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Title: Water, Energy, and Food Nexus in the Amu-Darya River Basin: Analysis of Water Demand and Supply Management Infrastructure Development at Transboundary Level

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Mary Virginia Santelmann

The levels of cooperation in efforts towards transboundary water management in the Aral Sea basin have ranged from high to low over the past few decades, due in part to diverse purposes for water use in the region. Two important and often conflicting uses are agriculture and hydropower, which tend to align by sector with national boundaries. Successful management and development of water resources of the Amu-Darya River, one of the two main rivers of the basin, will require building closer cooperation among states. Improvement in cooperative efforts, in turn, will require both water supply-oriented infrastructure development (such as dams and reservoirs), and demand-oriented infrastructure development (such as improvement of water conveyance in irrigation canals). The goal of this research was to evaluate four alternative scenarios for water, energy, and food security that could be achieved by the riparian states, as well as the sustainability dimensions of development of these infrastructures. The four scenarios were based on different combinations of infrastructure development, operational modes of upstream reservoirs, and piping of irrigation canals. For this purpose, the Interdisciplinary Nexus Sustainability Assessment Framework (INSAF) was developed that incorporates assessment of changes in WEF security for riparian states and Bio-physical, Socio-economic, and Geo-political dimensions of infrastructure development in the Amu-Darya River basin. The results of the research indicate that application of both a supply and demand management approach to water resources management and development increases the "basket of benefits" for water, energy, and food security achievements, and has a potential to improve cooperation and sustainable basin development by reducing tensions linked with water allocation and timing of water use in the basin.

Water, Energy, and Food Nexus in the Amu-Darya River Basin: Analysis of Water Demand and Supply Management Infrastructure Development at Transboundary Level

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Aminjon Abdulloev, Author

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INTRODUCTION

Improvement in water, energy, and food security can be achieved through use of a nexus approach which integrates management and governance across sectors and scales, reducing negative economic, social, and environmental impacts and increasing overall resource use efficiency. The term “nexus” has been defined as “single or multiple connections between several elements” (Leck et al. 2015). Transition from managing sectors such as water, energy and food in “silos” to an integrated approach (i.e., a “nexus approach”) that directly considers those connections can reduce trade-offs and build synergies across sectors (Hoff, 2011; Bazilian et al. 2011).

The nexus approach emerged in the international community in response to the global challenges of population growth, climate change, urbanization, and economic growth (Hoff, 2011). The approach can guide the management of resources in the areas of their scarcity, such as in the Middle East where water scarcity is among the highest in the world (Hoff et al. 2019; EcoPeace Middle East 2017) or in Central Asia. Due to the extensive development of irrigation during the 1960s and resulting desiccation of the Aral Sea, after becoming independent Central Asian countries have faced water scarcity and water timing issues that have caused tension and conflict among the riparian states in this region. A nexus approach could be the solution needed to reduce conflict while planning new infrastructure developments in Central Asian region.

This paper discusses how infrastructure development, including both construction and its operational management, might result in reduction of the water sharing and water timing tensions among the states on transboundary water resource management. This research explores ways in which indicators can be used to assess water, energy, and food security achievements realized through building infrastructure on transboundary rivers, and to evaluate the potential social, economic, environmental and political effects of proposed infrastructure developments. By highlighting both dimensions of water resource management (i.e., supply and demand management) in the process of planning and development of infrastructure along transboundary rivers, the work presented here helps evaluate potential benefits for achievement of water, energy, food security goals and reduction of social, environmental, and political trade-offs for the riparian countries. The overarching goal of this work is to promote equitable transboundary basin management and cooperation, while at the same time, reducing the potential for conflict in the region.

This paper focuses on the Aral Sea Basin and presents a case study of one of the two major rivers, the Amu-Darya, shared by four countries: Afghanistan, Tajikistan, Turkmenistan, and Uzbekistan (Figure 1.1.). The analysis of potential outcomes for this case study will be supported by comparisons to two other case studies from the Columbia River Basin, which provide examples of successful water management through canal piping projects and cooperation in the water-energy nexus on the Columbia River between Canada and the US.

Figure 1.1 Aral Sea Basin, Central Asia

The next section of this thesis provides a literature review of nexus development as a concept and approach. It is followed by the Methods section, in which the study region is described, and the methodology and tools used in the research are presented. The Methods section describes both the process used in development of a new assessment framework, the Interdisciplinary Sustainability Nexus Assessment Framework (INSAF), and the alternative future scenarios to be evaluated using INSAF. The Results section presents the outcome of the application of INSAF framework in an evaluation of the impacts of four alternative future scenario on water, energy and food security for the Amu-Darya Basin, across multiple dimensions of sustainability. This evaluation is conducted through application of a set of indicators that emerged from the development of the conceptual framework and assessment tool. The results are compared and contrasted with case study results from other regions in the Discussion section, and finally, the Conclusion section presents outcomes of the work and recommendations for further study and application of the research results.

1. LITERATURE REVIEW

Development of the Water-Energy-Food Nexus as a Concept.

The term “nexus” was used by the World Bank for the first time in the context of research on water, energy and food in the 1990s to link water, food, and trade before it was officially used for the Bonn 2011 Nexus Conference (The Water, Energy and Food Security Nexus: Solutions for the Green Economy, 16-18 November 2011). It was at the Bonn Conference where water, energy, and food were made the main pillars of the framework (Endo et al. 2017).

The meaning of the term “nexus” itself can be defined as single or multiple connections between several elements (Leck et al. 2015). However, scientists and practitioners were familiar with the interlinkages between sectors before the term was coined, these interactions were simply not referred to under the “nexus” term (Keskinen et al., 2016). Integrated resource management in general has a long history and was formed earlier in frameworks such as integrated natural resource management, integrated water resource management or environmental policy integration (Leck et al. 2015; Hoff et al. 2019).

The nexus approach gained popularity and was promoted and used by practitioners and scholars following the Bonn 2011 Nexus Conference held by the German Federal Government (Endo et al. 2017). The background paper for the conference stated that “improved water, energy and food security can be achieved through a nexus approach, an approach that integrates management and governance across sectors and scales.” This nexus approach underlines the need for integrated approaches to deal with complex issues at the intersection of natural and human systems (Hoff et al. 2019). Or as Hoff (2011) puts it: “Conventional policy- and decision-making in "silos" needs to give way to an approach that reduces trade-offs and builds synergies across sectors – a nexus approach." For example, in the water-stressed Middle East and North Africa (MENA) region, drip irrigation is thought of as a solution to increase food production (and reaching food security) which allows farmers to reduce water use (producing the same amount with less water) and requires less energy for water pumping. At the same time, introduction of drip irrigation may cause intensive extension of irrigated land, leading to even more water scarcity; reduction of return flows leading to a decrease in aquifer recharge and meaning less water for those who rely on the aquifer. Thus, assessment of these developments requires comprehensive impact assessment from a nexus perspective and evaluation of effects on water, energy, and food security combined to guide policy making for managing trade-offs and better-offs (Hoff et al. 2019).

A nexus approach implies the explicit inclusion of interlinkages among sectors and across disciplines (Bazilian et al. 2011; Leck et al. 2015). The Water-Energy-Food nexus emphasizes the inherent links among water, energy, and food resource systems and aims to overcome single-sector approaches to resource governance (Biggs et al. 2015). The nexus framework was built based on the principles of IWRM and other holistic approaches (Leck et al. 2015).

IWRM – A Water-Centric Integrated Concept

Application of hydrologic principles to water management led to the establishment and development of the integrated water resource management (IWRM) concept. The IWRM approach, promoting comprehensive management of all water uses, is a 60- year old concept that was rediscovered and broadly promoted in early 1990s (Bizwas, 2004). According to the Global Water Partnership (GWP) definition, IWRM is "a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.” (GWP 1992). However, this concept has been critiqued for lack of solid conceptualization, difficulties in practical operationalization, and of being overly water-centric (Biswas, 2004, Leck et al., 2015). The nexus approach, on the other hand, was intended to include different perspectives in its conceptual framework, to equally emphasize not only water, but other resources and sectors as well, such as energy, food, land, and ecosystems (e.g. FAO’s Nexus framework (FAO, 2014), Bizikova et al. 2013).

Diversity of Approaches to Nexus Framework

Researchers have included different combination of elements into the nexus framework. Figure 2.1. shows the framework developed for the Bonn 2011 Nexus Conference and described in “Understanding the Nexus”, a special publication conceptual paper for the conference included all three widely used components of the nexus framework (Hoff 2011). This framework shows the connections between water, energy, and food securities linked through water resources as a central element.

In the papers following the conference, authors also used several varieties of nexus frameworks. They modified the concept of the water-energy nexus as described in the conference by using or excluding the word “security”, including only two elements to the framework (water-energy nexus), using different components: water, energy, and security nexus (Figure 2.3.) (Stuki & Sojamo 2012), and by extending the number of elements (water, energy, food, and climate or land nexus) into the framework (Keskinen et al., 2016; FAO, 2014). Further, Zhang et al. (2018)

categorized nexus frameworks into two groups: those with a central element (e.g. Hoff 2011) and those without a central element (Bizikova et al. 2013) (Figure 2.2.).

The International Institute for Sustainable Development's (IISD) Water–Energy–Food Security Analysis Framework focused on optimization of water-energy-food security to guide landscape planning decision support. The IISD extended the framework, including three independent security frameworks (with set of indicators) for each of the three nexus elements and two "external layers" that highlight overlaps and linkages between the elements (Bizikova et al. 2013). Compared to Hoff's (2011) framework, the IISD framework approaches all three elements "equally" without highlighting any one of the three. However, Hoff (2011) puts water in a central position, highlights it as a resource – a concept that is extended in FAO's approach, as discussed later in this paper.

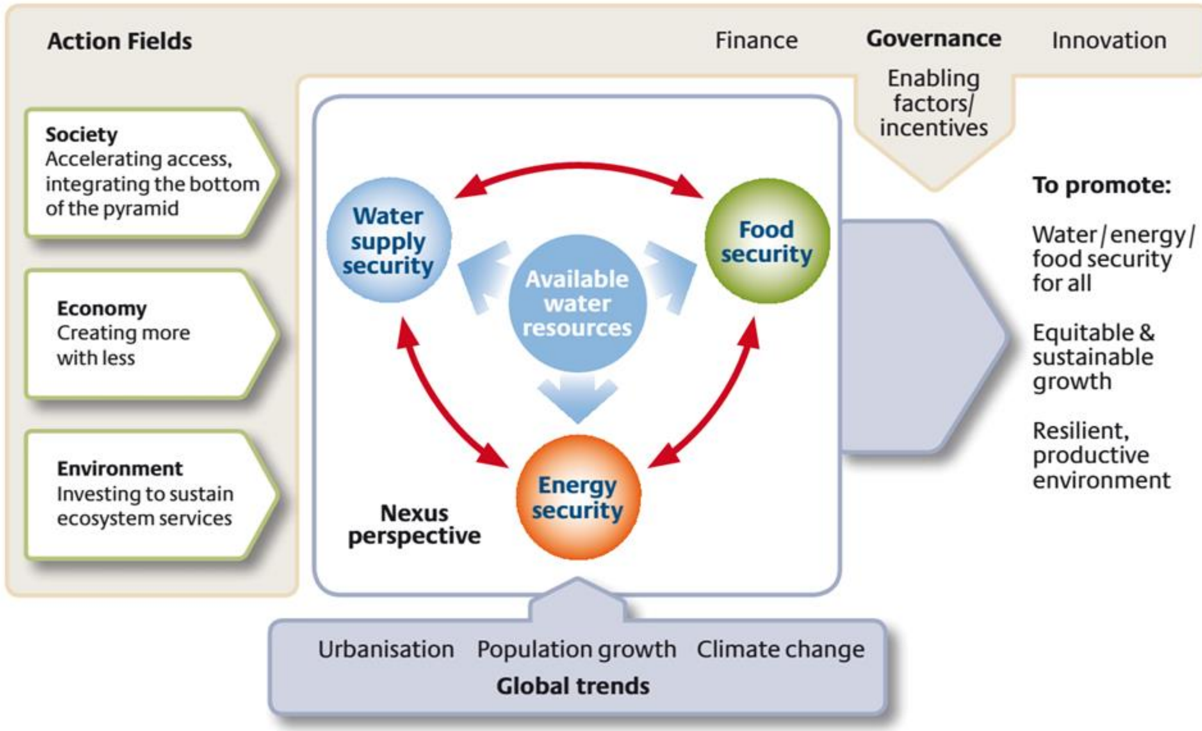

Figure 2.1. Water, energy, and food security nexus framework proposed by Hoff (2011)

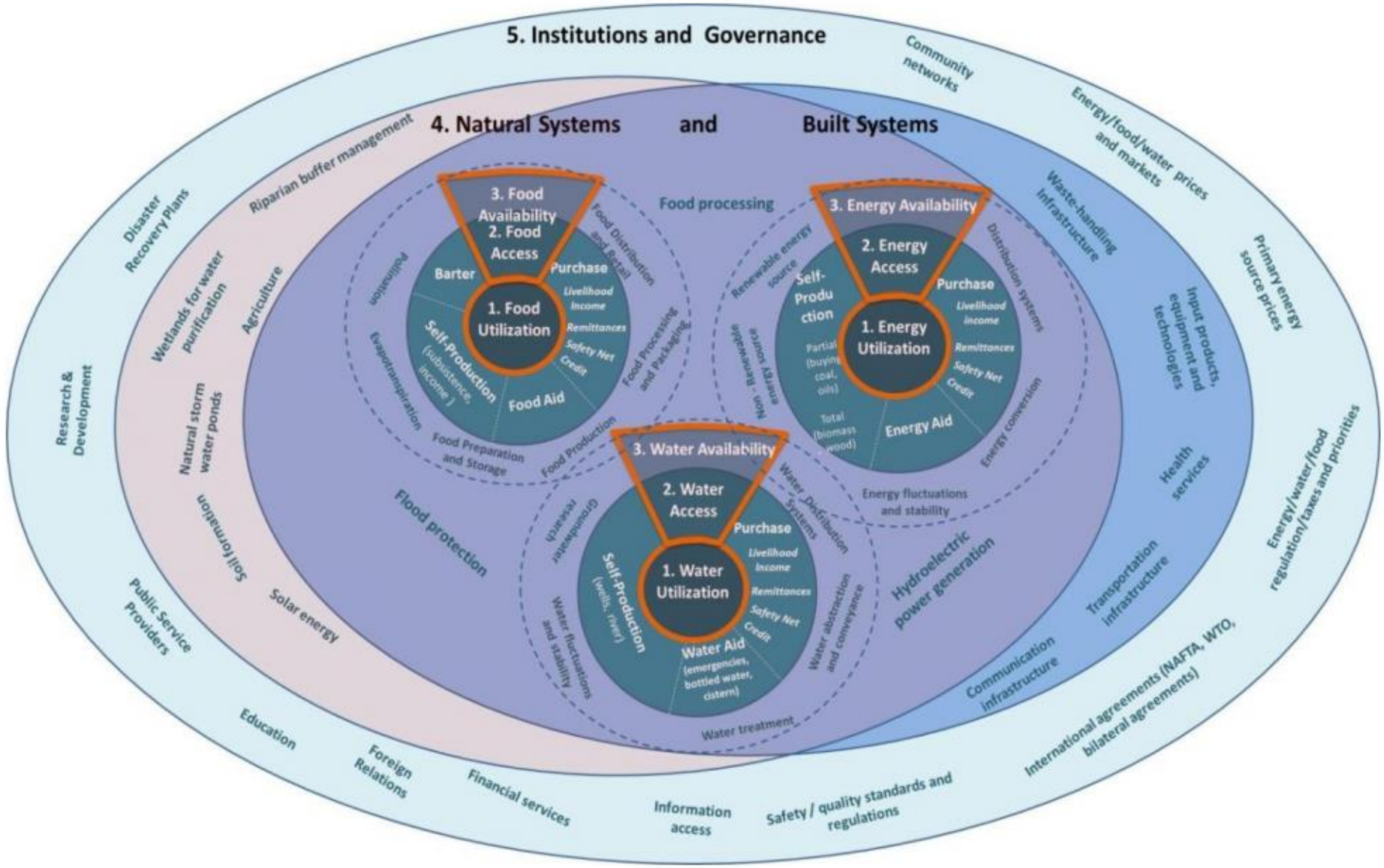

Figure 2.2. The framework linking water, food, and energy security proposed by Bizikova et al. (2013)

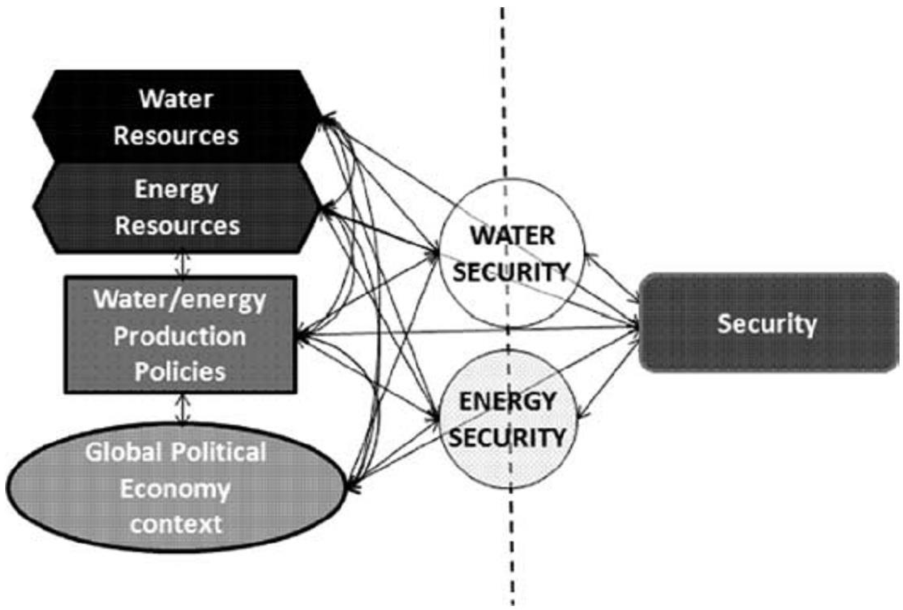

Figure 2.3. Water-energy-security nexus, framework applied for Central Asia. (Stuki & Sojamo, 2012)

Authors have used different interpretations of the nexus framework in the literature, defining diverse roles for the concept and several approaches for its application. Keskinen et al. (2016) differentiated among three definitions of the nexus approach – nexus as an analytical tool, as a conceptual framework, and as a discourse. As an analytical tool, the nexus concept is used to define the interlinkages by using qualitative and quantitative methods (Albrecht, Crootof & Scott, 2018). As a conceptual framework, a nexus approach can guide coherent policy and decision making to progress in sustainable growth and green economy (Bazilian et al. 2011; Hoff, 2011). As a discourse, the nexus concept can be used to frame the problem to identify trade-offs and to foster more cooperation among the sectors (Keskinen et al., 2016).

The water, energy, and food nexus (hereafter called the WEF nexus) framework can also be approached from different focal perspectives of policy-makers which depends for instance on the strategic priority of the country (Bazilian et al. 2011). For example, if approached from a water perspective, energy and food are perceived as the users of the resource, while from a food perspective water and energy are seen as inputs (Bazilian et al. 2011). Thus, the perspective taken will influence the policy design the experts who are involved will approach from the perspective of their sector since few people can be expert in all three areas (Bazilian et al. 2011).

Gaps in Nexus Research

Authors have identified several gaps in the knowledge and understanding of the WEF nexus that need to be further explored. Different possible directions for further research and development of the nexus concept were identified. Bizikova et al. (2013) for instance, defines three areas where knowledge of the WEF nexus should be further explored: “the nature of the relationships among the three elements; considerations of changes in nexus elements and other sectors such as infrastructure; and implications for policy development.”

To foster more integrated policy making to support practical implementation of integrated approaches, Bazilian et al. (2011) named “three promising directions” that stress:

1. Political motivators to encourage more integrated decision making rather than framing the approach on fully environmental impacts,
2. Capacity building and strengthening institutions on better understanding of nexus thinking, and
3. Application of modelling techniques to provide better understanding of trade-offs for informed decision making.

These early-identified directions for conceptual and practical application of the nexus approach helped to further clarify research directions, and led to the current framing of the problems addressed through nexus thinking. Further development of the framework faces constraints such as strong sectoral silos, lack of incentives for more integrated planning and policy making, and necessity for more clear understanding of the concept and practical experience to further guide its application (Hoff et al. 2019). Lack of evidence of positive results, and the potential risks of implementing a nexus approach in practice leads to reluctance of political leaders to allocate funding for a nexus approach (Hoff et al. 2019). This situation in turn holds back the further development of the concept based on the practical experience of nexus implementation (Hoff et al. 2019).

Gaps in Nexus Frameworks: Lack of Social, Political, and Environmental Dimensions

In recent works the nexus approach has been criticized for lack of incorporating social, economic, political, and environmental dimensions and for under-politicized perspectives (Albrecht et al. 2018, Leck et al., 2015). The connection of the nexus concept with political will is mentioned in some articles (Granit et al. 2012, De Strasser et al. 2016) but the connection is not linked with the concept forming a comprehensive framework for assessment. Political, economic, and social aspects have such an influence that even if the nexus-oriented infrastructure development or policies are technically very efficient, political or social aspects can influence the securitization of resources. This in turn can lead to suboptimal regional cooperation regimes, and, especially in transboundary basins, hinder the implementation, adoption or realization of those projects and policies (Granit et al. 2012). Thus, integrated approaches such as the nexus were fairly criticized for under-politicized perspectives (Leck et al. 2015). For example, Granit et al. (2012) mention the lack of political will in advancing water, energy, and food security in Central Asia but at the same time the research lacks further systematic analysis and inclusion of the role of political, social, and environmental aspects into the analytical or evaluation framework.

In several recent works, some authors include political and social dimensions in their research. De Strasser et al. (2016) admit that physical effects on transboundary rivers can be measured and includes socio-economic and geopolitical assessment of the basins into the “six step” framework (TRBNA). However, the research covers broad range of topics to conduct “nexus assessment of a basin”, with an emphasis on governance. Thus, the work fails to provide a detailed impact assessment of projects and policies that can be implemented at the basin level.

Yang et al. (2016) include consideration of irrigation diversions along with dams and climate change impacts. Their work identifies “acceptable” and “inacceptable” options that result from modeling. As a limitation however, they mention difficulty of including political aspects of water management that exist between India, China and Bangladesh in Brahmaputra Basin.

