors that are better at learning
Impact of Human Use on Seasonal Discharge		Maintenance of flows and water availability at operational time-scales	Partitioning of water flows in time	Impacts of other transformations depend on their need for or aversion to variability and peak flows, e.g., flooding and timing of irrigation season

4.3. How Will Managing the Nexus Change System Dependencies?

A defining feature of system regimes is the relationship between its subsystems, including its social and ecological subsystems at different scales and in different locations. Dependencies of subsystems can impede growth by acting as a limiting factor, for example, the dependence of agriculture on water. Their interruption can cause failures, like the loss of cooperation when centralized decision-making ceased in the Soviet Union. Dependencies also relate to power, with countries engaging in both cooperation and conflict over the control of downstream flows, countered by the need of those countries for foreign currency, food, or fossil fuels [90]. Changes in dependencies are therefore a fundamental part of transformations between system regimes that occur when boundaries are crossed.

Table 2 summarizes a set of alternative dependencies that can occur in different system regimes. Each pair of dependencies forms a continuum defining the strength of each dependency. At various times in its history, Central Asia has operated according to system regimes at different points in these continuums. We do not aim here to identify specific regimes, as this is discussed elsewhere (e.g., [23,71]). We aim only to draw attention to the alternative paths that have been and could have been followed.

Table 2. Examples of pairs of alternative dependencies, drawn from this analysis of Central Asia. System regime may rely to varying degrees on different dependencies. Avoiding or reducing one dependency may introduce another.

Dependence on ...	vs. Dependence on ...
Dams and Diversions	Naturally Available Water Supply
Centralized decision making, e.g., within Soviet Union	Capabilities and interactions of separate nation states, <i>i.e.</i> , decentralized
Goodwill and trust with other countries sharing water resource	Maintaining control over water resource, e.g., coercion or hegemony
Ongoing maintenance of large-scale infrastructure, e.g., dams and canals	Sufficiency of small-scale user-maintained schemes
Demand for exports, e.g., price of cotton	Self-sufficiency of closed local economy
Livelihoods through jobs, incl. export industries	Subsistence farming
Food imports	Food self-sufficiency or sovereignty
External expertise, e.g., construction, maintenance of complex irrigation infrastructure	Local expertise, e.g., local solutions with local training
Engineering solutions to maintain ecosystems	Continuing naturally required inflows
Economic strength to pay for system operation	Limitations of solutions with low ongoing monetary commitments
Institutional capacity to understand and act on complex interactions	Suitability of system regimes without complex interactions

There does appear to be a trend toward increasing interdependence [23] and away from self-sufficiency and direct dependence on immediate surroundings, consistent with the general concept of globalization [93]. While a key focus of the nexus is to reduce trade-offs between sectors, such reductions can instead create new dependencies between systems that could previously operate (more or less) independently. In other words, it creates new trade-offs elsewhere. In Central Asia, massive

engineering projects can be seen as an attempt to reduce trade-offs between users and between activities. Overcoming the limits of natural water availability through dams and pipelines means there is more water to share between human uses, and less risk of conflict. However, the expanded irrigated area is now dependent on that increased water availability and, hence, on the maintenance of extensive infrastructure as well as cooperative transboundary relationships [23]. In this case, increased interdependence may be to some extent unavoidable. Dependency on natural water availability cannot be maintained if a population grows too large, for example.

The trend towards interdependence is continuing in other ways. Rather than reducing irrigated areas, artificial barriers were created to maintain the level of the north Aral Sea with lower flows [65]. The health of the north Aral Sea is now dependent on the continued maintenance of those barriers. Maintaining (and achieving) low irrigation water losses depends on the maintenance and improvement of irrigation infrastructure and practices. While these are useful contributions to solving the current problems, they each create the need to commit to future financing, technology, skills, and labor to maintain these supporting systems. This was notably visible after the dissolution of the Soviet Union, as lack of time and finances reduced maintenance [56,70] and, hence, reduced productivity of irrigation water use. More generally, some relationships within the nexus have only recently become relevant. The conflict between irrigation and hydropower only exists because reservoirs successfully relieved trade-offs between competing irrigators and trade-offs between competing electricity users. We have ended up creating a dependency on the “institutional capacity to understand and act on the complex interactions” [7].