To close this gap and to contribute to the development of more comprehensive approach to operationalization of the nexus concept, the research presented here develops the Interdisciplinary Sustainability Nexus Assessment Framework (INSAF), an assessment framework that incorporates evaluation of water, energy, and food security achievements as well as evaluation of biophysical, socio-economic, and geopolitical dimensions of sustainability. The proposed framework is then applied to evaluate four different scenarios of construction and operation of two different types of infrastructure projects in the Amu-Darya River Basin – Rogun HPP and piping of the irrigation canals.

Current Gaps in Transboundary Nexus Research in the Aral Sea Basin: Water Demand Management

Nexus thinking can be applied at different geographical (e.g., transboundary or not) and thematic scales (demand and/or supply management). Albrecht et al. (2018) conducted a systematic review of 73 nexus articles (out of 245 previously published), with more detailed review of the 18 selected articles. Their classification of the geographical scale of the research identified 5 articles of transboundary focus and 6 articles of regional focus. Of those, articles with a focus area in Central Asia are reviewed below, together with additional works focusing on Aral Sea Basin (i.e. transboundary level) to define their thematic focus (Table 2.1.). The review below strives to identify potential gaps, with special emphasis on the articles that considered solutions for water management issues in the basin that have impact at transboundary level, the relationships among countries and types of infrastructure developments in the basin.

Table 1.1. Nexus research articles focused on Central Asia.

Citation	**Focus area**	**Main Topic**	**Types of infrastructure discussed**	**Aspects discussed: (economic, social, environmental, and political)**
Granit et al. 2012	Aral Sea Basin	Regional integration	Hydropower generation, irrigation	hydropower, regional power market, irrigation reforms, water flows and quality
Stucki & Sojamo, 2012	Central Asia	definitions, indicators, security	limited	macro-level impacts, sustainability, development, security
Soliev, Wegerich, & Kazbekov, 2015	Sir-Darya Basin	Historical analysis, benefit sharing,	Mainly irrigation canals,	Environment, institutions, governance, politics
Keskinen et al. 2016	Central Asia, South Asia, Mekong Region	Definitions for Nexus as: analytical tool, governance framework and emerging discourse	Dams, power grids, storage inf., hydropower	State actors, politics,
Jalilov, Varis, & Keskinen, 2015	Central Asia, Amu-Darya River	Infrastructure (mainly dams) benefit sharing	Hydropower plant,	Cooperation, hydro-economic model
Jalilov, Amer, & Ward, 2018	Central Asia, Amu-Darya River	Infrastructure (mainly dams), equity, pareto-cost-benefit sharing	Hydropower plant,	Economic outcomes, climate change, policies
Abdullaev, & Rakhmatullaev, 2016	Central Asia	Governance, Institutions, coordination, IWRM	Economics and financial aspects of infrastructure	Politics, governance, climate change
Rakhmatullaev, Abdullaev, & Kazbekov, 2017	Central Asia	Transformation, sustainable development	Green infrastructure, demand management	Economic development, natural resources, environmental degradation

De Strasser et al. 2016	Alazani/Ganykh, Sava, Sir-Darya, Isonzo/Soca	Assessment methodology development	Infrastructural intervention and planning	Policy, political will, ecosystems, social, economic, and environmental factors
Guillaume et al. 2015	Central Asia	Transferable principles, historical analysis	Dams, irrigation	Socio-ecological systems

Table 1.1. illustrates, for example, that Soliev et al. (2015) focused on institutions and took a historical perspective that affected sharing benefits among riparian states. It considers issue linkage and sharing benefits from transboundary infrastructure by use of economic mechanisms to help nexus implementation, based on lessons learned in the past. While this work focuses on historical analysis of irrigation infrastructure development with the link to hydropower, other authors mainly discuss construction of the dam in researching transboundary basins.

Governance of water, energy, and food production at a transboundary level using nexus thinking implies use of different approaches and challenges compared with national or regional levels. The transboundary context is influenced by several factors that do not exist at national or lower levels. Parties (stakeholders) at the transboundary level are represented by sovereign states as well as sectors, while at the national level they are represented by sectors. Laws and regulations at the national level are different from principles of international law. Relations between the countries are regulated by the principles of international law and their behavior is guided by respective national interests. The enforcement of regulations can be much more feasible at a national level than enforcement of agreed-upon principles at the transboundary level. Thus, considering nexus governance in a transboundary context implies additional challenges of different nature (Leck et al. 2015; De Strasser et al. 2016). In addition to the 'overall challenges' defined by Hoff et al. (2019) for a national level nexus approach (focused on resource optimization, interrelations between sectoral ministries and policy adaptation), nexus approaches at transboundary levels face challenges of equity, security, political interests, and different national development strategies.

In the process of this review, it became clear that research within the geographic region of the Aral Sea basin mainly focus on discussions about the dams, and thus can be summarized as exploring only water supply management. There is a significant a gap in “fully” including the demand side into the discussion and analysis of the nexus approach. De Strasser et al. (2016) mention the development of infrastructure together with policy measures that can be implemented at a transboundary level. The discussions about Central Asia in the paper are mainly about hydropower development. The role of agriculture is also highlighted, but no further detailed analysis is provided. This high interest in dam building could be explained because dam-building is a cause of tensions between riparian states in shared basins worldwide – e.g., the Mekong, Nile, and Aral Sea basins. However, less attention was paid to management of the demand side, the approach to planning, management, and development of the shared basins that has promising potential to widen the basket of benefits and come with solutions that may provide mutual benefits and reduce the tensions in transboundary water among riparian states.

Agriculture by far is the largest water use sector in the many of the basins and in Aral Sea Basin as well. The irrigation practices used in the Aral Sea Basin often have low water use efficiency, and in many cases rely on aging infrastructure. Implementation of water conservation projects including lining and piping of the canals might have positive impacts on water efficiency practices.

Basin development can be implemented through infrastructure development, development of common policies for constructions and management of infrastructure at transboundary level, and by establishing or strengthening existing institutions for nexus cooperation in the basin. Introducing water conservation practices and other types of innovative water storage technology may also bring significant impact on the water, energy, and food securities at transboundary level.

Nexus research conducted in other basins identify that other types of basin development with diverse infrastructure types could be considered. For example, the work of Samjgl et al. (2016) includes developments in the Mekong Basin driven from different nexus element perspectives. They include irrigation projects driven by food security, hydropower development, energy crops, and water diversions.

On the practical side, considerations of the governments in Aral Sea Basin paid much attention to increasing water storage capacity contestations and less to water efficiency enhancement practices and investment into water use efficiency.

This review of prior research highlights the fact that transboundary water management is not limited just to the analyses of dam development and management, as it is seen in most of the works on Central Asia and Aral Sea Basin, but may also focus on both water supply management and demand management that include among many other potential options:

- Water conservation projects
- Piping projects
- Irrigation efficiency improvements
- Aquifer recharge technologies
- Water resource management decision and policy making

Infrastructure controls where and when the water will flow, thus both dams and irrigation canals are the infrastructure that controls the natural flow of the river, in the case of Aral Sea basin, a transboundary river. As dams control the flow of water, so do the canals – the example of the

Aral Sea shows how building extensive canal systems to control water for irrigation caused the desiccation of the sea. Dams have several disadvantages including increased surface area for evaporation, altered streamflow regimes and altered water temperature, but water eventually reaches the sea.

The work presented here is intended to fill the gap created by one-sided (supply side only) thinking. Bringing the discussion of the piping of water in existing open (and often, unlined) irrigation canals to the assessment of project impacts at the transboundary level is a new contribution to regional discussions of water, energy, and food (hereafter called WEF) security. The combination of the two infrastructure developments (piping and hydropower) will bring more benefits for water energy and food security, and as a result might reduce the tensions over water allocation between riparian states. This approach can also stimulate thinking beyond just water allocation to consider allocation of multiple shared resources from water, energy, agricultural and food security perspectives. The results of the previous works on the water energy food nexus at the transboundary level, focusing on building dams and optimization of their management, will be used to make comparative before-after analysis with four different alternative future scenarios.

Limitations

The nexus approach can be explored from different perspectives that are beyond the scope of what has been considered here. For example, studies may focus on institutional impacts, governance, modeling and technical optimization of resource use, the historical perspective, international law, or interlinkage assessment. The focus of the current study is on the role of nexus thinking in planning for sustainable infrastructure development, and investments for transboundary water management. It explores the implications of specific projects with respect to their bio-physical, socio-economic, and geo-political impacts in the basin.

The proposed scenarios developed by Jalilov et al. (2015) and Bekchanov et al. (2015) were adapted here to help frame and evaluate potential achievements of the WEF securities, and are limited by lack of overt inclusion or consideration of the impacts of climate change. Rather, the impacts of climate change were seen as one of the exacerbating factors contributing to the overall potential for water scarcity in the basin together with population growth and urbanization. While governance and stakeholder assessment has been done for the basin in some previous papers (e.g., De Strasser et al. 2016), it should also be done across a full range of stakeholders and governance entities for the case of the selected infrastructure developments.

There are strong interconnections between the water, energy, and food resource base, sectors managing these resources, and disciplines, however these sectors are linked with other sectors beyond three "main" nexus elements. Wichelns (2017) for instance, makes the point that there could be other variables that can affect the nexus grid that are not included in current research. However, due to feasibility concerns, the scope of this framework is limited to the qualitative comparison of sectors and dimensions for which indicator data were available. Similarly, detailed quantification of the impacts of the changes in the basin that would result from infrastructure construction are beyond the scope of this work, due to lack of available data as well as limitations of time and resources.

2. METHODS

Overview

The methods described here involve development of an approach to evaluate and compare alternative future options (scenarios) for development and management of transboundary water resources to achieve water, energy, and food security. These developments involve but are not limited to development of infrastructure for managing water resources for irrigation, hydropower generation, and flood control. The methods involve five steps:

1. Development of a conceptual framework for analysis of alternative options that blends assessment of Water, Energy and Food Security with specific reference to three sectors; Socio-economic, Geo-political, Bio-physical Dimensions
2. Generating the alternative scenarios
3. Data collection and sources of data for indicators
4. Data processing- generation of scores (on a five-point scale) for each element of comparison for water, energy, and food security along three primary dimensions of their socioeconomic, geopolitical and biophysical impact.
5. Development of assumptions for how elements of the various scenarios will affect socioeconomic, geopolitical, or biophysical aspects of the water, energy, and food systems of Aral Sea Basin

The main objective of the thesis is to develop a new assessment framework, an assessment tool that can be used to compare alternative scenarios across the water, energy, and food sectors and for all three dimensions of sustainability (biophysical, socio-economic, and geo-political). Once the results of applying the new assessment framework have been obtained for both the current situation and the four alternative future scenarios, the results are then analyzed, compared, and discussed. Each of the five steps outlined above is discussed in detail in the sections below.

Development of the Interdisciplinary Nexus Sustainability Assessment Framework (INSAF)

The assessment framework developed for current research is used first, to make an assessment of infrastructure developments status and condition for water, energy, and food securities, then Interdisciplinary Sustainability Assessment Framework (INSAF) is used to evaluate positive and negative effects of infrastructure development in terms of bio-physical, socio-economic, and geo-political dimensions (after Tullos et al., 2010).

Since the INSAF framework is intended to be used to conduct a semi-quantitative analysis of three security components of the WEF nexus, and bio-physical, socio-economic, and geopolitical dimensions of different alternative scenarios of transboundary water development and operational management, the appropriate frameworks for each of the components and dimensions were explored to develop the framework. Semi-quantitative analysis represents the type of method where the effects of the developments under analysis to parameters measured are not quantified but rather the concentration (or qualitative direction) of the positive or negative results are estimated (Bertin, 1978). The INSAF framework is developed on the basis of the nexus concept and consists of the following components: resource base (also inputs), water security, energy security, food security, Interdisciplinary Assessment Framework, basin management and development, and three securities together with ecosystems grouped under goals (Figure 3.1.). These components are discussed in detail in the following sections.

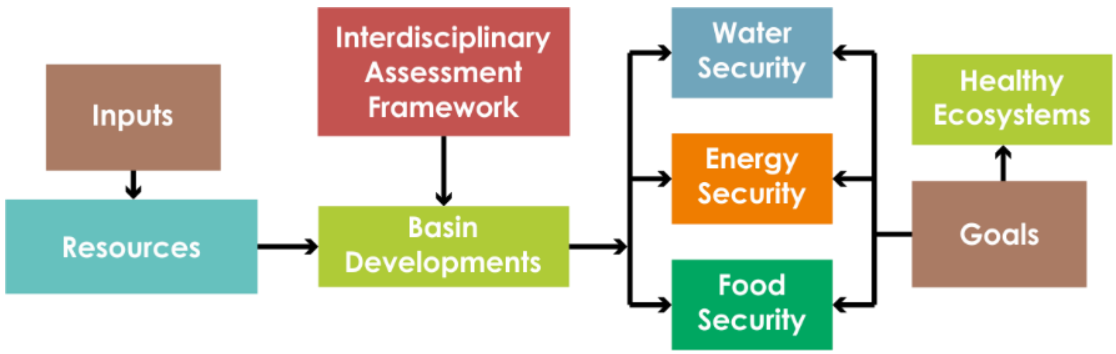

Figure 3.1. Interdisciplinary Nexus Sustainability Assessment Framework **(**INSAF). Structure and Components.

To establish the core structure of the framework – the nexus interlinkages concept, I investigated several potential frameworks that could be used in a WEF assessment (Hoff, 2011; Bizikova et al. 2013; FAO, 2014; Smajgl et al. 2016, Albrecht et al. 2018; Tullos et al. 2010) discussed in the Literature Review above, and from this review of the proposed concepts, developed my own conceptual framework, described in Figure 3.1.

All papers reviewed highlight the interactions between the water, energy, and food systems and envisage diverse application of the proposed concepts, including better understanding of the nexus concept, incentivizing its operationalization, and approaches for decision-making and policy-making support (Bizikova et al. 2013; De Strassser et al. 2016; Hoff et al. 2019; Keskinen et al. 2016), thus including specific elements to their proposed concepts. Among others, FAO’s (2014) perspective on the WEF nexus also recognizes the diverse interactions and links between human and natural resource systems and highlights the feedback between these systems to better manage the resource base which is used by people to meet different goals and interests (Figure 3.2.). This holistic vision that includes multiple interactions of utilizing resource base (inputs) for the achievement of goals (WEF security) through management (transboundary basin development) is taken as a “conceptual foundation” for the proposed assessment framework in this paper (Figure 3.1.). Inclusion of environmental systems as an important component into the nexus framework contributes to the comprehensiveness of the approach. Natural resources such as water, energy, ecosystem services, and land are all used by the WEF sectors in the achievement of their sectoral goals. Ecosystem services and their health are important for sustainable food production, water quality availability, and socio-economic stability.

The approach adapted from Smajgl et al. (2016) to the nexus concept allows better comprehension of interlinkages between the resources, across sectors, and goals. To illustrate the diversity of interlinkages that nexus approach allows us to identify, the framework draws connections among WEF sectors through resources and also shows the direct interactions between the sectors (Figure 3.3.). For example, the fact that both the energy and food sectors use water resources for hydropower production and agricultural production, respectively, shows that these two sectors are interlinked through water resources. An example of inter-sectoral links could be the use of energy for pumping water in irrigation that shows interlinkage between energy and food sectors, or in another example the negative impacts of agricultural activities on water quality, which shows food and water sector interlinkages. This “conceptual foundation” of the concept is then further expanded and complemented by including relevant frameworks with set of indicators that will be used for scenario assessment.

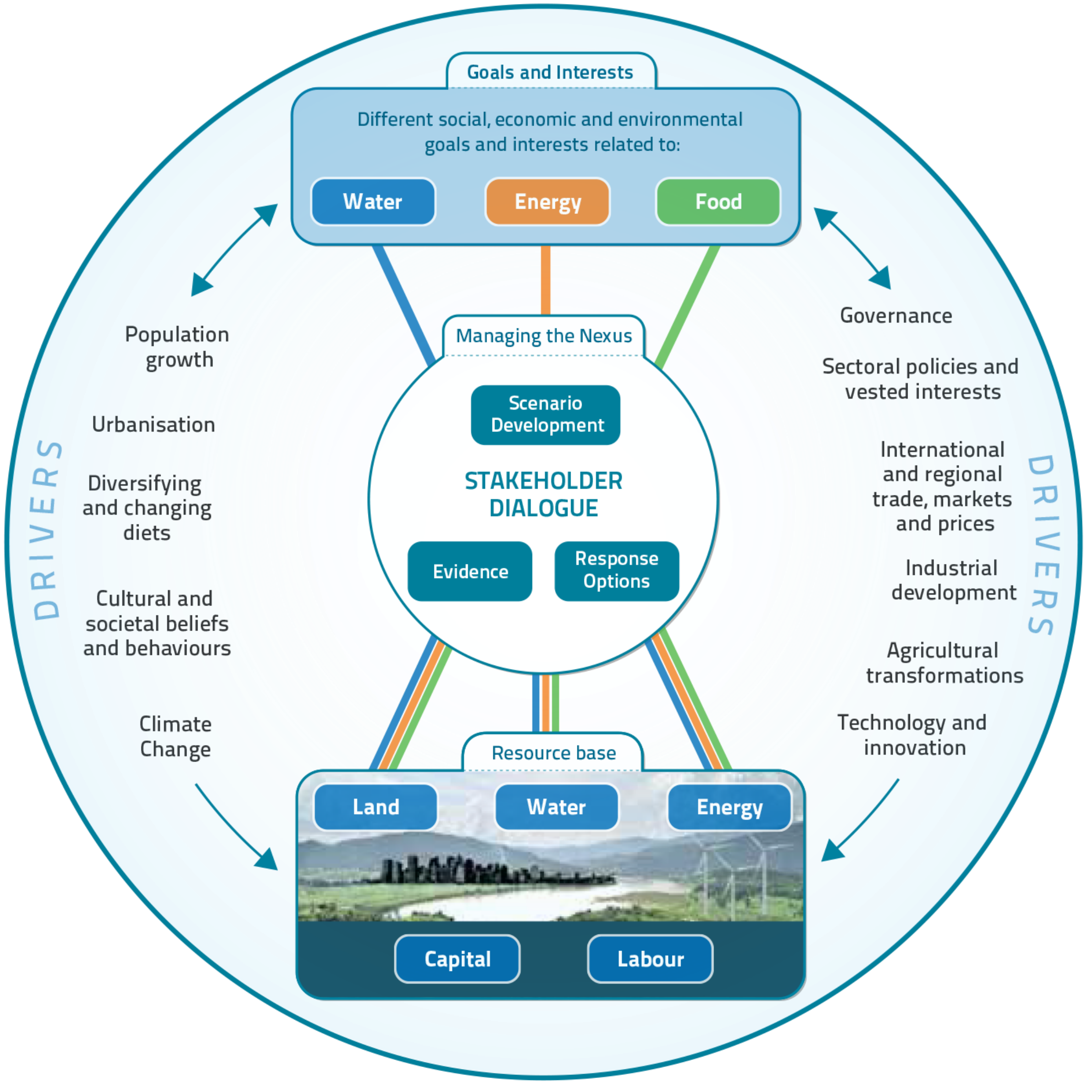

Figure 3.2. Water-Energy-Food Nexus framework (FAO, 2014)

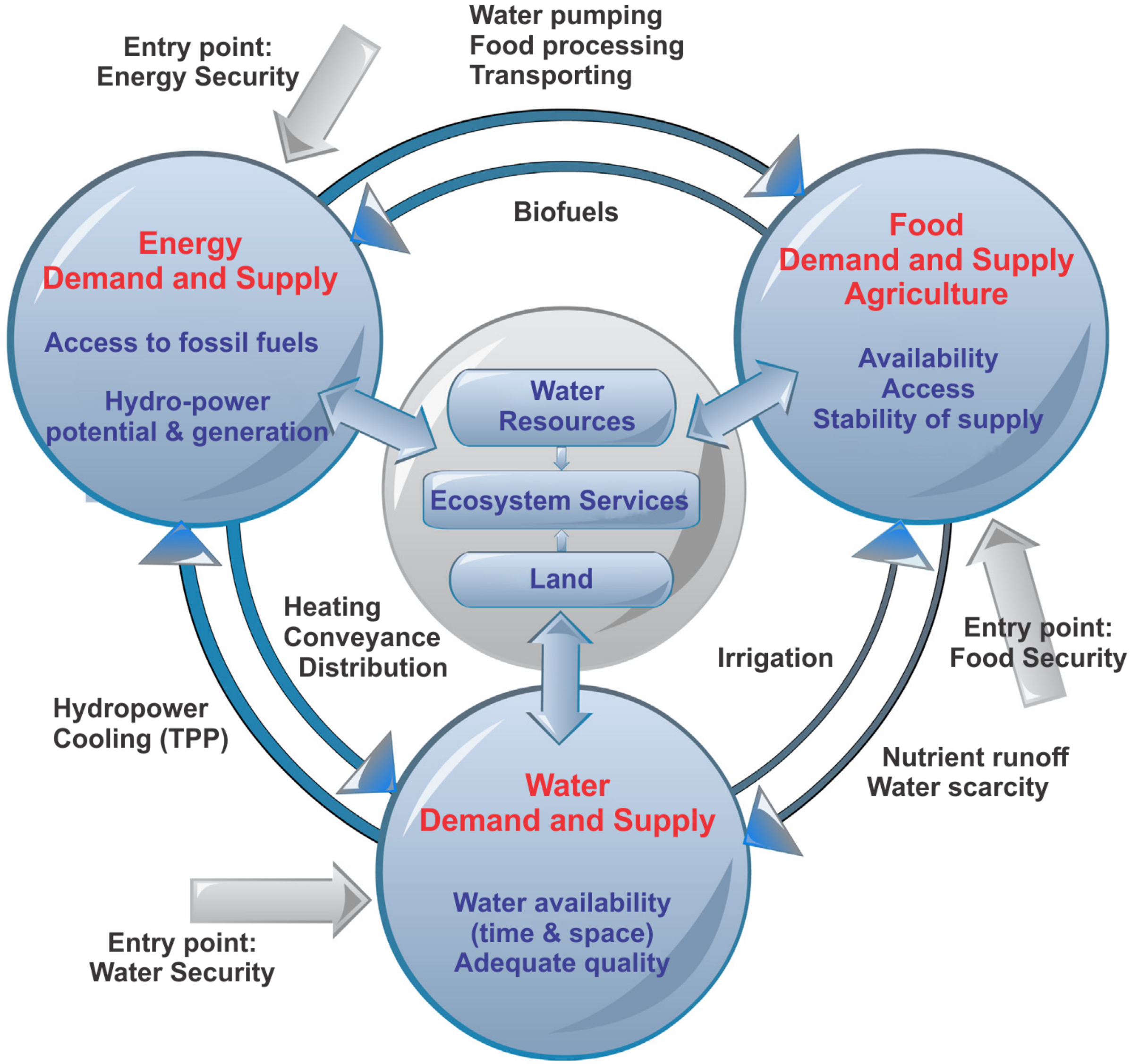

Figure 3.3. WEF Nexus framework adapted from Smajgl et al. (2016).

Water Security Framework

Water security achieved its prominence both in the policy arena and academic research area as an important and separate research discourse (Zeitoun, 2011, Lautze & Mathrithilake, 2012). The UN proposed a common definition of water security in 2013: “The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability”, highlighting both importance of the concept and necessity for its clear definition (UN-Water, 2013). The Water Security Framework developed by Lautze & Mathrithilake (2012) includes five elements, each consisting of set of indicators to calculate the index for quantitative assessment of the water security, and to define the boundaries of their water security concept. Similarly, the water security framework developed by the Asian Development Bank (ADB) presents a set of indicators grouped into five interdependent Key Dimensions (KD), adapted to the specificities of the Asian region (Figure 3.4.). This Asia oriented feature of the framework served as grounds for inclusion of the given approach to extend the water security component in the assessment conceptual framework developed here. Using the most recent available data, the framework was applied to make a snapshot evaluation of the water security condition of the Asian states in 2016. National Water Security Indexes, calculated according to the ADB water security framework, are used as a basis in the assessment of the baseline condition for the riparian states of Amu-Darya River.

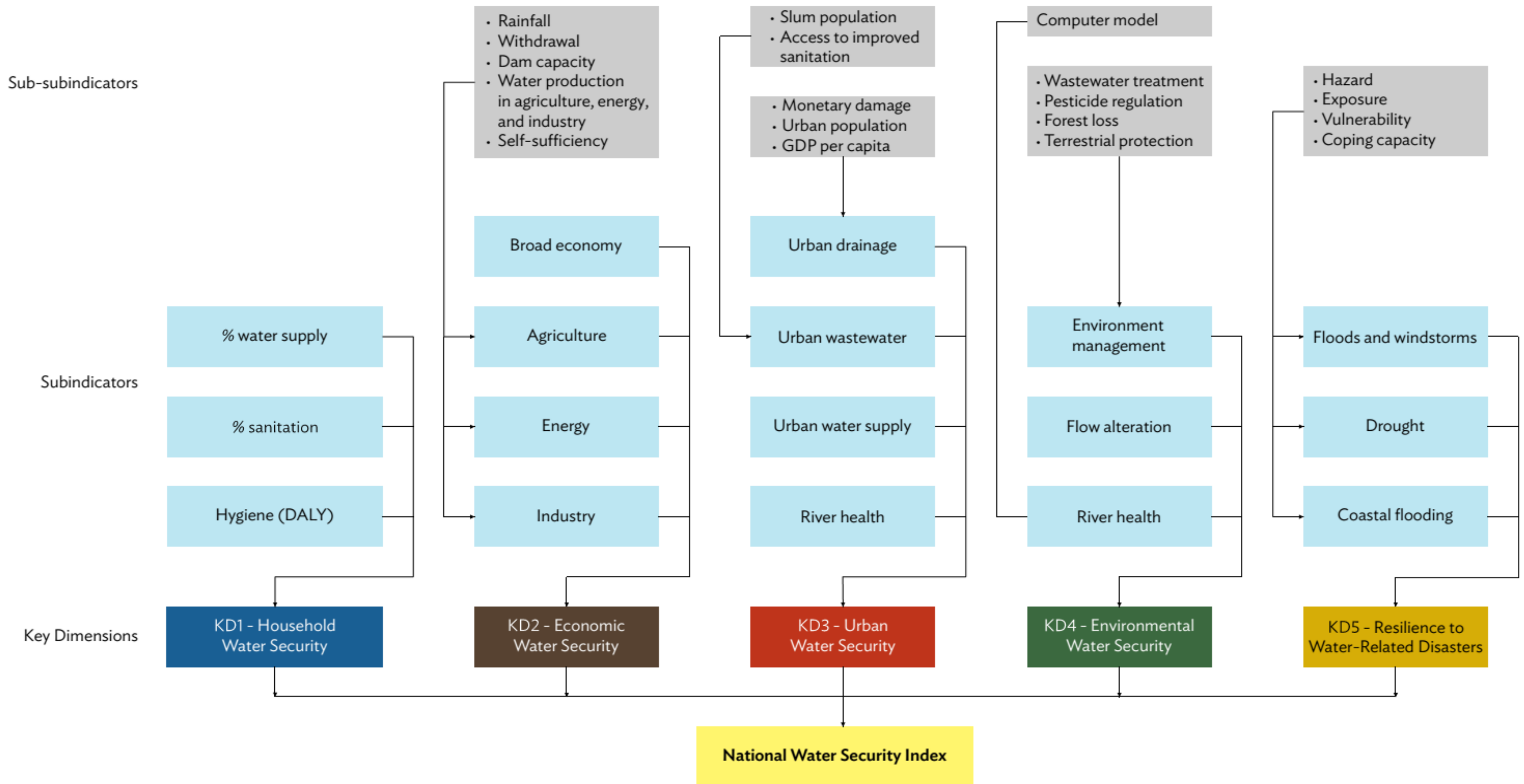

Figure 3.4. Water Security Framework (ADB, 2016) comprised of 5 Key Dimensions (KD)

Energy Security Framework

There are numerous papers proposing diverse conceptual frameworks for energy security with different goals, assumptions, and definitions of energy and energy security (Jewell, 2011). The International Energy Agency (IEA) defines energy security as “the uninterrupted physical availability at a price which is affordable, while respecting environmental concerns”. Their energy security assessment framework – Model of Short-term Energy Security (MOSES) — was built on existing approaches but not aligned strictly with any specific one. It was intended to provide policy insights addressing four dimensions of energy security: external and domestic factors influencing energy resources’ availability and production; energy sources exposure to risks (external and internal), and resilience to those risks (Jewell, 2011). The MOSES framework develops the set of indicators to evaluate the state of individual countries’ energy security with a special focus on oil and oil products and fossil fuels in general (Jewell, 2011).

The GEA (2012) report on energy security (based on the analysis of data from 130 countries), found that every one of the countries is vulnerable to one of the three defined dimensions: robustness (sufficiency of resource, stable and affordable prices), sovereignty (protection from external risks), and resilience (to diverse disruptions) of energy systems (Johansson et al. 2012). Cherp & Jewell (2013) discuss energy systems by grouping the system of connected elements such as different types of primary energy sources (PES), infrastructure, technology, and markets and define geographical and sectoral boundaries to make distinction between these systems. Such framework covering different systems and distinct element groups can be adapted for evaluation of particular energy security based on geographical (country, region) or sectoral (PES types, transmission, supply system) delineation with specific combinations of elements. Based on the developed framework or the definition of energy security, a set of indicators can be defined.

Stucki & Sojamo (2012) examined set of selected indicators to identify the possibility of assessing water and energy security in Central Asia by using qualitative and quantitative indicators and publicly available data. While selection of the indicators allowed them to identify strengths of energy reserves in Central Asian countries and weaknesses in terms of institutional arrangement and governance of the energy security situation in the region, they acknowledge that ranking of indicators could be a challenging task (Stucki & Sojamo 2012). Considering this, and based on existing literature discussed above, a set of indicators aligned with the proposed energy security concepts and the energy security framework was developed for the purpose of this study for the Aral Sea basin (Figure 3.5.). This energy framework is used by the author to make an assessment of the current status of energy security of the states in Amu-Darya river basin.

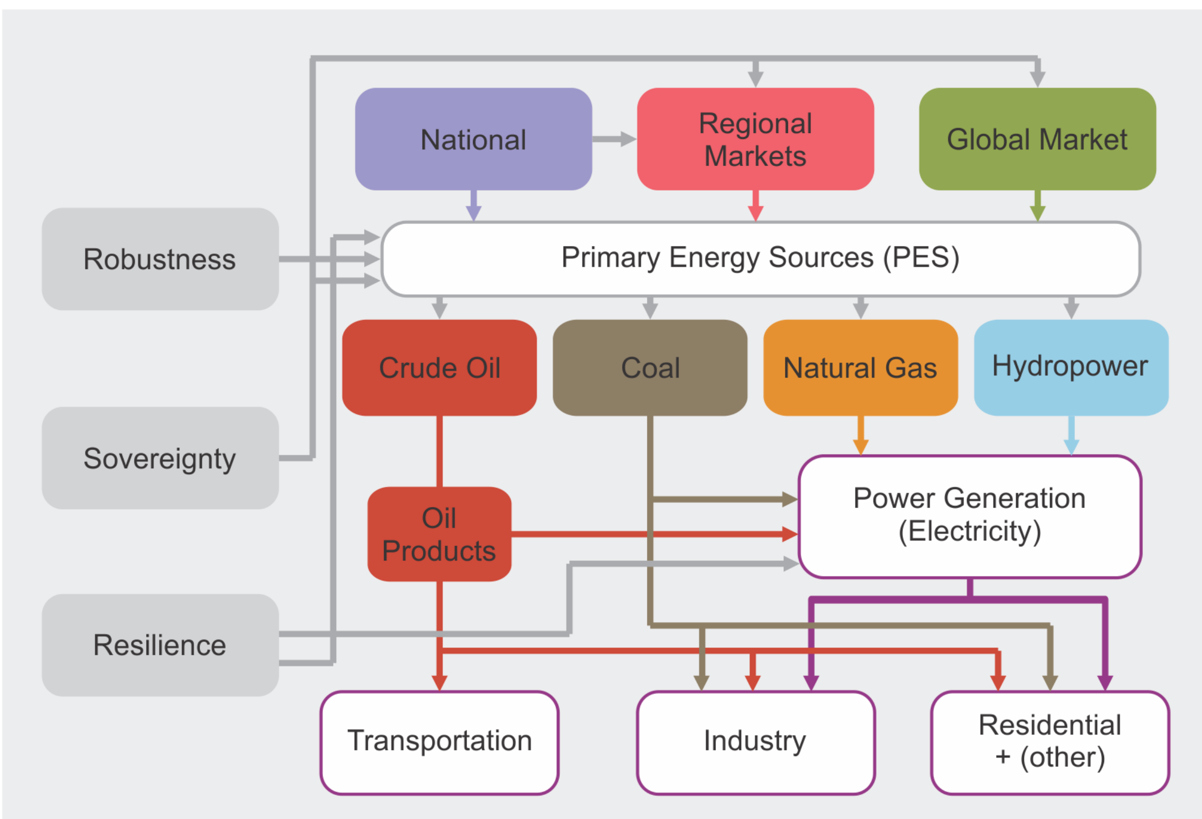

Figure 3.5. Energy security framework adapted from Cherp & Jewell, (2013), Jewell, (2011), GEA, Johansson et al. (2012), IEA/MOSES (Jewell, 2011), Stucki & Sojamo, (2012).

Food Security Framework

Based on the Food and Agriculture Organization's definition of food security introduced at the World Food Summit in 1996, four dimensions of food security are traditionally identified: availability, access, utilization, and stability (FAO, 2008). A framework (Figure 3.6.) built on these four dimensions incorporates physical determinants (first three) and a temporal determinant (the fourth) (Napoli et al. 2011). All four dimensions have a set of indicators. The Availability dimension identifies the presence and amount of food in the country, and includes such indicators as arable land, food production index etc. The Accessibility dimension includes diverse economic social indicators including improved water sources, rural population, GDP per capita etc. The Utilization dimension looks at the demand side, and includes such indicators as quality of food, food storage, and food waste. The Stability dimension highlights the reduction of potential risks that could be exposed through the other three dimensions and evaluates the changeability of conditions for the other three dimensions over time (Napoli et al. 2011).
Napoli et al. 2011 developed a comprehensive food insecurity assessment framework – Food Insecurity Multidimensional Index (FIMI) consisting of set of indicators. The FIMI index shows the current status of food insecurity in a country, taking into consideration four basic principles of food security (Napoli et al. 2011). In contrast with the FAO's latest data available for set of indicators, in the work of Napoli et al. (2011) the indicators were weighted and normalized to calculate an index for every country covered by the research. The framework was used to make an assessment of food security conditions in the countries which exhibited levels of undernourishment of 5% or above in the years 1990-1992, for the time period from 1990 to 2009. The FIMI index is also used to evaluate the current status of food security of states in the Amu-Darya River Basin.

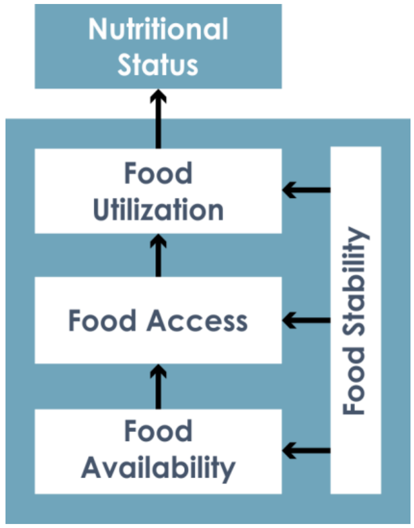

Figure 3.6. Food Security Framework (Napoli et al. 2011, FAO, 2008)

Incorporating political, socio-economic, and environmental dimensions

In order to expand the nexus analysis further and include the role of political, social, and environmental perspectives, several approaches and concepts were explored, including the Integrative Dam Assessment Model (IDAM, Tullos et al. 2010) to reflect these dimensions and extending the nexus analytical framework to make it more comprehensive. While the three frameworks discussed above (water security, energy security, food security) extend the elements of the "conceptual foundation" for these three sectors, incorporation of sustainability assessment through set of indicators grouped under Bio-physical, Socio-economic, and Geo-political aspects complements those WEF frameworks with additional dimensions. Inclusion of these sustainability dimensions into the systematic analysis extends previous research focused on nexus evaluation, where in most cases these dimensions were explored in only a limited way (by mentioning their importance), but were not included in the systematic assessment framework (see Literature Review section under Gaps). Further motivation for inclusion of these three dimensions of sustainability is discussed in the following paragraphs.

A closer look at the set of indicators of each of the security frameworks shows that although the set of indicators of each security framework include indicators to measure some of the political, social or economic aspects, these measurements are not present in all three frameworks. For example, the energy security framework measures the diversity of supply including renewable sources of energy but there is no indicator that highlights the proportion of renewable energy sources in the "energy basket", which together with indicators of greenhouse gas emissions have considerable effect on the environmental dimension of sustainability (which in the case of the current research is identified as a bio-physical dimension). Additionally, of those indicators evaluating some aspects of social, economic, political, or environmental dimensions that are included in security frameworks (for example, in the ADB's National Water Security Index), these dimensions are not easily "seen" because they are not shown as separate "independent" components of the assessment framework.

In contrast to the abovementioned approaches, the current study proposes to include the assessment of social, economic, political, and environmental aspects into the assessment framework that evaluates basin development, and present the results as "independent" indices. These indices consist of sets of indicators and are arranged/grouped under Bio-physical, Socio-economic, and Geo-political dimensions and form the Interdisciplinary Assessment Framework which is an integral part of the Interdisciplinary Nexus Sustainability Assessment Framework developed in this research.

Interdisciplinary Assessment Framework

The Interdisciplinary Assessment Framework is based on three pillars of sustainability and consist of set of indicators to evaluate Bio-physical, Socio-economic, and Geo-political dimensions of basin development. The Interdisciplinary Assessment Framework is meant to make an evaluation of the sustainability of the basin development – construction of infrastructure in a shared river and is adapted from the IDAM framework.

The Integrative Dam Assessment Model (IDAM) – an analytical tool developed by Tullos et al. (2010) is adapted for the purpose of this research to form the Interdisciplinary Assessment Framework by refining the set of indicators which are region specific and can be applied to a broader range of infrastructure, aimed at supply management and demand management (Table 3.1.). Originally, IDAM was developed to assess dam construction cost and benefits using a single analytical model. It evaluates the costs and benefits of dam construction on three sustainability perspectives by using qualitative and quantitative assessments.

A description of impact assessment and the methods used to define the magnitude of impact or benefits of indicators used in the Interdisciplinary Assessment Framework are presented as having positive and negative effects.

Table 3.1. List of sustainability indicators, adapted from Tullos et al. (2010)

Dimension	Effect	Indicator	
		Dam	Piping
Biophysical BP	BP 1 - Water quality and quantity BP 2 - Impact area BP 3 - Natural flow regime BP 4 - Climate change and air quality	Physical, chem, bio Inundation area Water timing CO_2 emission	 irrigating land water timing CO_2 emission
Socioeconomic SE	SE 1 - Local hydropower access SE 2 - Income (farm lands) SE 3 - Health impacts SE 4 - Wealth and macro impacts	Access level Hydropower export Import dependency	Feasibility Ag production Import dependency
Geopolitical GP	GP 1 - Basin population affected GP 2 - Political complexity (more cooperation, less tension) GP 3 - Legal and institutional framework GP 4 - Domestic governance	People moved Cooperation level	HHs benefited Cooperation level

One way of looking at the effects of the infrastructure development and operation could be by dividing the effects into primary (Bio-physical), secondary (Socio-economic), and tertiary (Geo-political). While the primary effect can be seen as direct effect – physically changing the natural systems, the secondary and tertiary effects can be seen as indirect effects changing the human systems or resulting from the physical changes of the nature and its implications for people (Table 3.2.).

Table 3.2. Impact classification of infrastructure development (Mapping of impacts)

Effect	Direct/primary	Indirect/secondary	Indirect/tertiary
Scenario	Bio-physical	Socio-economic	Geo-political
HPP + Piping	More water available More Ag land for reclamation	Food production increase More institutional capacity Development of cooperation/regulation mechanism Cost and benefit sharing dialogue	Less tension across borders Thinking out of the box Thinking beyond water allocation reduced dependency from global markets and "external powers" (geopolitical actors who supply primary resources)

Comprehensive evaluation of the effects of alternative scenarios of infrastructure development and their operational management with the Interdisciplinary Assessment Framework allows the assessment tool to show the positive and negative aspects of the sustainability of specific development scenarios. the development of this Interdisciplinary Assessment Framework as an analytical tool, with inclusion of the political, social and economic, and environmental dimensions, will also contribute to a more comprehensive assessment and potentially improve operationalization of the nexus approach, establishing the links beyond traditional frameworks focusing solely on nexus interlinkages. Putting all the discussed frameworks together produces the extended version of the INSAF framework (Figure 3.7.).

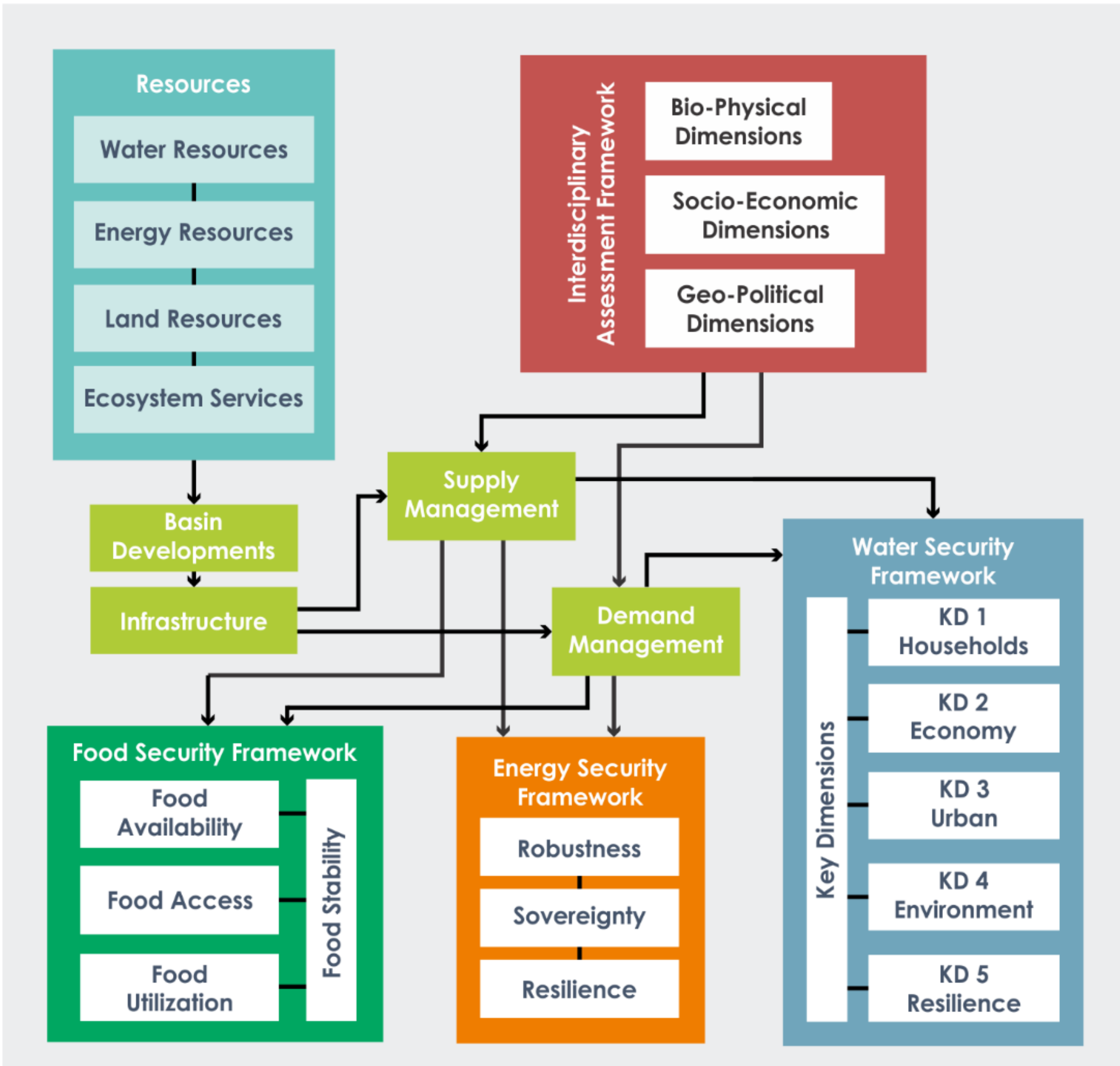

Figure 3.7. Interdisciplinary Nexus Sustainability Assessment Framework, extended version

Adapted from FAO (2014) & Tullos et al. (2010)

As mentioned earlier, WEF security frameworks include some indicators to evaluate political, social, environmental or economic aspects, thus the same events will affect the indicators of the Interdisciplinary Assessment Framework. This allows the building of connections between the frameworks which justifies the relationships among the three securities through Bio-physical, Socio-economic, and Geo-political dimensions, and shows the complexity of these interlinkages (Figure 3.8.). It is also worth mentioning that the frameworks are not meant to be summarized but rather, to show different dimensions of the effects as a results of the different scenarios of basin development. As seen from this figure, energy security has more links with the Geo-political dimension, which could be related for instance to the situation in the Aral Sea Basin, where construction of dams and reservoirs to achieve energy security by upstream countries resulted in tensions in the Geo-political arena due to concerns of downstream countries on water security for agriculture.