Similarly, the history of irrigation in Central Asia can be described in terms of interdependencies outside the region. Its political situation as part of the Soviet Union led to the dramatic expansion of irrigation. In particular, cotton was considered a valuable export crop. Even after the dissolution of the Soviet Union, cotton export remained politically important even when the contribution of the GDP of agriculture was smaller than that of the industry and services [22]. According to Porkka *et al.* [26], cotton contributes to 62% of the total agricultural blue water consumption in Central Asia, and eliminating virtual water flows (including cotton export) would reduce water scarcity for 47% of the population and completely eliminate it for 3%. Trade obviously plays a role in achieving food and energy needs, but the end result is that in Central Asia, the nexus is also “transboundary” in the sense that its history and future are closely tied to global trade relationships and agreements and the desire for foreign currency income.

There are, however, also examples of shifts towards self-reliance, and the dependencies that implies. Notably, the shift from cotton to food crops is a result of Central Asian countries trying to achieve food sovereignty [71], and the emphasis of upstream countries on hydropower aims to make them independent of imported fossil fuels [20]. We do not aim to predict or recommend what dependencies will be in place in the future, or whether self-reliance or interdependence is to be preferred. It is, however, clearly important, when trying to reduce trade-offs within the nexus, to understand how system dependencies will be altered.

4.4. What Say Should Global Stakeholders Have in Managing the Water-Energy-Food Security Nexus?

In light of Central Asia's global interdependencies, all people globally can be considered to have a stake in the boundaries to be crossed, what functions may be lost, or which dependencies might be added. This view appears to be shared by the governments involved in the International Fund for Saving the Aral Sea, who state that "international organizations, bi-lateral aid agencies and foreign governments have stepped up to cooperate" [94]. We have a role to play not just in defining the desired identity of the system, but also in supporting local people and organizations to make the appropriate transformations [20]. This is probably typical of most places in our increasingly globalized world. Folke *et al.* [87] boldly state that "society must seriously consider ways to foster resilience of smaller more manageable SESs [socio-ecological systems] that contribute to Earth System resilience and to explore options for deliberate transformation of SESs that threaten Earth System resilience."

Planetary boundaries are one definition of what it means to threaten Earth System resilience [33,84]. While there are difficulties in downscaling these boundaries, Central Asia, and the Aral Sea basin in particular, would probably be considered to be using more than its fair share of the freshwater planetary boundaries. The degradation of the biosphere it has caused is precisely the kind of impact that the planetary boundaries are trying to avoid. The planetary boundaries are expected to interact [84]. In this case, the loss of the Aral Sea is known to have resulted in impacts on "biosphere integrity" through the extinction of fish populations [55]. The increase in irrigation is naturally associated with agricultural expansion and, hence, "land-system change", alteration of "biogeochemical flows", and potentially the introduction of "novel entities", as well as an increase in "atmospheric aerosol loading" through increased dust storms arising from salinization and desertification [65]. At the same time, climate change is also obviously related to energy issues in Central Asia, such that the greater emphasis on hydropower rather than the barter of fossil fuels could be seen as a positive development. For most of these planetary boundaries, it is unclear how they translate into local boundaries, particularly in ambiguous cases where the land-system change could be seen as greening the desert and, hence, avoiding the reduction of forest cover elsewhere. It is, however, clear that the history of the nexus in Central Asia (and elsewhere) is considered to be intertwined with global sustainability.

4.5. What Role Does Global Data Play? Contributions and Limitations of the Analysis

This paper specifically makes use of global modeled data. While it is likely not as reliable as local models or measured data, it helps to appropriately set the scene. It draws attention to underlying, broadly applicable, and fundamental issues rather than more widely discussed details. Starting from a global perspective provides a broader context and makes it easier to relate case study observations to global trends and ideas. *Vice versa*, the use of global data to focus on local history adds value to the global model by providing a link to a wealth of existing place-based studies and a corresponding depth of analysis. From a practical perspective, using global data enhances the comparability of results across regions, even where data is sparse.