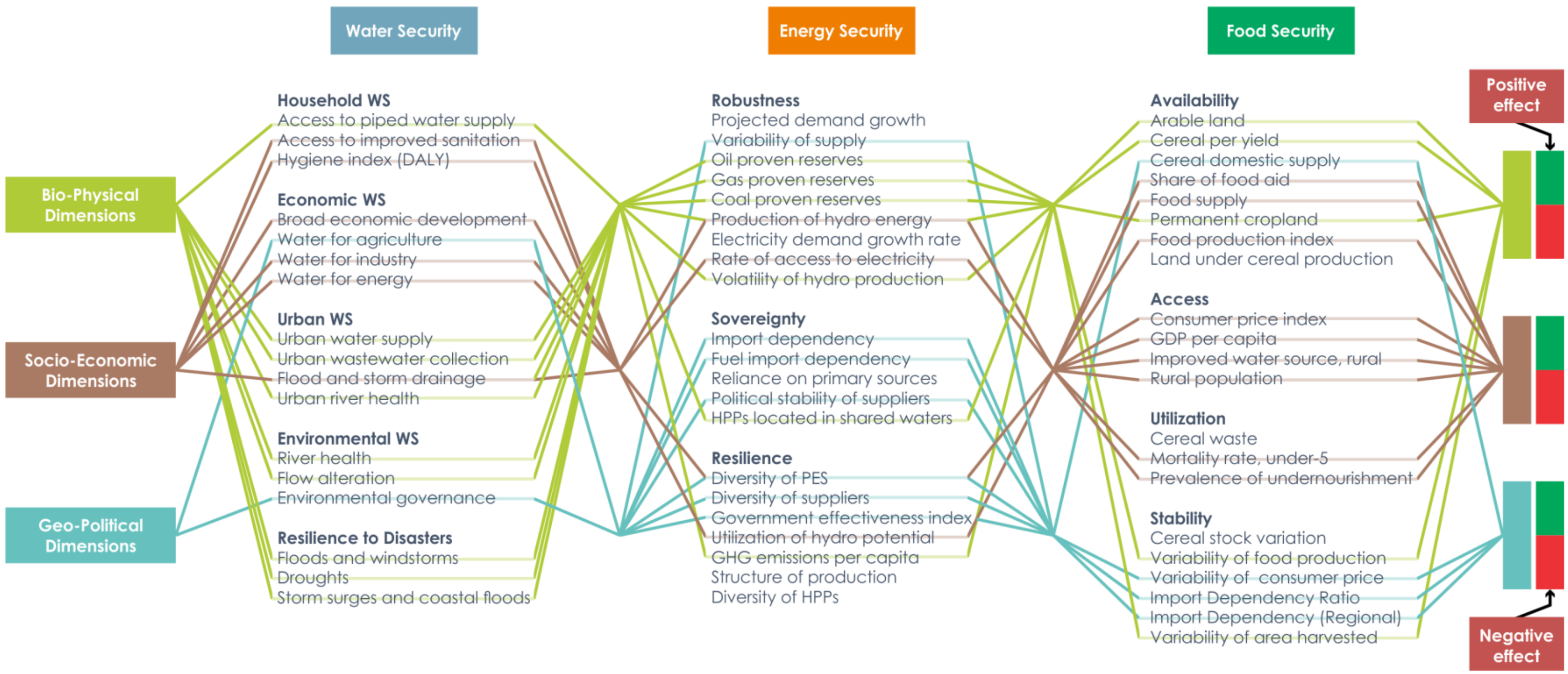

Figure 3.8. Identifying the interconnection between WEF security frameworks and the Interdisciplinary Assessment Framework

Development of the alternative scenarios

Different possible scenarios of Rogun HPP operation were discussed in previously published research (Jalilov et al. 2016; Jalilov et al. 2018; Bekchanov et al. 2015). Here, an additional scenario (No. 4) is proposed to consider the possible future scenarios that could emerge from different infrastructure development, as well as from different operational modes of the constructed Rogun HPP in Tajikistan. The assessment framework is then applied to assess the benefits as well as negative impacts to each country in the Amu Darya Basin. The added value of the current research is to explore how piping of irrigation canals along with construction of the dam could make a difference in the achievement of sustainable WEF security in the basin. Details of the proposed scenarios are described in Table 3.3. and 3.4.

Table 3.3. Main scenario parameters

	Scenario #1	Scenario #2	Scenario #3	Scenario #4
Scenario Theme				
Water allocation	Upstream priority	Downstream priority	Basin optimal	Basin optimal
Infrastructure	Dam only	Dam only	Dam only	Dam + piping of canals
Agricultural production Crops cotton/wheat	Negative effect	Positive effect	Positive effect	Positive effect + increase
Water for agriculture	Limitations in timely supply	Fully aligned supply with ag demand	Balanced	Balanced with additional water availability
Energy production	Enough to meet domestic demand and surplus for export	Limited, increase in variability	Domestic + surplus	Domestic + surplus
Cooperation	Unilateral actions/ limited cooperation	Power balance/limited cooperation/ benefit sharing agreement	Cooperation	Closer cooperation
Time period	After construction	After construction	Dam filling period + After construction	Dam filling period + After construction

Table 3.4. Description of the scenarios

Scenario	**Description**
Scenario No. 1. Upstream energy priority without irrigation piping	Assumptions of this scenario is that development is undertaken with limited or no cooperative action (Business as usual). States continue unilateral actions. Here, upstream Tajikistan's energy priority is secured through altering the operational mode of the Rogun HPP to maximize hydropower production and no piping projects are implemented.
Scenario No. 2. Downstream agricultural priority without piping	Assumptions of this scenario on cooperation are the same as in the previous scenario, with the difference that operation of Rogun HPP is set to maximize agricultural production in downstream Turkmenistan and Uzbekistan. It is worth noting that this scenario would be possible with compensations to upstream Tajikistan for "lost" energy benefits.
Scenario No. 3. Optimized operation without piping of canals	Optimized operation of the Rogun HPP to ensure optimal hydropower production and agricultural production. Cooperation among the states is well established with agreements on water energy sharing in place with downstream purchases of energy during summer time. Modeling of the Vakhsh HPPs cascade is used to optimize operation of Rogun dam based on water needs downstream, according to international norms and regulation (TEAS, Barqi Tojik, 2014).
Scenario No. 4. Optimized operation with piping of canals	Optimized operation of the Rogun HPP to ensure optimal hydropower production and agricultural production. Cooperation among the states is well established with agreements on water energy sharing in place with downstream purchases of energy during summer time plus implementation of piping of irrigation canals. Piping reduces water demands mainly by downstream countries for agricultural needs and with cooperative approach allows to expand harvested area. Piping also "conserves" the water which otherwise would be lost through evaporation and infiltration in canals.

3. STUDY AREA AND CONTEXT

Geographical context

Once the fourth largest inland sea in the world, the Aral Sea shrank to 10% of its 1960 volume (CAWater-Info, 2019) following the extensive irrigation projects which began in the 1960s and doubled the area of agricultural land in the region to about 8 million hectares. This was accomplished by diverting water from the two rivers feeding the Aral Sea to irrigate the Hunger Steppe deserted lands, the Karshi and Kyzylkum deserts (Duknovny, 2003).

The Aral Sea Basin covers the whole territories of current Tajikistan, Turkmenistan, and Uzbekistan, part of the territories of Kazakhstan, Kyrgyzstan, and to a smaller extent, includes portions of Afghanistan and Iran (about 8 percent), and less than 0.1 percent of China (Dukhovny & Sokolov, 2003). The drainage area of Aral Sea is 1.8 million km^2 (Micklin, 2007) and the area of the basin within the territory of the former Soviet republics is 158.5 million hectares (Dukhovny & Sokolov, 2003). About 0.59 million km^2 of this total territory are cultivable lands (CAWater-Info, 2019). Around 90% of Kyrgyzstan and Tajikistan is occupied by mountains, making these countries "water towers" of the region, while more than 50% of the territories of Kazakhstan, Turkmenistan, and Uzbekistan are deserts, and just 10% are mountainous, giving these countries huge potential for irrigation (CAWater-Info, 2019).

Prior to its drastic decline in volume, the surface area of the sea was 68,320 km^2 including 66,090 km^2 of water and 2,230 km^2 area of islands, about 1,066 km^3 in volume, and maximum depth of 69 m (Vinogradov & Langford, 2001). The region has sharply continental arid and semiarid climate regions with average precipitation of 270 mm including 600-800 mm in the mountain areas and 80-150 mm in desert areas (Dukhovny & Sokolov, 2003). Although the region has favorable temperature conditions to grow cotton and other heat-loving crops, the climate is characterized by high evapotranspiration and severely arid conditions (Raskin, et al. 1992). Variation of climate in different zones has its influence in water demands for irrigation due to difference in humidity ranging between 50-60% in old oases (traditionally irrigated areas) and 20-30% in newly irrigated (former deserts) areas (CAWater-Info, 2019).

The two main rivers in the basin are the Amu-Darya and Sir-Darya flowing from south-east to north-west leading to the Aral Sea with mean annual flow of 79.0 billion m^3/year and 37.9 billion m^3/year respectively and 116.9 billion m^3/year combined (Dukhovny & Sokolov, 2015). The Amu-Darya is the largest river in Central Asia in term of flow. Its length is 2540 km with a catchment area of 309,000 km^2. It is formed at the confluence of the Vakhsh and Pyandj Rivers, fed mainly by snowmelt (CAWater-Info, 2019). The Sir-Darya is considered as the longest river in the region.Its length is 3019 km, with catchment area of 219,000 km^2 and it is formed at the confluence point of the Karadarya and Naryn Rivers. Fluctuations of mean annual flows in these two rivers are 58.6-109.9 km^3 for the Amu-Darya and 23.6-51.1 for the Sir-Darya (Dukhovny & Sokolov, 2015). Analysis of hydrographs of Amu-Darya and Sir-Darya for the whole period of flow monitoring revealed the cycles of change in water flow over time: the Amu-Darya has four cycles with a periodicity of 19 years from 1934 to 2011, and the Sir-Darya has seven 12 year cycles (Dukhovny &Sokolov, 2015). Flow formation of the rivers is shown in Table 3.5.

Table 3.5. Surface water resources in the Aral Sea basin (mean annual runoff, km^3/year). (CAWater-Info, 2019)

Countries	River Basin		Total Aral Sea Basin	
	Sir-Darya	Amu-Darya	km^3	%
Kazakhstan	2.516	—	2.516	2.2
Kyrgyzstan	27.542	1.654	29.196	25.2
Tajikistan	1.005	58.732	59.737	51.5
Turkmenistan	—	1.405	1.405	1.2
Uzbekistan	5.562	6.791	12.353	10.6
Afghanistan and Iran	—	10.814	10.814	9.3
Total Aral Sea basin	36.625	79.396	116.021	100

Aral Sea Desiccation and its Consequences

According to instrumental observation which started in 1911 and continued till 1960, the water balance in the Aral Sea during this period was considerably stable (Micklin, 2007). Irrigation that was practiced for centuries did not changed the inflow to the Aral Sea until 1960s when in the period of 1965 to 2000 the growth of agricultural activity grew from around 5 million hectares to 7.9 million hectares, substantially reducing the flow into the sea from the two main rivers (Micklin, 2007). Construction of the ambitious infrastructure in the Soviet period was mainly driven by growing cultivated land for cotton and wheat production in Uzbekistan, Kazakhstan, and Turkmenistan (Pohl et al., 2017). This way, irrigated production of cotton between 1940 to 1986 was increased by 300% in Turkmenistan, 196% in Tajikistan, and 122% in Uzbekistan; increasing by 1986 the area of land just under cotton production to over three million hectares (Vinogradov & Langford, 2001). Water diversion from the rivers increased from 60.6 km^2 in 1960 to 116.271 km^3 in 1990 (Dukhovny & Sokolov, 2003). in the period from 1980 to 1999 mean annual runoff to the sea was at the levels of 3.5 – 7.6 km^3, or 6 to 13% of total runoff

(CAWater-Info, 2019). At this point in time, the Soviet Union was the second largest cotton producer in the world, producing 90% of its cotton in Aral Sea region (Raskin, 1992).

The desiccation of the Aral Sea had several negative environmental, social, economic, and health impacts. One of the indicators of the environmental degradation was the drop in the crop yields (Cai et al., 2003). Negative impacts on fish biodiversity, fishing industries, and navigation in the territories of Kazakhstan and Uzbekistan caused in turn in social and economic adversities to the population of Karakalpakstan in Uzbekistan, Kyzyl Orda in Kazakhstan, Aralks and Muynak (Micklin, 2007). Other negative impacts in different parts of the basin are: increase of the salinity of soils, deforestation of sea shores and tugay forests, windblown dust and chemicals causing serious health issues in the area as far as 100km from the exposed seabed, soil degradation and waterlogging.

Although the environmental trade-offs of mass water diversions became evident to those in scientific circles in the 1970s, it was only in the 1980s when the Soviet Union started to take practical actions on Aral Sea, admitting the problem of Aral Sea desiccation (Micklin, 1991 pp. 68-81). The two regional water management organizations, BVO (Basseynovoe Vodnoe Ob'edinenie – Basin Water Management Organization) Sir-Darya and BVO Amu-Darya were established in 1986 (Vinogradov & Langford, 2001) to introduce management of water resources in their hydrographic boundaries and to establish and maintain regulation mechanism of water allocation imposed by central ministry. Earlier, water resources management according to hydrographic boundaries were established only in some parts of the basin, for example, the Zerafshan, Amu-Darya downstream canals and Kirov major canal (Dukhovny, 2003). During the period of 1982 to 1988 some practical projects and policies on improving the water use efficiency were implemented as well (Micklin, 1991 pp. 18-20).

Water Allocation after Independence

After the collapse of the Soviet Union in 1991, the newly independent states (NIS) felt themselves responsible to deal with the problems of the Aral Sea, and through a number of agreements establishing the organization between five states, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, these NIS put their efforts into cooperative management of water resources in Central Asia (Micklin, 2007). Concurrently, after the collapse of the Soviet Union, countries continued their agricultural extension. After the 1980s, water started to become scarce, and supplies were unable to meet the increasing demand for agriculture (mainly for water-thirsty crops as cotton). Increased demand for water and its inefficient use through aged, improperly maintained infrastructure lead to water allocation tensions between the riparian countries. These tensions were increased by the intentions of the upstream countries to develop their hydropower capacity.

The institutional capacity of the basin was incapable of building strong, lasting agreements to avoid conflict between the countries due to the rapid changes in the basin (Wolf, Yoffe & Giordano, 2003). Dam construction initiatives led to souring relationships and resource-use crisis in the region. Agreement of 1992 signed by all five countries lacked sufficient provisions to tackle the water and energy linkage issue. Later, the agreement of 1998 between Kazakhstan, Kyrgyzstan, and Uzbekistan on water-energy exchange failed to incorporate an effective regulatory framework that could properly consider “free market” conditions and interstate relationships. These governance problems resulted in worsening of relations, leading to loss of trust among countries (Pohl et al., 2017).

Water Management "Rules"

Although a combination of international water law principles, regional agreements, and institutions form today's water resource management arrangement in the basin, water management "rules" in Central Asia date back to ancient times, and historical events of the twentieth century contributed to its current form. The earliest rules for water regulation were formed by following Oriental and later "Muslim water law (shariat)" which included the principles of "zoroastrizm" (videvdat); those legal frameworks included among others, principles of communal ownership, prohibition to pollution, common participation in operation and maintenance (Duknovny, 2003). While there is no possibility to return to the policies of the past, considering current water use patterns and demand, studying those principles might help to improve sustainable water use planning in the Aral Sea basin (McKinney, 1997). Water rules which had remained unchanged for centuries went through a drastic change during the seventy years of Soviet rule, with strict top-down centralized control over water resources (Dukhovny & Sokolov, 2003). Driven mainly by the desire to achieve the USSR's cotton independence, central planners in Moscow enlarged the local small-scale farming units by forming collective farms and diverting water to large distances (McKinney, 1997). Water management during this period was arranged as follows: each republic prepared five-year basin plans conducted by the local water related ministries for Amu-Darya and Sir-Darya that included water use planning for this period. Water allocations were planned by sectors and between republics with eventual submission of the plans to a central ministry (Minvodkhoz) in Moscow for final approval. The last plans from the Soviet era were approved in 1987 and 1982 respectively (McKinney, 2004). The BVOs for Amu-Darya and Sir-Darya, established in 1986, were responsible for implementation of those plans (Dukhovny & Sokolov, 2003).

Agreements and Institutions

Current cooperative management of the Aral Sea basin is based on the agreement that was engaged right after the collapse of the Soviet Union. The Agreement on Cooperation in the Joint Management, Use and Protection of Water Resources of Interstate Sources was signed in 1992 by the governments of all five post-Soviet countries. This agreement established the Interstate Commission for Water Coordination (ICWC) and is an entity that is thought to coordinate the management and allocation of shared waters between five states (Dukhovny & Sokolov, 2003). The newly formed arrangement inherited the principles and structure of interstate water allocation of the Soviet period (McKinney, 2004).

Later in 1993, two other organizations Interstate Council for Aral Sea (ICAS) and International Fund for the Aral Sea (IFAS) were established in the surge of high cooperative spirit between the states (Vinogradov & Langford, 2001). In late 90s, following the reorganization of the earlier established organizations, IFAS in its current form was establishd, merging the functions and roles of former ICAS and IFAS. The relation between the two organizations – ICWC and IFAS remains unclear (Vinogradov & Langford, 2001).

However, the agreement of 1992 and several regulatory legal documents that followed after its signature are only declarative and are not properly followed or enforced, and do not reflect “current nexus relations” (Janusz-Pawletta, 2015). The latest meeting of the heads of the states for IFAS was in 2009 when all countries agrees on the need for the reforming of the organization and including the discussion of the energy needs on water and not only water allocation. However, in light of lack of progress in this direction, Kyrgyzstan announced “freezing” its participation in 2016 (Pohl et al., 2017).

International Law

Currently the Agreement on Cooperation in the Joint Management, Use and Protection of Water Resources of Interstate Sources signed in 1992 is the only legally-binding regulatory document on which all five countries are signatories (Janusz-Pawletta, 2015). Central Asian countries are also members of different international regulatory norms and international laws, a situation that poses special obligations to the management and development of the transboundary water resources (Janusz-Pawletta, 2015). Two widely known conventions are: the UN Convention on the Law of the Non-Navigational Uses of International Watercourses, signed in 1997 that entered into force in 2014 and the Convention on the Protection and Use of Transboundary Waters and International Lakes of 1992 and its Protocol on Water and Health. Uzbekistan is the only country who is signatory to the former and to the latter, the three downstream countries of Central Asia: Kazakhstan, Turkmenistan, and Uzbekistan (Janusz-Pawletta, 2015). These two conventions embody approaches to establish cooperation and mechanisms for dispute resolution between riparian states that can bring more cooperation among the Central Asian states in finding solutions to problems in the basin (Janusz-Pawletta, 2015).

Water for Irrigation and Water for Hydropower

The core reason for the challenges faced by the countries in Central Asia is the disproportionate geographic distribution of natural resources among the countries. Water resources, arable land in the form of large plains suitable for agriculture, and energy resources, are unevenly distributed among the states in the basin. Downstream Kazakhstan, Turkmenistan, and Uzbekistan perform better economically, mainly due to energy exports (fossil fuels: oil, gas, and coal) and large areas of land suitable for irrigated agriculture. On the other hand, most of the water resources on which downstream countries depend originate in the territory of upstream Kyrgyzstan and Tajikistan, but these upstream countries have energy constraints due to lack of fossil fuel deposits and hydropower generation capacity (Pohl et al., 2017). To reach a balance for energy production and agriculture, resources must be managed to provide necessary amounts of water during the growing season and stable hydropower generation when energy is needed most. Timing in dam operations is crucial (Stuki & Sojamo, 2012).

Though a number of reservoirs were constructed in upstream countries in the 20^{th} century, their main purpose was the control of flow for irrigation while hydropower production was the secondary objective (Pohl et al., 2017). As infrastructure development was primarily to serve the irrigation needs, energy needs of upstream countries were met through the provision of alternative sources of energy (coal, gas) mainly from downstream countries. This arrangement was the achievement of a water-energy nexus established and managed by the central government in the Soviet era (Granit et al., 2012). This historical distribution of infrastructure development under the view of whole region as part of single country and geographical reasoning has contributed to building infrastructural interdependencies between the countries (Keskinen et al., 2016)

Driven by the desire to ensure energy security and resolve timing issues, Kyrgyzstan started to alter the operational mode of hydropower plants (HPP) constructed during the Soviet time to increase energy production (Duknovny, 2003) and renewed the plans for constructing increased hydropower capacities for Rogun dam in Tajikistan (Vakhsh river, a tributary to Amu-Darya) and Kambarata (on Naryn river) in Kyrgyzstan (Pohl et al., 2017). In pursuit of solving the continued electricity supply problem in Tajikistan, the country reactivated the construction of the Rogun HPP that was started during the Soviet time in 1976 and abandoned due to the collapse of the latter in 1990 when 80% of the construction works were completed. These developments caused concern in the downstream Uzbekistan. The downstream countries feared loss of capacity for irrigation would result from upstream countries' increasing capacity of flow regulation. Competing uses of water put the countries' different interests in conflicting positions, between the energy needs of Tajikistan and Kyrgyzstan for hydropower and Uzbekistan's irrigation needs (Janusz-Pawletta, 2014; Wegerich, 2008).

Rogun HPP

Rogun dam (the construction of which is currently under way on the Vakhsh River, a tributary to the Amu-Darya), started in 1976 during the Soviet time. With the capacity of 3600 MW, this dam is considered to be the largest HPP in Central Asia. The projected design includes installation of six 600 MW hydro-generators with total capacity of 3600 MW (3.6 GW). Mean annual electricity generation of the Rogun hydro power plant will be 17.0 billion kWh. The dam will be 335m high, that will make it the highest dam in the world. The reservoir behind the dam will be 13.5 km^3 in volume with an operational volume of 10.3 km^3. The surface area behind the dam will be 110.7 km^2. Rogun hydro power station will be a multi-functional infrastructure designed to perform diverse functions, including power generation, water flow regulation, flood risk reduction, and drought mitigation (MEWR.tj).

The design of the Rogun project was prepared by the "SredAzGidroproekt" (Tashkent Institute) in 1968 and construction started in 1976. In December 1987, near the unfinished tunnels, the Vakhsh river was blocked. Even after the collapse of the Soviet Union in 1991, by 1993 the height of the dam had reached 40m and length of the tunnels reached to 21 km.