Other global data could provide further insights, including extending the boundaries and new dependencies identified in the previous sections. This paper focused on blue water, given the importance of irrigation in Central Asia. Green water (available in soils directly from precipitation)

obviously also plays an important role in agriculture, generally [38]. Historical analysis of virtual water flows would also be beneficial [26]. The model used here treated physical transfers of water and the operation of reservoirs in a rather basic way, and glacier melt in-flows and evaporation from dams are not explicitly included. Improvement of these features is needed in order for these models to be used at finer spatial and temporal scales, particularly where large scale water supply schemes exist, as is the case in Central Asia [27]. This paper also focused primarily on water consumption. Future analyses could also consider water withdrawals and grey water impacts. The analysis of seasonal variation in discharge clearly shows that water withdrawals play a key role in transforming water availability over time. Increasing water use has been accompanied with significant water quality impacts, notably salinization [65]. Finally, this paper views the nexus through a water lens, interpreting historical water data in terms of its broader agriculture, food, and energy context. It would be of interest to use other global data (e.g., cited in [25]) to perform a similar exercise through an agricultural, food security, or energy security lens.

5. Conclusions

This paper used spatiotemporal data from a global model to illustrate the 20th century history of the nexus in Central Asia through a water lens. In the region, low natural water availability constrains potential water-dependent activities. Human consumptive use increased throughout the 20th century, primarily driven by irrigation at the expense of environmental water (e.g., the Aral Sea), resulting in high per capita water consumption. The evolution of different sectors over time follows economic development and population growth. Overall, water use and scarcity show a rapid upwards trend. However, in some areas, total water use stabilized or declined after the dissolution of the Soviet Union, likely driven by a shift in political and economic circumstances rather than as a direct response to increasing water scarcity. While the focus was on decadal water consumption, changes in monthly discharge showed evidence of the well-known effects of hydropower and irrigation. Despite its limitations, the use of global data in this paper played a key role in setting the case study within a global context and emphasizing generalizable lessons. This paper does not aim to provide specific recommendations regarding management of the nexus in Central Asia.

Accordingly, discussion of the results used the Central Asian case study to identify five transferable principles related to the nexus. This case study-based synthesis is a novel contribution of this paper, though these principles naturally build on solid foundations from existing literature, notably from socio-ecological systems and resilience theory. The first principle is that *the subsystems included/excluded from the nexus are case-specific and should be consciously scrutinized*. Discussion of the nexus in Central Asia would notably be incomplete without consideration of irrigated cotton production and ecological impacts, even though they are not strictly part of water, energy, and food security.

The second principle is that *it is important to reach an understanding of what boundaries can acceptably be crossed within the nexus*. Some trade-offs within the nexus are inevitable. Due to conservation of mass, changes in water use and storage will always result in some degree of change to the system. Consistent with the concept of planetary boundaries, we note that it is the crossing of boundaries that is of key importance, as it results in the transformation of the structure, functions, and

identity of the system. These transformations notably include the loss of functions (e.g., ecosystem services) and the creation of dependencies requiring ongoing commitments. The third principle is, therefore, that *it is important to understand how reducing trade-offs will modify system dependencies*.

In Central Asia (like elsewhere in the world), history shows that limits of water availability have been treated as a boundary to be crossed rather than respected, as part of what has been called a hydraulic mission. Most visibly, infrastructure projects have reduced the conflict between some human water uses by increasing localized water availability. This has come at the expense of ecosystems and industries dependent on the Aral Sea, and an increased dependence on upstream transboundary reservoirs and a commitment to the ongoing long-term maintenance of infrastructure. This trend towards increased interdependence is manifested also in engineering solutions to the Aral Sea crisis and the continuing influence of global trade (especially cotton). On the other hand, the development of Central Asia may be considered to have disproportionately contributed to several planetary boundaries, contributing to cumulative global impacts through the broader Earth system as well as through socio-economic connections. These dependencies and impacts respectively mean, as a fourth principle, that *global stakeholders have both a responsibility and a right to contribute to the shaping of the nexus*. In this context, we have found a fifth principle useful, namely that *use of global data combined with existing place-based studies can help to provide a global perspective*, enhancing the transferability and understanding of shared problems in our globalized world.