Construction of the machine room was 70% completed, and the transformer room was 80% completed (Energyprojects.tj). After the flooding in 1993, previous construction was partly destroyed. Construction of the dam is projected to occur in different stages, and the initial capacity will be 400 MW. So far two generators have been installed and launched. The initial generator with capacity of 100 MW was launched in November 2018. The second generator was launched on September 9th , 2019 on the independence anniversary of Tajikistan, and by the end of 2019 the accumulated water behind the dam reached 200 million m^3 (MEWR.tj).

In addition to energy production potential, the Rogun project with its expanded storage capacity may also provide more potential for irrigation downstream, energy production, flood control, and maintain ecosystem services. It could also change water availability downstream, which is linked with its operational mode (Bekchanov et al. 2015).

However, development of the dam was the reason for the increased tensions in the region. Construction and early initiatives of renewing the construction works after the collapse of the Soviet Union was strongly opposed by downstream Uzbekistan due to concerns over water availability for irrigated lands, while during the Soviet period this project was perceived as a positive component to be integrated into the larger framework (Wegerich, 2008).

There were several attempts by the Tajik government to renew the construction of the dam after becoming independent. Given the economic capacity of Tajikistan, financing the construction of the dam was quite challenging, and raising external funds was necessary. A partnership with the Russian Aluminum company (RusAl) eventually was terminated due Tajikistan’s withdrawal from the agreement (Menga & Mirumachi, 2016). In response to Uzbekistan’s continuous request for independent external assessment of the project, in 2010 Government of Tajikistan contracted World Bank to execute two studies (TEAS (Techno-

Economic Assessment Study) and ESIA (Environmental and Social Impact Assessment) (Menga & Mirumachi, 2016). The World Bank accomplished the studies of the Rogun dam in 2014 and results stated that "under normal security conditions a hydroelectric power station can be built" and "will not pose a threat to basin riparians in case of earthquakes or floods" (Menga & Mirumachi, 2016; The World Bank, 2014).

Some of the authors (Jalilov et al. 2018; Stucki & Sojamo, 2012) discussing further development of the new dams by upstream countries also discuss potential construction of Dashtijum dam, which will have a greater hydropower potential of 4000 MW, and greater water storing capacity of 17.60 km^3 (Jalilov et al. 2018). However, development of new hydropower plants will face several constraints, including financial capacity of the upstream countries. There are also security concerns considering the position of the reservoir in the Pyanj river shared by Tajikistan and Afghanistan.

It is important to note that harvesting the potential benefit of exporting energy both for Tajikistan and Kyrgyzstan will require completion of construction of the Central Asia South Asia (CASA 1000) electricity conduit. Based on the cooperation between Kyrgyzstan and Tajikistan as suppliers and Afghanistan and Pakistan and importers, the project includes a total of 1,222 km of connection line from to Kyrgyzstan to Pakistan. (Energyprojects, 2017). Thus, another reason limiting the potential for Dashtijum dam development is the lack of financial resources needed to complete the CASA project to be able to actually transfer the electricity produced to other countries for export. Until the completion of the CASA project, it is difficult to argue in favor of further developments of hydropower projects which produce energy that cannot be transported to other countries or markets.

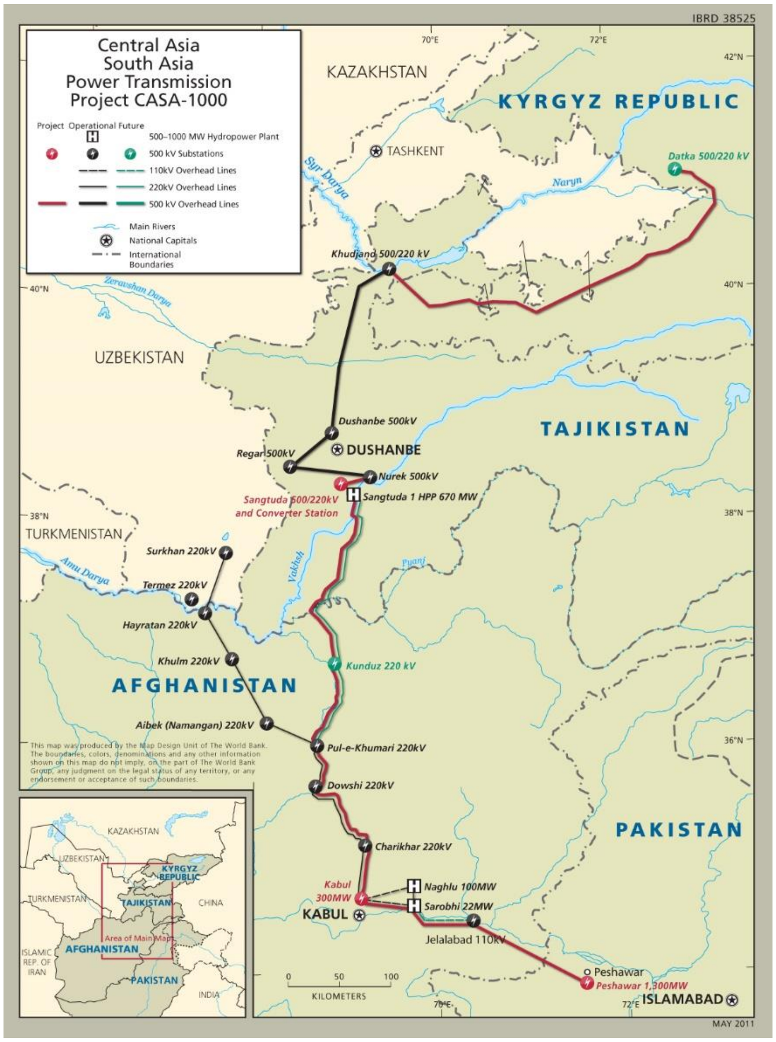

Figure 3.9. CASA 1000 Electricity Transmission System. Source: http://www.casa-1000.org/MainPages/CASAAbout.php#vision

Irrigation Systems of the Aral Sea Basin and Amu-Darya Basin

We hypothesize that managing water demand in the Aral Sea Basin's Amu-Darya River can potentially reduce the water resource management conflict among riparian states and provide additional positive impacts on water, energy, and food security goals achievement. Since more than 90% of water in the basin is used for irrigation purposes, demand management in irrigation water use can result in substantial water consumption reductions leading to an increase in the possibilities of benefit-sharing. The opportunity to consider and expanded “basket of benefits” provides room for maneuvering, and to consider diverse cooperative options based on the nexus approach which could ultimately reduce the level of stress on water allocation among riparian states.

Discussions on improving sustainable irrigation water management in Central Asia trace back to the efforts towards saving the Aral Sea. These discussions included possibilities to manage both supply side and demand side, driven by increasing demand for water due to population growth and the need for food production. Opportunities were made possible by economic and social growth through investing to infrastructure improvement and rehabilitation, water efficiency improvements, changing agricultural practices from growing water thirsty crops, and also after states became independent and shifted to a market economy, introduction of different water pricing mechanisms (Cai, McKinney, & Rosegrant, 2003).

Although previous efforts to enhance irrigation water use efficiency were conducted with the intention to restore the levels of the Aral Sea, at present, restoration of the Aral Sea seems far from reality (Micklin, 2014). A more practical focus concerning the Aral Sea should be on 1) stabilizing the levels of the sea to environmentally adequate conditions; 2) exploring what could be done to minimize the damages to the environment and people’s lives that resulted from the dessication of the Aral Sea; and 3) to implement adaptation efforts to identified and possible future risks that can emerge from outcomes of Aral Sea desiccation. Nowadays, the perspectives of these discussions have changed from the perspective of environmental degradation to the perspective of managing scarce water resources that cause continuous conflicts among riparian states on water allocation. This scarcity is partly the results of extensive increase of irrigated lands during 1960s to 1980s, doubling the extent of agricultural lands to increase the production of cotton in the region. Discussions on reducing water demand during the last years of the Soviet period were likely driven to attract funds (i.e., convince the central government to invest into infrastructure) for rehabilitation from the central budget. However, during the early periods of independence, the economic situation of the newly-independent countries made it impossible for them to provide the resources necessary to implement those plans. As a result, discourse highlighting the problem and raising the alarm concerning the environment decreased after the countries became independent.

Irrigation system development of the Soviet period was different from the historical development in the region, with a newly-imposed centralized management of development (Brite, 2016). Water use efficiency for irrigation was very low during the Soviet period and after its collapse (Dukhovniy, 2003; Micklin, 2007). Business as usual for irrigation practices in Aral Sea will lead not only to worse environmental outcomes, but also worsen economic results (Cai, McKinney & Rosegrant, 2003). Before discussing the potential for water conservation in the Amu-Darya River, the following sections explore the irrigation practices in the basin.

Water Losses and Potential for Water Conservation

While discussing the possibilities to restore the Aral Sea, Micklin (2007) considers several options for water conservation that could be then put back into the stream. Among those, water consumption reduction is seen as the only possibility to substantially increase the flow to the Aral Sea (Micklin, 2007). An estimate from 1988 suggests that the total withdrawals from the two rivers in the basin were equal to 100 km^3, and **35 km^3 were lost** through infiltration in main, inter, and intra-farm distribution networks (Micklin, 1991 pp. 13-20). Uzbekistan and

Turkmenistan have the largest acreage of the irrigated land (54% and 22%, respectively) in the Aral Sea Basin. irrigation of these lands has caused depletion of flow from the region's two major rivers – the Amu-Darya and Sir-Darya (Micklin, 2007).

To contribute to water-saving Uzbekistan has already taken some steps, for example: from 1990 to 1998 the total irrigated area for cotton dropped from 45% to 25% while the area of winter wheat rose to 28% (Dukhovny & Sokolov, 2003). This was the probable reason for the decline in water withdrawal during this period from 109 km^3 to 92 km^3 (a 16% decrease) while the area of irrigated land increased by 10% (Micklin, 2007).

Afghanistan is typically not included in the water allocation discussions and is not part of the agreement existing between post-Soviet states. As a result, its role in water use is not taken into account. However, as soon as Afghanistan enters the phase of peace and reconstruction and its political situation changes, it will increase diversions of water to develop its agriculture, particularly from the Panj river (Spoor & Krutov, 2003).

Irrigation practices in Tajikistan

Average monitored water withdrawal in Tajikistan for the period of 1985-2008 was 10 to 14.5 km^3 (FAO, 2012). As of 2016, the total arable land area in Tajikistan is 730,000 hectares (Aquastat info). Of a total 11.87 km^3 of water withdrawn in 1994, nearly 78% was from surface water resources and 91% of this amount was used for irrigation (FAO, 2012). About 67% (479,000 ha) of the irrigated land is located in the Amu-Darya river basin (FAO, 2012). In 1994, the length of the inter-farm irrigation canal network was 27,991 km, out of which 38% was concrete canals (FAO, 2012). On-farm canals were 5,259 km, 13.3% of which were concrete canals, 21.9% were piped, and the remaining 64.8% flowed through unlined earthen canals (FAO, 2012).

As a result of improved water use practices, and increased efficiency in management and use, Tajikistan was able to reach 20% greater efficiency in water use saving 1.8 km^3 out of the allocated limit of 8.8 km^3 (Rahimov & Kamolidinov, 2014). Further increase of irrigation efficiency and developing new lands will contribute to achieving food security in Tajikistan, which has the lowest index for food security in the region according to FAO.

Water use efficiency and irrigation water distribution network in Turkmenistan

The main source of surface water in Turkmenistan is from Amu-Darya, which accounts for 88% (GEF, UNDP) of the total available water resources for the country. By 2040 (according to climate change projections) the temperature in Turkmenistan will increase by 2°C, and change will accelerate, reaching from 2-3°C to 6-7°C by 2100 (UNDP, GEF). According to Uzbekistan's Hydromet Center, the flow of the Amu-Darya will decrease by 10-15% by 2050 (UNDP, GEF). Total irrigated area in the basin was constantly increasing during the 30 year period at the end of the Soviet era, and tripled (from 1965 to 1994) from 0.5 million hectares to 1.7 million hectares, exceeding 2 million hectares by 2004 (Stanchin & Lerman, 2007). However, according to FAO (2012) data, the cultivated area was estimated at 1,910,000 hectares. During the Soviet era, the cotton-sown area accounted for 50% of the irrigated lands, while 30% was under feed crops (Stanchin & Lerman, 2007). Land area in cotton was reduced to 40% from 50% by early 2000, grain crops were increased from 15% of 1990 to 50% of the total agricultural land (Stanchin & Lerman, 2007). Currently, four main crop types are grown that are supported by the government quotas: wheat (55% of total agricultural land), cotton (35%), sugar beet (1%), rice (also 1%). The remainder is used for growing vegetables, grapes and other fruits and crops (UNDP, 2015).

Mean annual water withdrawal is 26 billion km^3, most of which comes from the Amu-Darya. According to a 1996 agreement between Turkmenistan and Uzbekistan (a supplement to the Agreement of the 1992 between all five countries), water allocation is 50% out of the total flow of 44 $km^{3,}$ or 22 km^3 for each country, subject to change as of actual river flow calculated at the Kerki gauging station (FAO, 2012). Total groundwater reserves are estimated at 3.4 km^3, only 1.3 km^3 of which is reachable. Actual groundwater use is 0.4-0.5 km^3 (Stanchin & Lerman, 2007). The contribution of agriculture to the total national GDP of $20,001 million in 2010 was 12%, while in 2000 it constituted 24% of the GDP (FAO, 2012).

According to Stanchin and Lerman (2007) by 2004 water conveyance losses surpassed 30% and the structure of the water use was as shown in Figure 3.10.

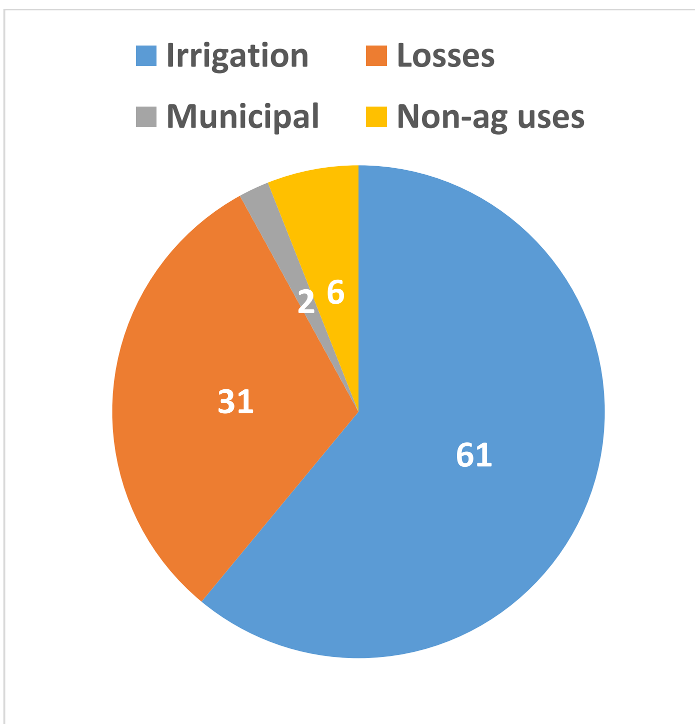

Figure 3.10. Adapted from to Stanchin and Lerman (2007).

The main canal which is used to withdraw water from Amu-Darya is Kara-Kum canal, which was built in 1950s and is 1400 km long. It is the longest irrigation canal in the world. Its capacity is estimated at 630 m^3/s (FAO, 2012), and it is used to irrigate more than 1,200,000 ha of land. Water is brought to the mainly furrow-irrigated farm fields through a system of hierachic canals including main, secondary, tertiary canals, and ditches which are mainly open-air and generally unlined, accounting for losses through evaporation and filtration in the conveyance (Stanchin & Lerman, 2007). Karakum-Canal is classified as large multi-purpose canal; inter-farm canals are those that serve several farm associations and their total length is 8,000 km; on-farm canals are located in the territory of farm associations (500-3000 ha) with a total length of 34,000 km, about 83% of which are earthen canals and account for half of losses due to seepage (MWE, 2002). According to "Giprovodkhoz" of Turkmenistan, about 50% of water withdrawn for irrigation — nearly 12 km^3 — is lost annually between the point of diversion and final delivery to farmers (UNDP, GEF).

The irrigation canal system is served by 3500 pumping stations, with more than 250MW of installed capacity (UNDP, 2015). The water management sector is the second highest energy consuming sector in Turkmenistan, accounting for 25% of the total consumption (UNDP, 2015). Most of the large and small pumps used in the irrigation system are powered by electricity and only about one-third of the small pumps are diesel powered, with production capacity of 0.5m^3/s and pressure less than 10m (FAO, 2012). Most of the diesel pumps (total 1179) are installed in areas that are not connected to electricity grid mainly in Dashoguz velayat , consuming 15 million liters of fuel annually (UNDP, 2015). The irrigation and water sector is responsible for nearly 6.9 Mt CO_2/year or 27% of total national greenhouse gas (GHG) (CO_2) emissions, and 11% of emissions linked with energy sector (UNDP, 2015).

Water is delivered with no charge, but high penalties are incurred if the limits are exceeded (UNDP, 2015). Official allocations of water are defined by the types of soil. For heavy loamy soils defined as 6700 m^3/ha for cotton, 4500 m^3/ha for winter wheat, and 29,000 m^3/ha for rice (UNDP, 2015). According to official data of 2004, 3,940 m^3/ha of water were used to irrigate wheat and 7,040 m^3/ha for cotton, while agronomic norms suggest 6,400 m^3/ha and 11,000 m^3/ha, respectively for each crop type (Stanchin & Lerman, 2007). About 70% of the soils in Turkmenistan are considered salinized and 11% are considered highly salinized; at a national scale, salinization has resulted in a 25% reduction of productivity (UNDP, 2015).

In efforts to improve irrigation efficiency, an Israeli drip irrigation pilot project was implemented for 6,000 ha land near Ashgabat with a cost of $2,250/ha, resulting in expected 30 to 50% water use reduction (Stanchin & Lerman, 2007). For the period of 2015 to 2021 the project is being implemented with financial contributions of UNDP ($100 000), GEF ($6,185,000), and Turkmenistan’s Water Resources Ministry ($72,000,000) for the improvement of the water resource sector (UNDP, 2015).

Irrigation practices in Uzbekistan

After the collapse of the Soviet Union, the government of Uzbekistan maintained some aspects of central management linked to cotton production and pricing. In the mid-1990s the country was the fourth largest producer and third largest exporter of cotton in the world (FAO, 2012). As a result of the change in state policy driven by the desire to enhance national food security, wheat production was increased from 1 million tons per year in 1991 to 5.2 million in 2004. During the Soviet period Uzbekistan was dependent on imports of 3-4 tons of wheat from other Soviet republics (Abdullaev et al. 2009). Furrow irrigation techniques were employed on 67% of the area equipped for full control irrigation (a total of 4,280,510 ha in 1994) (FAO, 2012 UZB).

In 2005, of total cultivated land of 4.2 million hectares in Uzbekistan, 89% were irrigated lands (FAO, 2012). Agricultural irrigation in Uzbekistan is based on the system of pumps and canals. For example, the Karshi pumping system pumps 350 m^3 of water from Amu-Darya to the height of 170m; Amu-Bukhara pumps 270 m^3 of water 57m above the river (FAO, 2012). ON most cropland, furrow irrigation is practiced (67.9%). Sprinkler irrigation was introduced in the early 1990s with 5000 ha irrigated land (FAO, 2012). The total length of the irrigation system is about 196 000 km with an inter-farm network of 28 000 km, 33% of which is lined, and an on-farm network of 168 000 km where most (79%) consist of unlined earthen canals, 19% are concrete canals and 2% are piped (FAO, 2012). Because of the frequent frosts during September and April, it is only possible to grow a crop once a year (FAO, 2012).

The estimated agricultural extent in 2016 for Uzbekistan was a total cultivated area of 4770 thousand hectares (Aquastat database). Out of this, a total irrigated area of nearly 56% is located in the Amu-Darya basin (FAO, 2012). Currently, the main crops grown in Uzbekistan are cotton and wheat. However, water use practices are still a major concern for management of water resources, as in all Central Asian countries who rely on infrastructure built during the Soviet time.

In the early 1980s, the efficiency of the irrigation water delivery network was estimated to be 60% in the Aral Sea Basin and 52% to 60% in Uzbek Republic indicating that 40% of the water withdrawn was lost before it reached the field (Micklin, 1991 pp. 13-20). Based on this estimate, from 121 km^3 of water withdrawn, conveyance losses were equal to over 50 km^3. At the same time some amount of the water withdrawn was returned to the river as return flows (25%)

(Micklin, 1991 pp. 13-20). Average efficiency of the irrigation network in 1994 as calculated from the point of withdrawal to the irrigated field was 63% (FAO, 2012).

In 1980s 120km^3 of water was withdrawn and conveyance efficiency were 60%, 25% efficiency improvement to 80% could allowed to withdraw 90km^3 which is 30km^3 less (25%) (Micklin, 1991 pp. 13-20). Some improvements were made during Soviet period to enhance canals' efficiency to bring withdrawals from 24,000m^3/ha of late 1970s-early 1980s to 13,700m^3/ha in late 1980s and further developments were targeted to bringing the withdrawals down to 8,000 m^3/ha, meaning 62 km^3 water was needed to irrigate 7.8 million hectares; irrigated land is currently estimated at 8.2 million hectares (Micklin, 2014)) (Micklin, 1991 pp. 13-20). Total irrigated area in the region was 7.6 million ha, and 4.3 million hectares are located in the Amu-Darya basin (Raskin et al. 1992).

According to Micklin (1991 pp. 13-20) Dukhovny's prognosis for the possibility of reducing average annual withdrawal to 8,000 m^3/ha would rise "productive efficiency" to 65%, which would have been achieved through reducing losses by: 1) water delivery and distribution network (main, inter-farm, intra-farm canals) (34% of savings), 2) at fields (21% of savings), 3) salt flushing water use reduction (30% of savings) 4) evaporation and transpiration (15% of savings) (Micklin, 1991 pp. 13-20). As seen from Dukhovny's estimation, canal piping could be utilized to reduce both delivery losses and evaporation and infiltration (not clarified whether in the field or through conveyance), bringing reduction from 34% to about 50%. Taking the estimation of late 1980s of 13,700 m^3/ha and reduction to 8,000 m^3 /ha, irrigating 4.3 million hectares of irrigated land in Amu-Darya basin will result in an annual reduction of 24.5 km^3 of losses, 34% and 50% of which (8.33 km^3 and 12.25, respectively) will potentially be realized through piping of the canals.