These principles can contribute to the successful implementation of nexus approaches to understand complex interactions, reduce trade-offs, and build synergies. The process of developing integrated solutions to water, energy, and food security necessarily involves the transformation of the system. The assessment of solutions needs to understand the functions that may be lost and the dependencies that may be introduced. Evaluating these changes requires a shared understanding of which boundaries should be avoided and which can be crossed. In today's globalized world, every person is, in principle, a stakeholder in this process, contributing directly or indirectly to international decision-making. Governments, researchers, businesses, civil society, and consumers should all have their role to play, some large, some small, as discussed in other papers of this special issue. These roles should include seeking to better understand the effects of transformations, participating in judging what constitutes unacceptable changes, and reflecting on how their actions help shape transformations within the sustainable water-energy-food security nexus.

Acknowledgments

The authors would like to thank three anonymous reviewers for their comments which helped improve the paper. The authors also thank their colleagues in the Water and Development and Research Group, Aalto University for their support and useful comments. Joseph Guillaume received funding from the Academy of Finland funded project NexusAsia (Grant No. 269901) and Matti Kummu received funding from the Academy of Finland funded project SCART (Grant No. 267463).

Author Contributions

Joseph Guillaume and Matti Kummu designed the analysis. Joseph Guillaume and Stephanie Eisner performed the analysis. Joseph Guillaume, Matti Kummu, Olli Varis, and Stephanie Eisner contributed to discussion and writing and editing.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Hoff, H. *Understanding the Nexus: Background Paper for the Bonn2011 Nexus Conference: The Water, Energy and Food Security Nexus*; Stockholm Environment Institute: Stockholm, Sweden, 2011.
2. Granit, J.; Jägerskog, A.; Lindström, A.; Björklund, G.; Bullock, A.; Löfgren, R.; de Gooijer, G.; Pettigrew, S. Regional options for addressing the water, energy and food nexus in Central Asia and the Aral sea basin. *Int. J. Water Resour. Dev.* **2012**, *28*, 419–432.
3. Hayami, Y.; Ruttan, V.W. *Agricultural Development: An International Perspective*; The Johns Hopkins Press: Baltimore, MD, USA; London, UK, 1971.
4. Kummu, M.; Gerten, D.; Heinke, J.; Konzmann, M.; Varis, O. Climate-driven interannual variability of water scarcity in food production potential: A global analysis. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 447–461.
5. Siebert, S.; Döll, P. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *J. Hydrol.* **2010**, *384*, 198–217.
6. Orr, S.; Pittock, J.; Chapagain, A.; Dumaresq, D. Dams on the Mekong river: Lost fish protein and the implications for land and water resources. *Glob. Environ. Chang.* **2012**, *22*, 925–932.
7. Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; *et al.* Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* **2011**, *39*, 7896–7906.
8. Hussey, K.; Pittock, J. The energy-water nexus: Managing the links between energy and water for a sustainable future. *Ecol. Soc.* **2012**, *17*, doi:10.5751/ES-04641-170131.
9. Water in the West. *Water and Energy Nexus: A Literature Review*; Stanford University: Stanford, CA, USA, 2013.
10. Scott, C.A.; Pierce, S.A.; Pasqualetti, M.J.; Jones, A.L.; Montz, B.E.; Hoover, J.H. Policy and institutional dimensions of the water-energy nexus. *Energy Policy* **2011**, *39*, 6622–6630.
11. Rahaman, M.M.; Varis, O. *Central Asian Waters: Social, Economic, Environmental and Governance Puzzle*; Helsinki University of Technology: Helsinki, Finland, 2008.
12. Dukhovny, V.A.; de Schutter, J. *Water in Central Asia: Past, Present, Future*; CRC Press/Balkema: London, UK, 2011.
13. United Nations Economic Commission for Europe (UNECE). *Strengthening Water Management and Transboundary Water Cooperation in Central Asia: The Role of Unece Environmental Conventions*; UNECE: Geneva, Switzerland, 2011.

14. United Nations Environmental Programme (UNEP). *Environment and Security in the Amu Darya Basin*; UNEP: Nairobi, Kenya, 2011.
15. Stucki, V.; Wegerich, K.; Rahaman, M.M.; Varis, O. Introduction: Water and security in Central Asia—Solving a rubik’s cube. *Int. J. Water Resour. Dev.* **2012**, *28*, 395–397.
16. Unger-Shayesteh, K.; Vorogushyn, S.; Merz, B.; Frede, H.G. Introduction to “water in Central Asia—Perspectives under global change”. *Glob. Planet. Chang.* **2013**, *110*, 1–3.
17. Karthe, D.; Chalov, S.; Borchardt, D. Water resources and their management in Central Asia in the early twenty first century: Status, challenges and future prospects. *Environ. Earth Sci.* **2015**, *73*, 487–499.
18. World Bank. *Water Energy Nexus in Central Asia: Improving Regional Cooperation in the Syr Darya Basin*; World Bank: Washington, DC, USA, 2004; pp. 1–59.
19. Wegerich, K. Coping with disintegration of a river-basin management system: Multi-dimensional issues in Central Asia. *Water Policy* **2004**, *6*, 335–344.
20. Abdolvand, B.; Mez, L.; Winter, K.; Mirsaedi-Gloßner, S.; Schütt, B.; Rost, K.; Bar, J. The dimension of water in Central Asia: Security concerns and the long road of capacity building. *Environ. Earth Sci.* **2015**, *73*, 897–912.
21. Varis, O. Resources: Curb vast water use in Central Asia. *Nature* **2014**, *514*, 27.
22. Stucki, V.; Sojamo, S. Nouns and numbers of the water-energy-security nexus in Central Asia. *Int. J. Water Resour. Dev.* **2012**, *28*, 399–418.
23. Soliev, I.; Wegerich, K.; Kazbekov, J. The costs of benefit sharing: Historical and institutional analysis of shared water development in the Ferghana valley, the Syr Darya basin. *Water* **2015**, *7*, 2728–2752.
24. Jalilov, S.-M.; Keskinen, M.; Varis, O. Sharing benefits in transboundary rivers: An experimental case study of Central Asian energy-agriculture dispute. *Water*, submitted.
25. Varis, O.; Kummu, M. The major Central Asian river basins: An assessment of vulnerability. *Int. J. Water Resour. Dev.* **2012**, *28*, 433–452.
26. Porkka, M.; Kummu, M.; Siebert, S.; Flörke, M. The role of virtual water flows in physical water scarcity: The case of Central Asia. *Int. J. Water Resour. Dev.* **2012**, *28*, 453–474.
27. Aus der Beek, T.; Voß, F.; Flörke, M. Modelling the impact of global change on the hydrological system of the Aral sea basin. *Phys. Chem. Earth A B C* **2011**, *36*, 684–695.
28. Malsy, M.; Aus der Beek, T.; Eisner, S.; Flörke, M. Climate change impacts on Central Asian water resources. *Adv. Geosci.* **2012**, *32*, 77–83.
29. Weedon, G.P.; Gomes, S.; Viterbo, P.; Shuttleworth, W.J.; Blyth, E.; Österle, H.; Adam, J.C.; Bellouin, N.; Boucher, O.; Best, M. Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. *J. Hydrometeorol.* **2011**, *12*, 823–848.
30. Haddeland, I.; Clark, D.B.; Franssen, W.; Ludwig, F.; Voß, F.; Arnell, N.W.; Bertrand, N.; Best, M.; Folwell, S.; Gerten, D.; *et al.* Multimodel estimate of the global terrestrial water balance: Setup and first results. *J. Hydrometeorol.* **2011**, *12*, 869–884.
31. Flörke, M.; Kynast, E.; Bärlund, I.; Eisner, S.; Wimmer, F.; Alcamo, J. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob. Environ. Chang.* **2013**, *23*, 144–156.