However, according to latest estimates, in order to irrigate 3.2 million hectares of the irrigated land in Uzbekistan, 46 km^3 of water is withdrawn.   This is an efficiency of just 60% (author's estimation), constituting 14,375 m^3/ha (REGNUM, 2019). Out of the irrigation canals, about 23% are concrete canals which haven't been properly maintained and repaired for 30-35 years (Table 3.6.).As a summary of the chapter above it could be concluded that there is sufficient evidence to justify the assumption that there is a potential for water conservation through implementation of demand strategies across the countries of the basin.

Table 3.6. Water withdrawal and irrigation network efficiency. Sources: Micklin (1991 pp.13-20), REGNUM (2019), CA Water Info.

Year	**1960-65**	**1976-1980**	**1980s**	**1986**	**By 1990**	**Dukhovny's prognosis**	**1995**	**2019**
Water withdrawal m^3/ha	18,700 (Amu) 17,088 (ASB)	24,500 (Amu) 19,283 (ASB)	16,700 (ASB) 23,216 (Kara-kum)	13,700 (ASB)	11,000 (ASB)	8,000 (ASB)	13,000 (CA Water info)	14,375 (UZB) (REGNUM)
Productive use of withdrawn water	51% *	41% *	39%	N/A	59%	65%	N/A	N/A

*Productive use of irrigation water

Water Demand Management

Some water management infrastructures need to be pushed for implementation, while others face opposition to their development. Water demand management projects such as canal piping projects relate to the former, and dam construction relate to the latter. To minimize the tensions and conflict that emerges from opposed infrastructure, and maximize the benefits that can be realized through the demand managing ones, water management projects should be designed more comprehensively, with supply and demand management occurring together in combination. Infrastructure that was built 60 years ago with different vision and driven by different needs cannot be expected to meet the requirements and standards of contemporary needs. There is a need for investment for infrastructure development with a new vision that incorporates the current knowledge and does not compromise the needs of the future, including the needs of the environment.

Some reasons that changes to water management practices of the past are needed include the fact that: 1) environmental externalities were neglected 2) water use efficiency was not the priority 3) operation and maintenance expenses were thought not to be covered by the system itself but from the central budget funds, due to significance of cotton as a resource (raw material) to the nations' economy. Thus, the irrigation systems that were developed over the past seventy years in Central Asia were economically inefficient.

Along with managing supply, which was the priority during the first half of twentieth century, demand management considering overall scarcity of the resources became important. There are several ways to manage water demand, including water pricing regulation, market mechanisms, policy mechanisms and infrastructure rehabilitation, introduction of new water use efficiency technologies, introducing innovating agriculture and irrigation methods, even genetically modified crops to able to survive draughts and water scarcity resistant crops. Considering the proportion of water used for irrigation (90% of overall water consumption), conservation programs have great potential to conserve water from irrigation water use.

A review of the literature related to irrigation water management in the Aral Sea Basin, including water demand management for the region, reveals some proposals in the past. Raskin et al. (1992) discuss three possible adjustments for water demand management: 1) distribution losses – the amount of water delivered to the field but not used and lost due to evaporation and deep percolation; 2) recycling or reuse – using water in more than one application before discharge; 3) transmission loss – evaporation and infiltration losses in canals and conduits carrying the water. Cai, McKinney & Rosegrant (2003) discuss the possibilities to improve irrigation practices by introducing salt discharge penalties, crop changes, and annual infrastructure improvement investments. The recent estimates and researches also indicate and propose the potential for water conservation. Reconstruction of the irrigation in **6 million hectares could likely save 12 km^2** of water per year and cost $16 billion (estimates of early 2000s) and the maximum potential savings of 28 km^2 could be reached by implementing other techniques (for example, so called Israeli model) and will cost more (Micklin, 2007). However, there will be a need to make an economic assessment of the rationale for spending funds on old system restoration, which is often more expensive than building new ones (Micklin, 1991 p. 45).

Water Conservation

The fact that during the period of 1990 to 2010 irrigated land increased from 7.9 million ha to 8.2 million ha (Micklin, 2014, CAWater-Info, 2019) indicates that there is an increasing demand for agricultural expansion due to population growth and food security achievement goals and this trend tends to be continued. Keeping up with these dynamics requires more sustainable irrigation options, thus a vision of future infrastructure development should consider resource optimization and efficiency improvements. A key lesson emerging from the data collected from different sources is that a considerable amount of water could be saved by reducing the losses in conveyance through the aged, inefficient canals (Micklin, 2007). One of the options to reducing the water losses due to evaporation and filtration is water conservation measures. Water conservation programs basically include improving the technology or method of water conveyance such as piping and lining of the irrigation canals and are differentiated from water efficiency programs that involve on-farm improvement of water use and installation of water-efficiency technology on-field. Considering the satiation of irrigation systems in the Aral Sea Basin, lining and piping of the irrigation canals holds great promise for reducing water losses.

Piping of Irrigation Canals

Disadvantages of the canals and the ways of the losses from the canals are evaporation, infiltration, long time for the water it takes to travel from one point into another because of two reasons: 1) the elevation of the area doesn't allow efficient gravity flow for the stream in the canal 2) levelling of the canals, because of the sedimentation which is brought along with the stream and collected as sediment in parts of the canal it changes the level of the canal and hinders the flow of water by creating additional obstructions. In some of the parts of the canals losses are counted for 30 to 70% (GEF).

Some of the mainline canals have large volume of water flow such as Karakum canal in Turkmenistan with capacity of 600m^3/s, where piping or lining could not be an option. Thus, for the canals of high capacity, concrete lining would be a better option. However, life expectancy of the service of the different approaches are different. While lining of the canals might be less expensive than putting the pipes, in the long run their benefits may be higher. For some of the parts of the irrigated agriculture systems the piping could be irrational at all, because of inefficiency of water use and the low yield rates of the soil.

Considering the significant funds to be invested and some other factors piping all of the canals poses to be a challenging task. Piping of the canals could be driven or limited by different factors:

- financial rationale,
- volume of the canals,
- amount of water that could be conserved.

Identified sections of the irrigation water delivery network that has highest ratio of losses could be piped initially. Prioritization of the piping of the canals could be made according to the improving efficiency rate. For example, if the conveyance efficiency could be raised up to 0% loss from the canals of 30% efficiency resulting in 70% efficiency enhancement then this canal could be given priority to the one with 10% or 30% efficiency enhancement potential. Another indicator for prioritization could be the rates of losses due to evaporation and (in)filtration. In the areas of flat relief water evaporation is high due to longer time it takes for water to come to one point from another. If stays at one place for long time losses for evaporation higher. Evaporation has significant influence at the areas where the elevation is not sufficient and it takes the water longer time to flow a distance reaching from the point of the diversion to the farm field. In such conditions there will be more losses for infiltration and more losses due to evaporation in distribution canals.

Piping projects provide multiple of benefits on top of the direct benefits that is additional amount of conserved water. Allowing the possibility of the introduction of the new irrigation efficiency technologies. There will be easier possibility of introducing new irrigation technologies in the farm since the water in the pipes will be pressurized, sprinkler irrigation may be introduced without additional costs for the farmers to on-farm pumping installations.

Since there will be more water available as a result of piping of the irrigation canals there will be less resistance to review the current limits of water allocation. And eventually its potential to reduce the water allocation conflict between states. The idea proposed in this paper is considering the future infrastructure developments in both supply and demand perspectives has a potential to contribute for achievements in this direction. The studies on water conservation and irrigation canal piping program in the Columbia River Basin in the United States can serve as an example of successful practices.

Water balance and significant effect on groundwater recharge.

Of course, there may be limitations of a demand-based approach. Canal piping effects on the recharge of the aquifers/ground water of the region and basin should be taken into account as one of the potential negative outcomes and addressed properly. Historically the extension of the irrigation system was done in areas where there was no agricultural activity and settlement. Thus, any aquifer recharge occurring at present isrelatively new for the basin. Water uses that depend on ground water can also be converted from piping of ground water to use of piped water of the canal.

A water balance approach can be employed to assess the effects of piping on groundwater recharge and some measures could be taken to minimize any negative effects.

For example, in the Deschutes River Basin, a tributary to Columbia River, about 5% of the conserved water from the piping is reserved to mitigate the negative effect to groundwater recharge (Aylward et al. 2012). In the Deschutes River Basin, irrigation canals have been in existence for about 100 to 150 years, while in the Aral Sea Basin they are 50 to 60 years old.

Canal piping programs in Columbia River Basin

In the western United States driven by flow restoration, canal piping projects were implemented since the 1990s under the general framework of water conservation programs. Choices for land use by adoption of water conservation practices were promoted for improvement of agricultural performance supported by policy making and conducting sustainability and economic analyses (Santelmann et al. 2001). Water conservation programs include canal lining and piping. Distinction should be made among water conservation and water efficiency programs. Water efficiency programs are seen as on-field, farm-based irrigation practices that include introduction of dripping irrigation, sprinklers, pivot irrigation and other irrigation efficiency technologies. While water conservation programs are mainly based on improvement of the water conveyance infrastructure to minimize losses due to seepage, evaporation, and infiltration during water diversions. Both water conservation and water efficiency programs are seen under the water demand management side.

Water scarcity due to population growth, surge in allocation of additional amount of water for environment, losses due to aged infrastructure for irrigated agriculture, and climate change induced impacts on precipitation and water availability were and are still the main drivers putting pressure on water governance in the Columbia River Basin. Considering current scarcity issues and future increase in water demand, water management community proposed and implemented several measures including water transfers, water leasing, and water conservation programs. Realization of water conservation programs were partly made possible due to the water law system of the Western United States with its prior appropriation doctrine.

Piping projects implemented in the Columbia River Basin were funded by different sources including local funds, state funds, and federal funds. Federal and state funds were made available through different environment protection and rehabilitation programs. Depending on the funding structure of the projects, conserved water allocated proportionately to in-stream and out-of-stream uses. For example, if 50% of the funds came from the Federal funds half of the conserved water would be left for instream use and the other half allocated to other beneficial uses.

Among the many “making water available for stream” approaches, water conservation through piping of irrigation canals, substantially contributed in achieving flow restoration targets in the Western United States and Columbia River Basin (Kendy et al., 2018). Compared with other measures like market based approaches that involve payments for “not to use water” and leaving it instream, piping of the canals provide both environmental and economic benefits, as its focus is two dimensional providing both water for instream and out-of-stream beneficial uses. Along with benefits however, some concerns arise such as the influence of piping to the ecosystem surrounding the irrigation canals and changes in hydrological cycle locally, thus the area where piping projects were implemented could be monitored to track the impacts to ground water recharge over time. (Deschutes Water Conservancy, 2012).

Water conservation program is responsible for the bigger portion of any other strategies that were used for flow restoration, although it is more expensive than instream water transitions and leases (Aylward, 2008; Kendy et al. 2018). As a result, the degree of tensions grounded at water scarcity issues between riparian water users – Irrigation Districts – bulk water users unifying water right holders were reduced and cooperative attitude to water resources management established.

Financing

Discussions of infrastructure development couldn't avoid the financial part of the topic. Lack of financial resources is probably the main excuse for under-improvement of the irrigation systems. However, there funds that are spent for development and rehabilitation from the internal funds and with support of the international donors and IFIs. Some active actors include Asian Development Bank, Islamic Development Bank who provided several loans for improvement of the irrigation systems. States also invested in the improvement of irrigation systems from the central budget, for example in Uzbekistan during 2014-2017 of about $1.5 billion were spent for improvements in irrigation sector. Though piping of the canals require considerable investment initially, afterwards there will be less costs for maintenance as it required for the canals currently.

Direct benefits from the piping of the canals is conserved water that could be allocated in multiple ways that will also depend where the funding is coming from (donors demand environmental protection and restoration, states to allocate water for economic benefit). If it is the international funding attracted through the green bonds water may be allocated to the Aral Sea. If the funding comes from the relevant government of the state it can be allocated for the crops of high value and restoration of the degraded soils that can potentially bring more economic benefits. Another option is storing the conserved water in the new storage capacities built in upstream countries with the possibility of using the conserved and stored water during the dry years. Another "optimal" solution could be distributing water to all three needs upon the agreement of the countries and getting access to green or climate bonds and international private and donor financing.

To be able to conduct the assessment of exact estimates of potential water conservation, both in terms of technical data and financial calculations, detailed data on the lengths of the canals, evaporation, filtration of each sections or at least separate network systems need to be collected. Due to the lack of detailed research of this technical issue some assumptions are made based on the available data to conduct evaluation of the scenarios developed in this research.

Conclusion and caveat of the section

Analysis of the current agricultural water use practices and irrigation systems in the countries of Central Asia shows that challenges already exist in the sector, independent of the regulation of the operation of the dams in upstream Tajikistan. Rather, these challenges are linked with the existing aging irrigation system and poor water use management. In contrast to fears and concerns over the negative impacts of hydropower development, there can also be benefits to agriculture. According to Bekchanov et al. (2015), construction of new storage capacity could protect the downstream agriculture sector in the dry years when annual flow can drop to as low as 80% of mean multiyear annual flow. A more cooperative attitude among the riparian states and establishment of favorable interexchange among the water, energy, and food sectors might make this arrangement possible. Further, exploration of the scenarios in the following sections shows multiple benefits to nexus sectors and beyond by assessing potential socio-economic, environmental, and political implications of the considered scenarios. Consideration of the supply management and demand management infrastructure development also explores the potential minimization of basin-wide inequities and potential for resource optimization.

It is obvious that the building of infrastructure alone cannot solve the whole problem. The infrastructure projects need to be accompanied by relevant legislation and policy reforms and change of attitude towards the traditional irrigation practices and value of water. Technological innovations can help inspire such reforms, but are not a replacement for them.

4. RESULTS

This section presents the results of application of the INSAF framework developed in this research to identify status and condition of water, energy, and food securities in the Amu-Darya basin. The starting point for the analysis is assumed to be the set of conditions prior to construction of the Rogun HPP and piping of irrigation canals, and serves as a baseline for comparison with four proposed scenarios. The section of the INSAF framework that is intended to assess scenario sustainability along Bio-physical, Socio-economic, and Geo-political dimensions – Interdisciplinary Assessment Framework (IAF) is applied only to the alternative scenarios, to evaluate positive and negative effects of the infrastructure development in the basin. The INSAF Framework evaluates the directions of changes that might be incurred by infrastructure development, namely construction and different operational regimes of the Rogun HPP, and piping of irrigation canals. The changes in status and condition are evaluated through assessment of potential achievement vectors (positive or negative). Different operational modes of the reservoir and several options of infrastructure combination are presented through the development of the future scenarios.

Results are presented in the following sequence:

1) development of the four scenarios
2) assessment of current status of water, energy, and food security in the basin – baseline condition (application of WEF security framework)

3) evaluation of potential achievement vectors of water, energy, and food security for each country in the basin according to the four different scenarios (application of WEF security framework)
4) assessment of positive and negative effects to Bio-physical, Socio-economic, and Geo-political dimensions of sustainability (application of Interdisciplinary Assessment Framework)

Steps 3 and 4 together represent the application of the INSAF framework.

Scenarios

Four proposed scenarios are developed based on the assumptions of different operational modes of the Rogun HPP after its construction in Tajikistan and piping of irrigation canals in three countries of the basin: Tajikistan, Turkmenistan, and Uzbekistan. Based on the changes that are expected to result from the different scenarios, potential achievements for water, energy, and food security for each riparian states and positive and negative effects on sustainability of the basin as whole are evaluated. Comparison of alternative scenarios allows us to identify and evaluate positive and negative economic and ecological effects relative to current conditions, of potential future changes (Santelmann, 2001). Scenarios for Central Asia discussed in previously published works (Jalilov et al. 2018; Jalilov et al. 2018; Bekchanov et al. 2015) served as a basis for the development of the four scenarios in this research. The primary contribution of the current research compared to previous works is to explore a scenario which include demand management options for the basin, for example piping of irrigation canals (Scenario 4).

Four scenarios are proposed:

1) Rogun HPP constructed and its operational regime set to energy priority, to maximize hydro-energy production in upstream Tajikistan;

2) Rogun HPP constructed and its operation set to prioritize agricultural production in downstream Turkmenistan and Uzbekistan;

3) Rogun HPP constructed and its operational regime set to maximize the benefits for all the countries and ecosystem health in the basin;

4) Rogun HPP constructed and piping of irrigation canals implemented. Operational regime of the Rogun HPP set to maximize the benefits for all the countries in the basin incorporating the resulting decreased changes in water demand for agriculture, and increasing water allocation for ecosystem health.

The major parameters of the scenarios are described in the Table 4.1.

Table 4.1. The Main Scenario Parameters.

	Scenario #1	Scenario #2	Scenario #3	Scenario #4
Scenario Theme	Upstream Energy Priority	Downstream Agriculture priority	Basin Optimal with Dam	Basin Optimal with Dam Piping
Water allocation	Upstream priority	Downstream priority	Basin optimal	Basin optimal
Infrastructure	Dam only	Dam only	Dam only	Dam + piping of canals
Agricultural production Crops cotton/wheat	Negative effect	Positive effect	Neutral or Positive effect	Positive effect + increase
Water for agriculture	Limitations in timely supply	Fully aligned supply with ag demand	Balanced	Balanced with additional water availability
Energy production	Enough to meet domestic demand and surplus for export	Limited, increase in variability	Domestic + surplus	Domestic + surplus

Cooperation	Unilateral actions/ limited cooperation	Power balance/limited cooperation/ benefit sharing agreement	Cooperation	Closer cooperation
Time period	After construction	After construction	Dam filling period + After construction	Dam filling period + After construction

The first two scenarios (adapted from Jalilov et al. 2015) illustrate prioritizations of the interests of downstream agriculture (Scenario 2) and upstream hydropower (Scenario 1), and present the situation where the countries proceed with unilateral actions without reaching an agreement that allows all the countries in the basin to benefit.. Scenarios 3 and 4 are based on increases in the cooperative attitude of riparian countries which promote shared water resource management and development in order to achieve mutually beneficial results. The feasibility and benefits of such transboundary cooperative arrangements are illustrated first through discussion of the example of the cooperative arrangements achieved by the US and Canada in development and management of the Columbia River.

The Columbia River Treaty

The Columbia River Treaty (CRT) between the US and Canada illustrates how cooperative management of water resources can lead to advancement of mutual benefits in energy and water security goals. This case is used as an example to identify the potential outcome of future scenarios in the Amu-Darya River management where this kind of cooperative water resource management and development could be realized. The CRT started in the 1940s with negotiations between the two governments, and tasks set for International Joint Commission (IJC) cooperation on Columbia River development were established with signing of Columbia River

Treaty in 1964 (Krutilla, 1967). The primary focus of the treaty is hydroelectricity and flood control with flexibility to include other concerns as countries deem necessary. As a result of the treaty, The US receive flood protection for the period of sixty years up until 2024 for which Canada received $64.4 million from the US for the construction of the three dams in the upstream portions of Columbia River with total reservoir storage of 15.5 million acre-feet (19.1 km^3) (IWG, 2019). This arrangement resulted from research in engineering and economics as well as efforts to set principles for sharing the benefits between the states (Krutilla, 1967).

The amount received by Canada was one-half of the calculated cost of would be counted by damages floods during the 60 years of the treaty. It was meant to be paid annually, however, Canada opted to receive the funds as a one-time payment (IWG, 2019). Canada was also entitled to one half of the downstream hydropower benefits, calculated as the increase in hydropower capacity with and without utilizing Canadian storage (Columbia River Treaty, 1964). The cooperation established between the two countries allowed them to achieve their water security and energy security goals. Building more protection against devastating floods, United States improved its resilience to natural disasters. Additionally, both countries benefited from production of cheap hydroelectricity and making energy security of both countries more diverse and robust.

Although the treaty serves as an example of strong, positive transboundary cooperation there are several concerns, such as consideration of the needs and cultural values of the First Nations and tribes, and consideration of environmental impacts, that are not included in the treaty and could be included and discussed during the 2014/2024 period (Watson, 2012). Concerns surrounding negative environmental externalities were omitted in the original treaty, leading to increased impacts or inability to reduce negative Bio-Physical impacts. While the primary interests of the riparian states of the Columbia River were increased protection from floods and hydropower, the losers of development without consideration of interests of all stakeholders are tribes whose economic, social, and cultural well-being is dependent on fish and the eco-system. In the Aral Sea Basin, the main interest of the countries is also in agriculture and hydropower and there is a risk of omitting the interests of local populations including those who are dependent on fisheries and ecosystem health. In the case of Columbia River, there seems to be great promise from promotion of collaborative learning to strengthen the future management and development of the river to promote dialogue (Watson, 2012).

Water Allocation Mechanisms in the Aral Sea Basin

The role of limits (established amounts and proportions of water withdrawal for every riparian state) is very important for building of the scenarios. Jalilov et al. (2015) provides no clarification on whether scenarios based on the current limits or scenarios will require changes in water allocation limits. It could be assumed that country scenarios are based on unilateral change of flow regulation. In the case of the upstream countries, these changes in flow regulation are driven by energy needs, and, in the case of downstream countries, by leveraging political power or concluding “water-energy” exchange agreements. In the scenarios built by Barki Tojik, (2014) it is stated that all the modeling scenarios are based on respecting the existing agreements between the states and international norms and regulations, in accordance with the water needs downstream.

Initially water allocation limits were established by the Scientific-Technical Council’s session of Ministry of Land Reclamation and Water Resources of USSR on 10th September 1987, protocol No 566. The Nukus 1995/1996 declaration secured the commitment of the Central Asian countries to the limits established in this document. According to Protocol No 566, water distribution among riparian republics of the former Soviet Union in Amu-Darya river and its tributaries is based on 1) existing water consumption as of 1987, and 2) calculation of the norm of water consumption. The amount and proportion of limits to water withdrawal established by Protocol N0 566 are shown in Table 4.2.

Table 4.2. Annual volume of water distribution according to Protocol No. 566 – Amu-Darya river (BWO Amu-Darya).

Republic	**Volume of annual water intake (km^3)**	**In per cents (%)**
Uzbek SSR	29.6	48.2
Tajik SSR	9.5	15.4
Kyrgyz SSR	0.4	0.6
Turkmen SSR	22.0	35.8
Total	**61.5**	**100**

After the collapse of the Soviet Union the responsible organization for the distribution of the limits became the ICWC, established in 1992. The procedure of distribution and approval of the interstate limits included the following steps: every country submits the prognosis of water needs to two subordinate divisions of ICWC BWO Amu-Darya and BWO Sir-Darya; these two organizations prepare their recommendations based on the water availability assessment and submit for approval in the regular ICWC sessions; integral part of the consideration of the limits are the operational regimes of the major reservoirs of the respective rivers. If the actual amount of water is higher than expected, it is released to the Aral Sea, if less, a re-consideration session is organized (Barqi Tojik, 2014). The signed protocol of the ICWC session becomes the legal basis of interstate water distribution for the irrigation and non-irrigation period (Barqi Tojik, 2014). It is worth noting that the established distribution does not include losses from the river and reservoirs (3.85km^3/year), sanitary releases (3.15km^3/year), and Afghanistan’s water withdrawals (2.10km^3/year) (Barqi Tojik, 2014). The mean actual withdrawals from the Amu-Darya Basin for the period from 1992 to 2010 are shown in the Table 4.3.