32. Salmivaara, A.; Porkka, M.; Kummu, M.; Keskinen, M.; Guillaume, J.; Varis, O. Exploring the modifiable areal unit problem in spatial water assessments: A case of water shortage in monsoon Asia. *Water* **2015**, *7*, 898–917.
33. Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; *et al.* A safe operating space for humanity. *Nature* **2009**, *461*, 472–475.
34. Rockström, J.; Falkenmark, M.; Allan, T.; Folke, C.; Gordon, L.; Jägerskog, A.; Kummu, M.; Lannerstad, M.; Meybeck, M.; Molden, D.; *et al.* The unfolding water drama in the anthropocene: Towards a resilience based perspective on water for global sustainability. *Ecohydrology* **2014**, *7*, 1249–1261.
35. Allouche, J.; Middleton, C.; Gyawali, D. Technical veil, hidden politics: Interrogating the power linkages behind the nexus. *Water Altern.* **2015**, *8*, 610–626.
36. Siebert, S.; Kummu, M.; Porkka, M.; Döll, P.; Ramankutty, N.; Scanlon, B.R. A global data set of the extent of irrigated land from 1900 to 2005. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 1521–1545.
37. Müller Schmied, H.; Eisner, S.; Franz, D.; Wattenbach, M.; Portmann, F.T.; Flörke, M.; Döll, P. Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 3511–3538.
38. Rockström, J.; Falkenmark, M.; Karlberg, L.; Hoff, H.; Rost, S.; Gerten, D. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resour. Res.* **2009**, *45*, W00A12.
39. Schewe, J.; Heinke, J.; Gerten, D.; Haddeland, I.; Arnell, N.W.; Clark, D.B.; Dankers, R.; Eisner, S.; Fekete, B.M.; Colón-González, F.J.; *et al.* Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3245–3250.
40. Kummu, M.; Ward, P.J.; de Moel, H.; Varis, O. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ. Res. Lett.* **2010**, *5*, 034006.
41. Cai, X.; Rosegrant, M.W. Global water demand and supply projections. *Water Int.* **2002**, *27*, 159–169.
42. De Fraiture, C. Integrated water and food analysis at the global and basin level. An application of Watersim. *Water Resour. Manag.* **2007**, *21*, 185–198.
43. Defense Mapping Agency. Digital Chart of the World, Accessed via Diva-gis Repository. Available online: <http://www.diva-gis.org/Data> (accessed on 14 July 2015).
44. Global Runoff Data Centre. *Major River Basins of the World*; Federal Institute of Hydrology (BfG), Global Runoff Data Centre: Koblenz, Germany, 2007.
45. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2014.
46. Wallace, J.S.; Acreman, M.C.; Sullivan, C.A. The sharing of water between society and ecosystems: From conflict to catchment-based co-management. *Philos. Trans. Royal Soc. Lond. B Biol. Sci.* **2003**, *358*, 2011–2026.
47. Falkenmark, M. The massive water scarcity now threatening Africa: Why isn't it being addressed? *Ambio* **1989**, *18*, 112–118.
48. Falkenmark, M. Fresh water: Time for a modified approach. *Ambio* **1986**, *15*, 192–200.
49. Falkenmark, M.; Lindh, G. *Water for a Starving World*; Westview Press: Boulder, CO, USA, 1976.