Table 4.3. Mean water distribution between 1992 and 2010 (Source: BWO Amu-Darya as of 1992-2010) in total volume and as a percent of total.

Countries	**km^3/year**	**%**
Kyrgyzstan	0.202	0.36
Tajikistan	8.8	15.61
Turkmenistan	20.1	35.62
Uzbekistan	21.3	37.74
Aral and Priaralie	6.014	10.67
Total	**56.4**	**100.0**

Water, Energy, and Food Security

Before presenting the results of the scenarios assessment, the current status of water, energy, and food security in each of the countries of the basin is presented (Figure 4.1.). The current status of water, energy, and food security is evaluated by application of the INSAF framework developed here with the exception that it does not include assessment of three sustainability dimensions (which could be evaluated by employing IAF framework). The current status WEF Security in Amu-Darya Basin is based on calculations of water security index by ADB (2016), the author's calculation of energy security by using the energy security framework proposed in this research, and the food security calculation by Napoli et al. (2011).

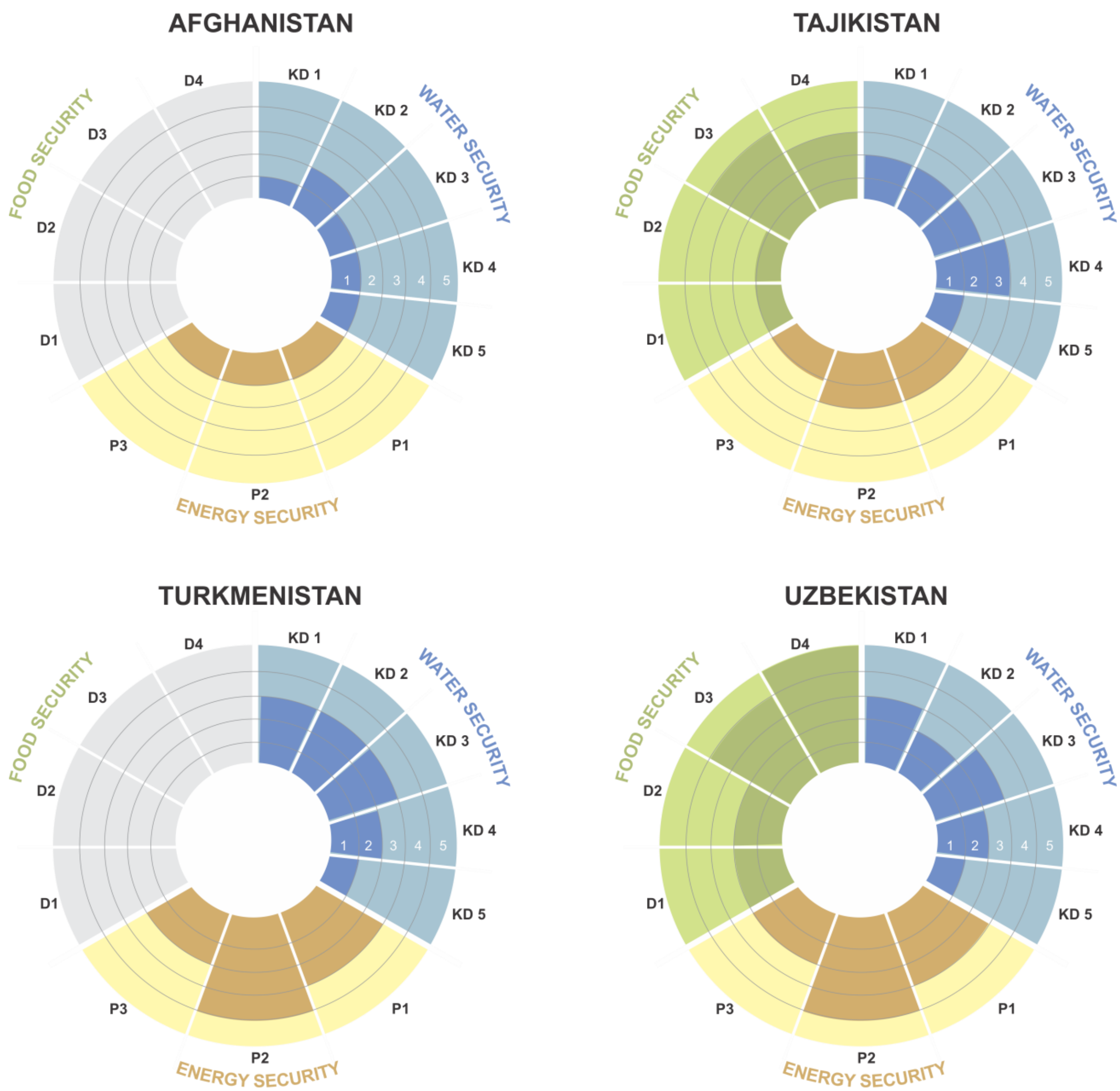

Figure 4.1. WEF Security current status. Left to right, top to bottom: Afghanistan, Tajikistan, Turkmenistan, Uzbekistan. The grey areas in the figure means that no data available for that sectors (Turkmenistan and Uzbekistan Food security). Water security metrics are based on data from ADB (2016); Energy security metrics presented here were calculated here by author based on application of concepts and major criteria from MOSES framework, Global Energy Assessment framework (Johansson et al. 2011); Food security metrics are based on the data from FAO (2014), Napoli et al. (2011).

INSAF Applied to Scenarios

The results of the application of the INSAF framework to the four alternative future scenarios show the directions of change whether positive or negative and based on qualitative assessment. It is not intended to provide a quantitative assessment of the future "status" of the WEF security in the basin. Conducting such a quantitative assessment of application of INSAF framework could require collection of additional data and use of modeling approaches to estimate future conditions, which is beyond the scope of this work.

Water Security

The results of the application of water security framework to evaluate positive or negative vectors of change to water security for every state in the basin according to four proposed scenarios, are presented in Figure 4.2. and further discussed in the sections that follow.

	WATER SECURITY	Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB
KD 1	**Household WS**																
	Access to piped water supply	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Access to improved sanitation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hygiene index (DALY)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KD 2	**Economic WS**																
	Broad economic development	-	1	-	-	-	1	-	-	-	1	-	-	-	1	1	1
	Water for agriculture	-	1	1	-1	-	-	1	1	-	-	1	1	-	-	1	1
	Water for industry	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Water for energy	-	1			-	-1	-	-	-	1	-	-	-	1	-	-
KD 3	**Urban WS**																
	Urban water supply	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Urban wastewater collection	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Flood and storm drainage	-	1	1	1	-	1	1	1	-	1	1	1		1	1	1
	Urban river health	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
KD 4	**Environmental WS**																
	River health	-	-	-1	-1	-	-	-	-	-	-	-	-	-	-	1	1
	Flow alteration	-	-1	-1	-1	-	-1	-1	-1	-	-1	-1	-1	-	-	-	-
	Environmental governance	-	-	-	-	-	-	-	-	-	1	1	1	-	1	1	1
KD 5	**Resilience to Disasters**																
	Floods and windstorms	-	1	1	1	-	1	1	1	-	1	1	1	-	1	1	1
	Droughts	-	-1	-1	-1	-	-1	-1	-1	-	1	1	1	-	1	1	1
	Storm surges and coastal floods	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 4.2. Water security assessment results for basin countries for 4 Scenarios. KD – Key Dimension.

Figure 4.2. illustrates that the outcome of the scenarios i.e. construction of the dam and its operational modes and piping of irrigation canals do not necessarily affect all of the elements of the framework, and/or every of the indicators. Many of the metrics used to assess water security do not change in response to implementation of a given scenario. This outcome (neutral impact) is also true for some elements of the energy and food security frameworks. For example, while a particular scenario may affect water availability for agriculture they may have a negligible effect on household access to water or sanitation practices in the Water Security's Key Dimensions 2 and 1, respectively.

Key Dimension 2 of the water security framework (comprised of four indicators) assesses how water management capacity of each country, including infrastructure, contributes to the general economic performance. Building a dam or piping a canal will effect these indicators in a different way for individual countries. Urban water security is enhanced through adding more capacity to controlling flooding. Flooding damages cities, requiring spending of government funds, which indicators measure as proportion of the GDP spent annually for disaster recovery. Urban river health and river health in general rely on sustainable management of the river. These indicators might show improvement in the 4th scenario where water consumed by piping of the canals will add potential for improvement in management of environmental flows in the river basin.

Environmental water security (KD 4) which depends on such indicators as river health index, flow alteration, and environmental governance show the detrimental effects of flow regulation and infrastructure development. Construction of an additional reservoir in the river will definitely change the flow of the river, and produces a negative impact in all scenarios except for scenario 4, where additional amount of water that made available after canal piping may allow leaving more water for instream use. Increased instream flows also add positive score to the indicator that shows the improvement in environmental governance.

Along with the primary purposes of building the Rogun reservoir, (generating power and regulating the flow for agricultural needs), the dam could also serve for additional purposes, such as flood control and reserving water for drought low flow years. While the flood control capacity of the dam could be maintained throughout all four scenarios, the first two scenarios, which prioritize either the maximum production of energy or maximizing agricultural production, might be challenged to perform this function due to absence of necessary amount of water or storage capacity at the time of need.

Energy Security

The results of application of the Energy Security Framework to evaluate positive or negative vectors of changes in energy security for every state in the basin according to four proposed scenarios is presented in Figure 4.3. and further discussed in the following section.

	ENERGY SECURITY	Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB
P 1	**Robustness**																
	Projected demand growth	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Oil proven reserves	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Gas proven reserves	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Coal proven reserves	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of hydro energy	-	1	-	-	-	-1	-	-	-	1	-	-	-	1	-	-
	Electricity demand growth rate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Rate of access to electricity	1	1	-	-	-1	-1	-	-	1	1	-	-	1	1	-	-
	Volatility of hydro production	-	1	-	-1	-	-1	-	-	-	-	-	-	-	1	-	-
P 2	**Sovereignty**																
	Import dependency	-	1	-	-	-	-	-	-	-	1	-	-	-	1	-	-
	Fuel import dependency	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Reliance on primary sources	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Political stability of suppliers	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	HPPs located in shared waters	-	-1	-	-	-	-1	-	-	-	-1	-	-	-	-1	-	-
P 3	**Resilience**																
	Diversity of PES	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Diversity of suppliers	1	-	-	-	-	-	-	-	1	-	1	1		-		
	Government effectiveness index	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Utilization of hydro potential	-	1	-	-	-	1	-	-	-	1	-	-	-		-	-
	GHG emissions per capita	1	1	-	-	-	-	-	-	1	1	-	-			-	-
	Diversity of HPPs	-	1	-	-	-	-	-	-	-	1	-	-	-		-	-

Figure 4.3. Energy security assessment results for basin countries for 4 Scenarios. P – Perspectives (Johansson et al. 2012).

The Energy security status of an individual state is built around three perspectives, robustness, sovereignty, and resilience. Robustness measures the short term ability of the country to meet the growing demand for energy sources mainly relying on internal resources, and also reliability of infrastructure and storing capacity. Sovereignty measures the degree of dependency on foreign energy systems and markets, vulnerability to the influence of country's major suppliers and power balances that exist in the market by concentration of production powers. The resilience perspective is a measure of the natural and technological ability to cope with disruptions. Construction of the Rogun HPP will mostly benefit upstream Tajikistan and Afghanistan, and in the first scenario where water allocation is aligned to enhance energy production there is a potential that it might also disturb the work of hydropower plants downstream of Rogun dam. Even if the upstream and downstream countries come to a compromise agreement on the production of energy and timely allocation of water for irrigation (Scenario 3), natural conditions might exacerbate the issue of volatility of power production during summer and winter when there are major differences in flow between these two seasons. in contrast, in the 4^{th} scenario, with decreased water demand and reduced need for water releases from the reservoir during the summer period, there could be more room to eliminate some of the power production volatility. Since a sovereignty perspective is mainly concerned with oil imports and exports and other primary energy sources, construction of the hydropower plant might not have much influence on this perspective. However, the availability of hydropower will allow Tajikistan to rely less on imported energy and to reduce the potential electricity imports with growing internal demand. Additionally, the fact that the Rogun HPP is located in the shared river might add to negative shift on the general performance of the indicator for all four scenarios.

Resilience perspective shows preparedness of the country to unpredictable shocks to its energy system and comprises the indicators to measure diversity of different energy supplies. While the Rogun dam is adding to Tajikistan's diversity of suppliers but just to diversity of HPPs, it adds to the diversity of suppliers for mainly Afghanistan and in a less degree (considering the proportion of hydropower in overall energy needs) to Uzbekistan and Turkmenistan depending on the cooperative scenarios (3 and 4). Construction of the Rogun HPP allows Tajikistan to utilize the hydropower potential of the country and thus this indicator shows improvement in all four scenarios.

Tajikistan's energy diversification strategy included construction of the coal based power plants aimed at reducing the resilience to disruptions in the work of the main HPP – Nurek which supplies about 90% of country's energy demand. Thus except in the case of the scenario 2 where agricultural production priority will force turning on of thermal plants in all other three scenarios there will be reduction of GHG emissions. Stable energy export to Afghanistan will also allow this country to reduce its dependency for burning fossil fuels, thus positively impacting the GHG emissions indicator.

Food Security

The results of application of the Food security framework to evaluate positive or negative vectors of changes in food security for every state in the basin according to four proposed scenarios are presented in Figure 4.4. and further discussed in the sections that follow.

	FOOD SECURITY	Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB	AFG	TAJ	TKM	UZB
D 1	**Availability**																
	Arable land	-	-	-1	-1	-	-	1	1	-	-	-	-	-	-	1	1
	Cereal per yield	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Cereal domestic supply	-	-	-	-	-	-	1	1	-	-	-	-	-	-	1	1
	Share of food aid	-	1	-	-	-	-	-	-	-	1	-	-	-	1	-	-
	Food supply	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Permanent cropland	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Food production index	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Land under cereal production	-	-	-	-	-	-	1	1	-	-	-	-	-	-	1	1
D 2	**Access**																
	Consumer price index	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	GDP per capita	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Improved water source, rural	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Rural population	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D 3	**Utilization**																
	Cereal waste	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mortality rate, under-5	-	1	-	-	-	-	1	1	-	1	-	-	-	1	1	1
	Prevalence of undernourishment	-	1	-	-	-	-	1	1	-	1	-	-	-	1	1	1
D 4	**Stability**																
	Cereal stock variation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Variability of food production	-	-	-	-	-	-	1	1	-	-	1	1	-	1	1	1
	Variability of consumer price	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Import Dependency Ratio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Import Dependency (Regional)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Variability of area harvested	-	-	-1	-1	-	-	1	1	-	-	1	1	-	1	1	1

Figure 4.4. Food security assessment results for basin countries for 4 Scenarios. D – Dimensions.

Due to the indirect nature of the assessment of most food security indicators, measuring the direct effects of infrastructure development presents some degree of challenge.

In the second scenario, where agricultural production is prioritized, it may be possible to enhance the area of arable land in downstream countries, while increasing the arable land in the 1st scenario is limited, due the fact that increasing energy production will leave no room for improvement. In the third scenario, keeping the existing arable land area will be also supported by slight increase. Only in the 4th scenario it will be possible to increase the arable land with the new amount of water available after irrigation canals piping. These increase could be substantially greater than would be the case in the 3rd scenario. In turn, depending on the government policy, there could be an increase in the domestic supply of the cereals, which again could be substantial in Turkmenistan and Uzbekistan. The fact that national income will be increased because of power exports in Tajikistan (surplus electricity production estimated at 200 million USD) might favorably affect the purchasing power of the nation for food, and investment in improving the food security situation in the country in a many different ways. Together with enhancement of flood regulation and resilience to droughts, these projects could lead to reduction of Tajikistan's dependency on the external food aids.

Both infrastructures – the dam and piping, might have only indirect impacts on the access dimension of the food security in all of the considered countries. Thus, these impacts are negligible compared to other measures that are likely to have more significant influence on indicators' performance. Only GDP per capita might have positive change in Tajikistan, with additional energy export income. Considering the GDP of the country the influence of this income could be significant ($200 million from surplus energy exports, GDP $7.15 billion (2017).

The increased indicator of GDP per capita will also probably result in lower child mortality and more coverage with electricity access to better health service, thus resulting in the improvement of child mortality and undernourishment indicators in Tajikistan. These favorable conditions might emerge in the scenarios where energy production is prioritized and coordinated. Although downstream countries have lower score on these two indicators of the utilization dimension, enabling more agricultural production can reduce the number of people suffering from undernourishment and child mortality among rural populations, those who are mainly involved in agricultural sector in Turkmenistan and Uzbekistan.

With respect to stability, which mainly measures the volatility of the stock and supply of food in the country, development of the two types of infrastructure might have a major effect on the variability of food production and harvest area. The former (variability) could be reduced as a result of more reliable flood control by the dam, and provision of more water in drought years, and also greater water availability through canal piping in the fourth scenario.

In figures 4.5 to 4.8 the results of application of the WEF security frameworks are presented across the four scenarios with projections of the achievement changes to compare to WEF security basis conditions for all four countries in the basin.

The evaluation on WEF security is made on the basis of the previous research in the basin: reports of development agencies, reports and assessments of International Financial Institutions, state policies and strategies, and UN organization’s reports (FAO, WB, ADB, Barqi Tojik, Jalilov et al. 2015, Bekchanov et al. 2015, Pohl et al. 2017, Stuki and Sojamo 2013, Johansson, Jewell and Cherp, GEA, MOSES IEA)

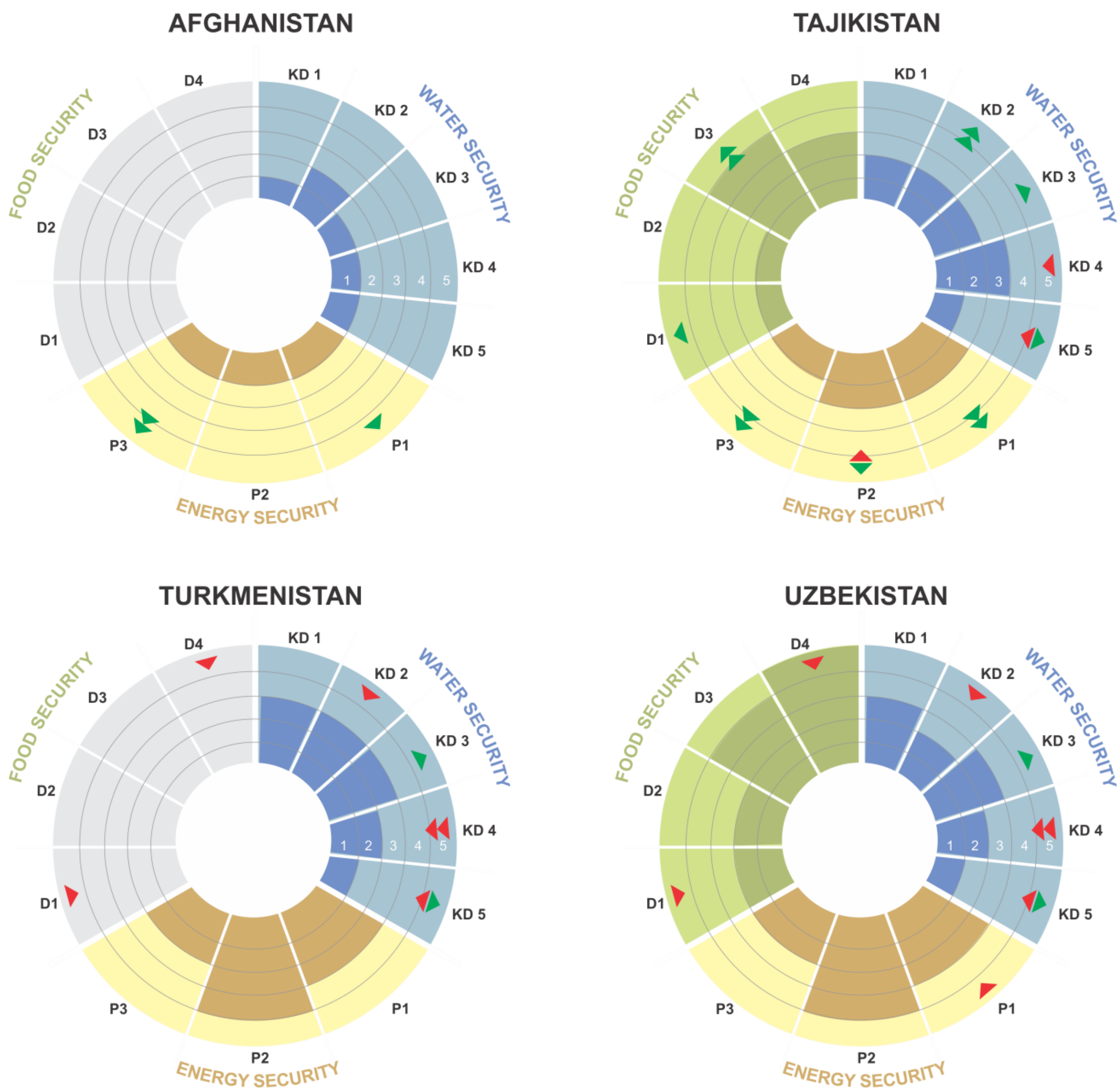

Figure 4. 5. WEF Security achievement results for Scenario 1.