50. Klein Goldewijk, K.; Beusen, A.; Janssen, P. Long-term dynamic modeling of global population and built-up area in a spatially explicit way: Hyde 3.1. *Holocene* **2010**, *20*, 565–573.
51. Unger-Shayesteh, K.; Vorogushyn, S.; Farinotti, D.; Gafurov, A.; Duethmann, D.; Mandychev, A.; Merz, B. What do we know about past changes in the water cycle of Central Asian headwaters? A review. *Glob. Planet. Chang.* **2013**, *110*, 4–25.
52. Schär, C.; Vasilina, L.; Pertziger, F.; Dirren, S. Seasonal runoff forecasting using precipitation from meteorological data assimilation systems. *J. Hydrometeorol.* **2004**, *5*, 959–973.
53. Belyaev, A.V. Water balance and water resources of the Aral sea basin and its man-induced changes. *GeoJournal* **1995**, *35*, 17–21.
54. Wegerich, K. Passing over the conflict. The Chu Talas basin agreement as a model for Central Asia? In *Central Asian Waters: Social, Economic, Environmental and Governance Puzzle*; Helsinki University of Technology: Helsinki, Finland, 2008; pp. 117–131.
55. Aladin, N.V.; Plotnikov, I.S. Large saline lakes of former ussr: A summary review. In *Saline Lakes V*; Hurlbert, S., Ed.; Springer: Houten, The Netherlands, 1993; Volume 87, pp. 1–12.
56. O'Hara, S.L. Central asia's water resources: Contemporary and future management issues. *Int. J. Water Resour. Dev.* **2000**, *16*, 423–441.
57. Rashid, K.; Nodirbek, M.; Asqar, N.; Dilafuz, K.; Jobir, S. Qualitative and quantitative assessment of water resources of Aydar Arnasay lakes system (AALS). *J. Water Resour. Prot.* **2013**, *5*, 941–952.
58. Van Beek, E.; Bozorgy, B.; Vekerdy, Z.; Meijer, K. Limits to agricultural growth in the sistán closed inland delta, Iran. *Irrig. Drainage Syst.* **2008**, *22*, 131–143.
59. Van der Ent, R.J.; Savenije, H.H.G.; Schaeffli, B.; Steele-Dunne, S.C. Origin and fate of atmospheric moisture over continents. *Water Resour. Res.* **2010**, *46*, W09525.
60. Pastor, A.V.; Ludwig, F.; Biemans, H.; Hoff, H.; Kabat, P. Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 5041–5059.
61. Dahl, C.; Kuralbayeva, K. Energy and the environment in Kazakhstan. *Energy Policy* **2001**, *29*, 429–440.
62. Renaud, F.G.; Syvitski, J.P.M.; Sebesvari, Z.; Werners, S.E.; Kremer, H.; Kuenzer, C.; Ramesh, R.; Jeuken, A.; Friedrich, J. Tipping from the holocene to the anthropocene: How threatened are major world deltas? *Curr. Opin. Environ. Sustain.* **2013**, *5*, 644–654.
63. Gordon, L.J.; Peterson, G.D.; Bennett, E.M. Agricultural modifications of hydrological flows create ecological surprises. *Trends Ecol. Evol.* **2008**, *23*, 211–219.
64. Gerten, D.; Hoff, H.; Rockström, J.; Jägermeyr, J.; Kummu, M.; Pastor, A.V. Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 551–558.
65. Micklin, P. The aral sea disaster. *Annu. Rev. Earth Planet. Sci.* **2007**, *35*, 47–72.
66. Saiko, T.A.; Zonn, I.S. Irrigation expansion and dynamics of desertification in the circum-Aral region of Central Asia. *Appl. Geogr.* **2000**, *20*, 349–367.
67. Gordon, L.J.; Steffen, W.; Jönsson, B.F.; Folke, C.; Falkenmark, M.; Johannessen, Å. Human modification of global water vapor flows from the land surface. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 7612–7617.

68. Rockström, J. Water for food and nature in drought-prone tropics: Vapour shift in rain-fed agriculture. *Philos. Trans. R. Soc. Lond. B* **2003**, *358*, 1997–2009.
69. O'Hara, S.L. Irrigation and land degradation: Implications for agriculture in Turkmenistan, Central Asia. *J. Arid Environ.* **1997**, *37*, 165–179.
70. Abdullaev, I.; de Fraiture, C.; Giordano, M.; Yakubov, M.; Rasulov, A. Agricultural water use and trade in Uzbekistan: Situation and potential impacts of market liberalization. *Int. J. Water Resour. Dev.* **2009**, *25*, 47–63.
71. Abdullaev, I.; Rakhmatullaev, S. Transformation of water management in Central Asia: From state-centric, hydraulic mission to socio-political control. *Environ. Earth Sci.* **2015**, *73*, 849–861.
72. Molle, F.; Mollinga, P.P.; Wester, P. Hydraulic bureaucracies and the hydraulic mission: Flows of water, flows of power. *Water Altern.* **2009**, *2*, 328–349.
73. Yanitsky, O.N. The shift of environmental debates in Russia. *Curr. Sociol.* **2009**, *57*, 747–766.
74. Libert, B.; Orolbaev, E.; Steklov, Y. Water and energy crisis in Central Asia. *China Eurasia Forum Q.* **2008**, *6*, 9–20.
75. Vassolo, S.; Döll, P. Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resour. Res.* **2005**, *41*, W04010.
76. Mekonnen, M.M.; Hoekstra, A.Y. The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 179–187.
77. Zhao, D.; Liu, J. A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services. *Phys. Chem. Earth A B C* **2015**, *79–82*, 40–46.
78. Alcamo, J.; Döll, P.; Henrichs, T.; Kaspar, F.; Lehner, B.; Rösch, T.; Siebert, S. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol. Sci. J.* **2003**, *48*, 317–337.
79. Schlüter, M.; Khasankhanova, G.; Talskikh, V.; Taryannikova, R.; Agaltseva, N.; Joldasova, I.; Ibragimov, R.; Abdullaev, U. Enhancing resilience to water flow uncertainty by integrating environmental flows into water management in the Amudarya river, Central Asia. *Glob. Planet. Chang.* **2013**, *110*, 114–129.
80. Cai, X.; McKinney, D.C.; Rosegrant, M.W. Sustainability analysis for irrigation water management in the Aral sea region. *Agric. Syst.* **2003**, *76*, 1043–1066.
81. Jalilov, S.-M.; Amer, S.; Ward, F. Water, food, and energy security: An elusive search for balance in Central Asia. *Water Resour. Manag.* **2013**, *27*, 3959–3979.
82. Eamus, D.; Froend, R.; Loomes, R.; Hose, G.; Murray, B. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Aust. J. Bot.* **2006**, *54*, 97–114.
83. Walker, B.; Holling, C.S.; Carpenter, S.R.; Kinzig, A. Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.* **2004**, *9*, 5.
84. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, doi:10.1126/science.1259855.

85. Dearing, J.A.; Wang, R.; Zhang, K.; Dyke, J.G.; Haberl, H.; Hossain, M.S.; Langdon, P.G.; Lenton, T.M.; Raworth, K.; Brown, S.; *et al.* Safe and just operating spaces for regional social-ecological systems. *Glob. Environ. Chang.* **2014**, *28*, 227–238.
86. Raworth, K. A safe and just space for humanity: Can we live within the doughnut. *Oxfam Policy Pract. Clim. Chang. Resil.* **2012**, *8*, 1–26.
87. Folke, C.; Carpenter, S.R.; Walker, B.; Scheffer, M.; Chapin, T.; Rockström, J. Resilience thinking: Integrating resilience, adaptability and transformability. *Ecol. Soc.* **2010**, *15*, 20.
88. Luce, R.D.; Raiffa, H. *Games and Decisions: Introduction and Critical Survey*; Duncan: New York, NY, USA, 1985.
89. Pierce, S.A.; Sharp, J.M.; Guillaume, J.H.A.; Mace, R.E.; Eaton, D.J. Aquifer-yield continuum as a guide and typology for science-based groundwater management. *Hydrogeol. J.* **2012**, *21*, 331–340.
90. Sojamo, S. Illustrating co-existing conflict and cooperation in the Aral sea basin with TWINS approach. In *Central Asian Waters: Social, Economic, Environmental and Governance Puzzle*; Helsinki University of Technology: Helsinki, Finland, 2008; pp. 75–88.
91. Gready, P. Rights-based approaches to development: What is the value-added? *Dev. Pract.* **2008**, *18*, 735–747.
92. Cornwall, A.; Nyamu-Musembi, C. Putting the “rights-based approach” to development into perspective. *Third World Q.* **2004**, *25*, 1415–1437.
93. Young, O.R.; Berkhout, F.; Gallopin, G.C.; Janssen, M.A.; Ostrom, E.; van der Leeuw, S. The globalization of socio-ecological systems: An agenda for scientific research. *Glob. Environ. Chang.* **2006**, *16*, 304–316.
94. International Fund for Saving the Aral Sea. *From the Glaciers to the Aral Sea—Water Unites*; International Fund for Saving the Aral Sea: Tashkent, Uzbekistan, 2015.

© 2015 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).