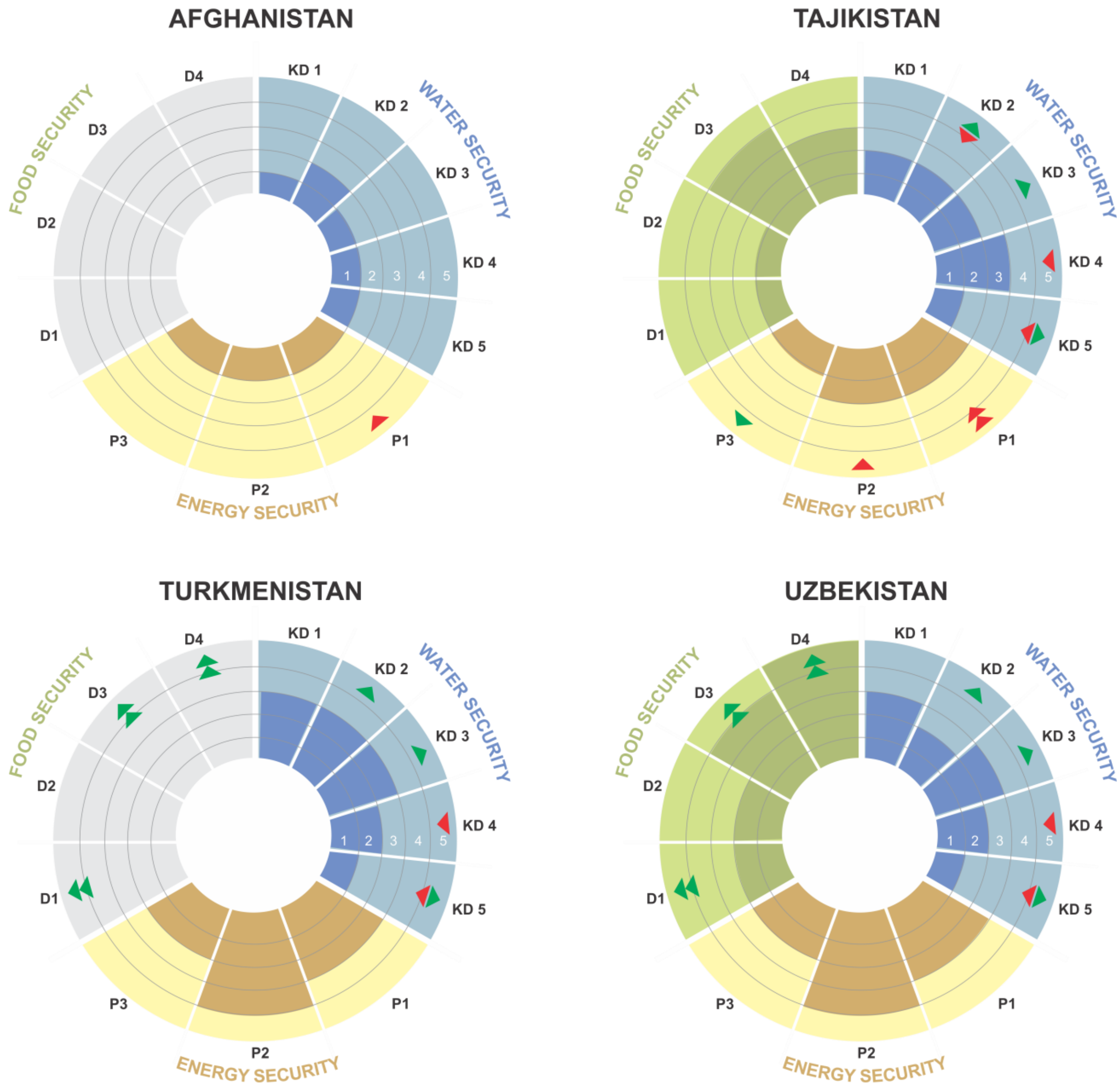

Figure 4. 6. WEF Security achievement results for Scenario 2.

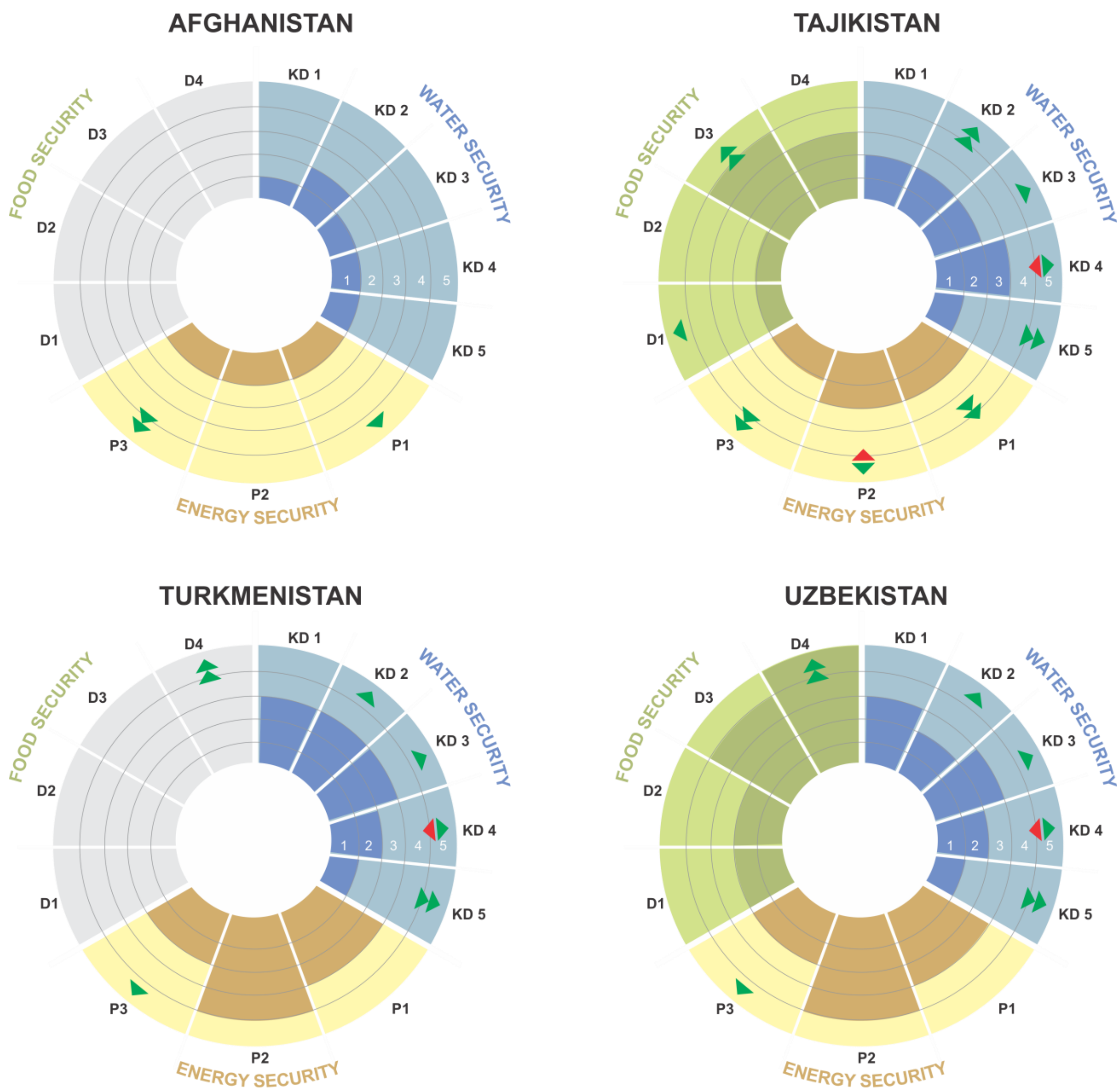

Figure 4. 7. WEF Security achievement results for Scenario 3.

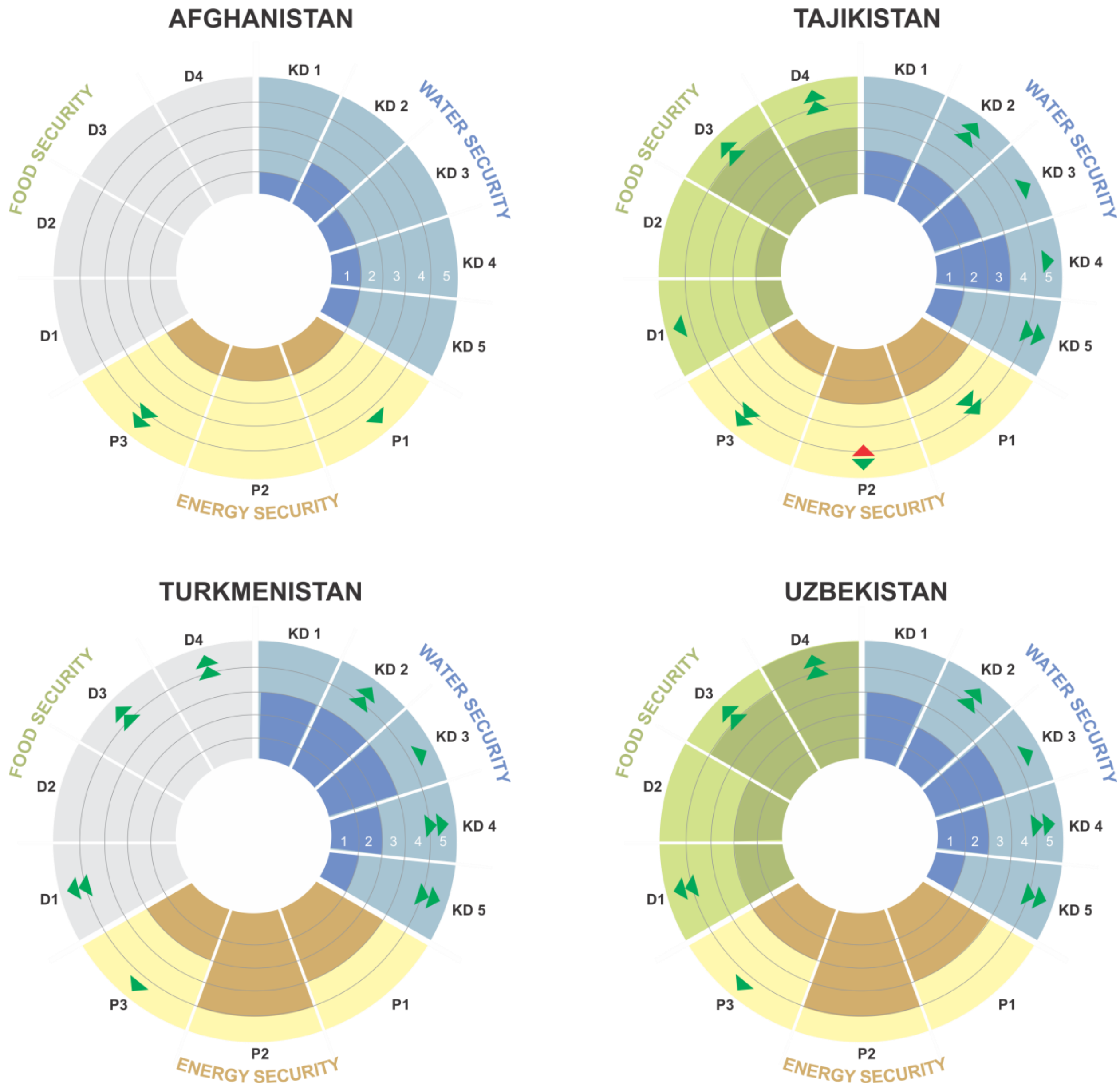

Figure 4. 8. WEF Security achievement results for Scenario 4.

Evaluation of Bio-Physical, Socio-Economic, and Geo-Political Dimensions. Application of Interdisciplinary Assessment Framework

Bio-Physical, Socio-Economic, and Geo-Political Dimensions of achieving Water, Energy, and Food securities are evaluated by using the Interdisciplinary Assessment Framework which is the integral part of the INSAF framework and meant to make assessment of sustainability of infrastructure development in the Amu-Darya river basin. The results of the evaluation are presented in Figure 4.9. and comparison of the results among four scenarios presented in Figure 4.10. Results are based on the indicators adapted from IDAM framework (see Tullos et al. (2010) for more details on description of indicators). Detailed description of the evaluation is presented in Table 4.4.

While the results for the WEF security assessment are presented separately for each country, the Bio-physical, Socio-economic and Geo-political dimensions of sustainability are assessed for the whole basin. There are several reasons for this approach to assessment. First, most of the indicators for the political dimension show the relationships between the countries and analysis for every country could be repetitive. Further, since the sustainability analysis is conducted to assess the sustainability of managing the shared water resources of the Amu-Darya River, natural resources, and ecosystem health of the basin, every country in the basin has to use and manage the resources in a sustainable manner. If one country's approach is not sustainable there is a negative impact on sustainability for the whole basin. Socio-economic dimension will be different for all the countries, and in an equity analysis, a negative outcome for one country means a lack of sustainability for the whole basin that will be reflected in the political situation in the basin. A basin-wide approach is also applied to promote basin-scale thinking and planning.

Dimensions	Scenarios	WATER SECURITY S1	WATER SECURITY S2	WATER SECURITY S3	WATER SECURITY S4	ENERGY SECURITY S1	ENERGY SECURITY S2	ENERGY SECURITY S3	ENERGY SECURITY S4	FOOD SECURITY S1	FOOD SECURITY S2	FOOD SECURITY S3	FOOD SECURITY S4
Bio-Physical	BP 1 - Water quality and quantity	--	--	--	0	0	0	0	0	0	0	0	0
	BP 2 - Impact area	0	0	0	0	0	0	0	0	--	+	0	+
	BP 3 - Natural flow regime	--	--	--	+	--	--	--	--	0	0	0	0
	BP 4 - Climate change and air quality	0	0	+	+	+	+	+	+	0	0	0	0
Socio-Economic	SE 1 - Local hydropower access	0	0	0	0	+	0	+	+	0	0	0	0
	SE 2 - Income (farm lands)	0	+	0	+	0	--	0	+	0	+	0	+
	SE 3 - Health impacts	--	--	0	+	--	0	0	0	--	--	0	+
	SE 4 - Wealth and macro impacts	0	0	+	+	0	0	+	+	0	+	0	+
Geo-Political	GP 1 - Basin population affected	0	--	0	0	--	0	0	0	--	--	0	0
	GP 2 - Political complexity	--	--	+	+	--	--	+	+	0	0	0	0
	GP 3 - Legal and institutional fmwrk	--	--	+	+	--	--	+	+	0	0	+	+
	GP 4 - Domestic governance	--	0	0	+	0	--	0	+	0	0	+	+

Figure 4.9. Results for Bio-Physical, Socio-Economic, and Geo-Political Dimensions according to Interdisciplinary Assessment Framework Evaluation.

Table 4.4. Details of Results for Interdisciplinary Assessment Framework

	Water Security	**Energy Security**	**Food Security**
Bio-Physical Effects	Due to absence of anadromous fish life in the river there are less concerns on the negative water quality effects linked with changes in water temperature which is considered as one of the main impacts of reservoirs on water quality. However, there could be water quality issues linked with algae-blooms in the reservoir. Water quantity issues leading to effects on river health can be reduced with the piping of the canals in case of Scenario 4 and remains negative in other scenarios.	Natural flow regime is changed due to the construction of the dam. Dam development, mainly driven by reaching energy security. Improving demand management could reduce flow regime changes. Since the dam is built for hydropower generation which a source of renewable energy it has a potential to reduce CO_2 emissions and contribute to climate change mitigation and air quality and build more capacity for climate adaptation.	Impact area of the dam depends on the operational regime of the reservoir which is different in four proposed scenarios. In energy priority regime the cultivated land for grains might become vulnerable while in the second and fourth scenarios there is a room for increasing grain harvest areas.
Socio-Economic Effects	Achieving water security in scenarios 2 and 4 where agricultural production might be increased, results in more income for farmers. The first two scenarios where whether energy production or ag production is prioritized, are detrimental to public health due to fluctuations of access to water for upstream (Scenario 2) and downstream (Scenario 1) countries.	Construction of the new HPP increases the level of local access to hydropower in all scenarios except the second when the ag production is prioritized. Significant increase in the incomes might be possible in the Scenario 4, while in other scenarios there could be limited increase. Prioritizing energy production might have negative health impacts due to unreliable access to water. Scenarios 3	Prioritizing agricultural production in Scenario 2 and cooperative attitude together with piping of the canals in Scenario 4 could result in improved food security and also to food exports by downstream countries which provides additional income for farmers and food producers. Scenarios 1 and 2 might have negative impact on health due to lack of access to water incurring financial losses

		and 4 with optimized hydropower and agricultural production and reduced water demand (Scenario 4 only) might have positive macro effect for the whole basin.	and limited income from hydropower leading to increased undernourishment. Scenario 4 allows all basin countries to improve their food security through increase of ag land.
Geo-Political Effects	Prioritizing whether hydropower production or agricultural production for achieving water security in scenarios 1 and 2 means unilateral actions by the countries which leads heightens political tension between the countries driven by contradiction to needs of the states and resulting in both low domestic governance as well as intrastate relationships. In Scenarios 3 and 4 on the other hand reaching water security by balancing the work of the reservoir and improving demand management leads and also needs cooperative attitude of the countries reducing tensions.	Efforts to achieve energy security in Scenario 1 with significant change in flow regime makes downstream agriculture vulnerable and suboptimal utilization of the potential of the HPP in the Scenario 2 both lead to heightened tensions among countries. While in Scenarios 3 and 4 energy security is reached by optimal distribution of water resources to meet the needs and expectations of both hydropower and agriculture production. Achieving energy security goals in a cooperative manner will reduce the geopolitical tension between states.	Prioritizing hydropower production might limit agriculture al production in downstream countries leading to endangering food security for certain group of people thus adding to increase of tensions among states due to domestic governance. This tension might be reduced by optimal water allocation (Scenario 3) and even increased (Scenario 4), with implementation of piping of irrigation canals and potentially extending agricultural land to enhance food security situation.

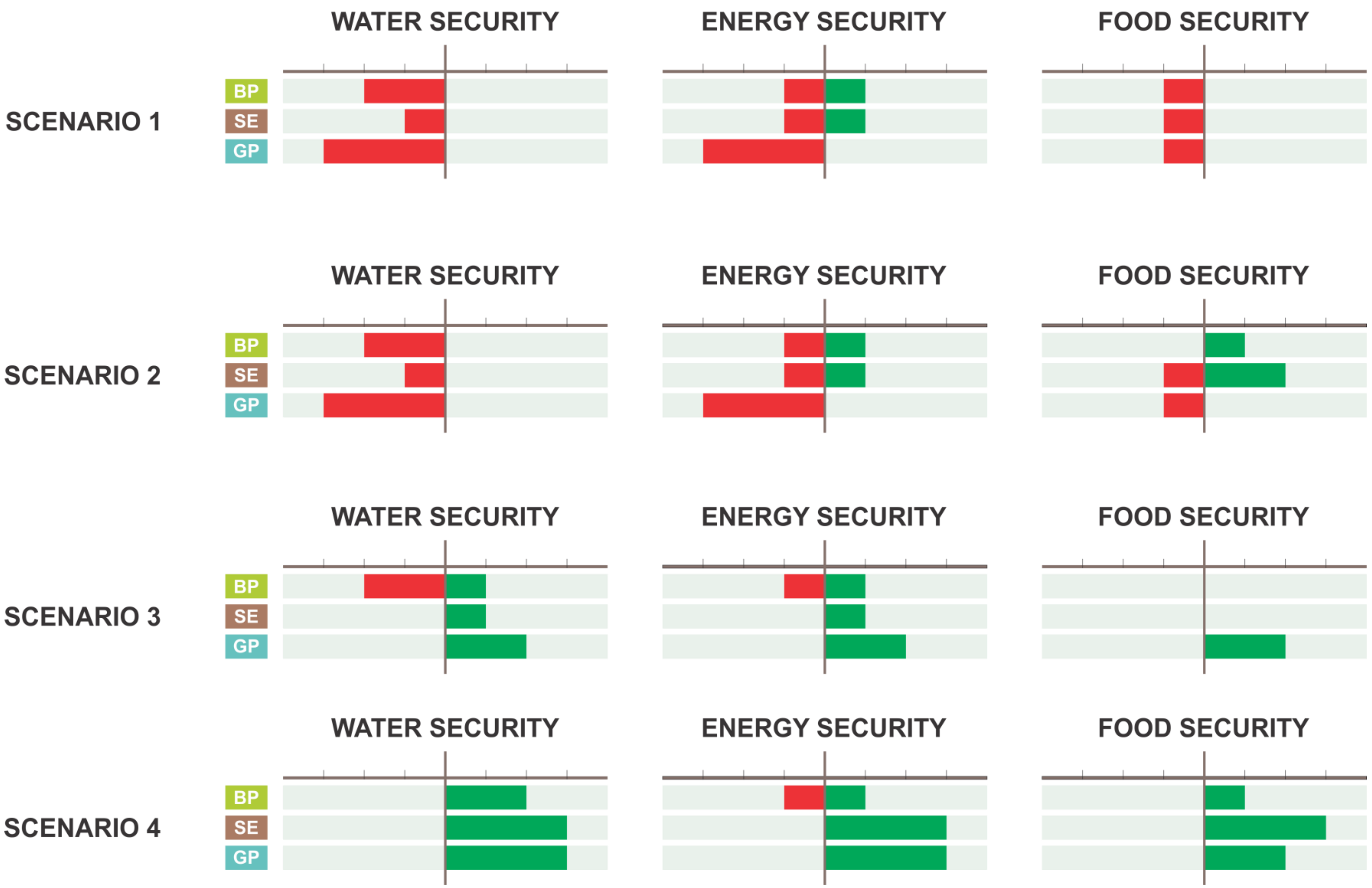

Figure 4.10. IAF application results for all four scenarios representing changes in Bio-physical, Socio-economic, and Geo-political dimensions in the basin across WEF security achievements.

Discussion

The fact that infrastructure development in the shared river affects all the countries and all three WEF security achievements in four countries, confirms the interlinkages between these sectors promoted by nexus concept. However, these changes are diverse among the states and across four proposed Scenarios. For example, changes in basin affect only Energy security achievements in Afghanistan which can be observed in all four scenarios, and mainly Water security and Food security achievements in downstream states. As for Tajikistan, the results affect all WEF security achievements. IAF results for sustainability dimensions' assessment for the basin according to Scenarios 1 and 2 show heightened negative effects especially in Bio-physical and Geo-political dimensions leading to more tensions on water allocation among states. Conversely, Scenarios 3 and 4 show positive results for sustainability dimensions. As political dimension which reflects the tensions among countries might be the source of continued conflicts on water allocation and timing the results from the Scenario 4 allows to assume that it has strong interlinkage with cooperation. By identifying this correlation, the framework supports the promising potential of basin development assessment through use of indexes and indicators.

It worth mentioning that the weight of the indicators in each of the frameworks could be different. Although presented results indicate positive (+1 or +) or negative (-1 or --) directions of change for WEF security achievements and three sustainability dimensions, negative change of one indicator can overweight positive change in two other indicators. For example, negative effect on water security for agricultural needs might be unacceptable for decision makers even if the scenario improves the water security for the river health and lower flow alteration. Thus, defining the weight of the indicators to changing the basis conditions through further quantification will lead to more detailed results for better comparison among scenarios.

It is also important to keep both negative and positive results because achievement in one does not mean it reduces the negative impact of the other.

In Table 4.5. The results are compared for WEF security achievements and assessment of sustainability dimensions across four proposed scenarios to define thresholds of sustainability and choices that incorporate nexus thinking.

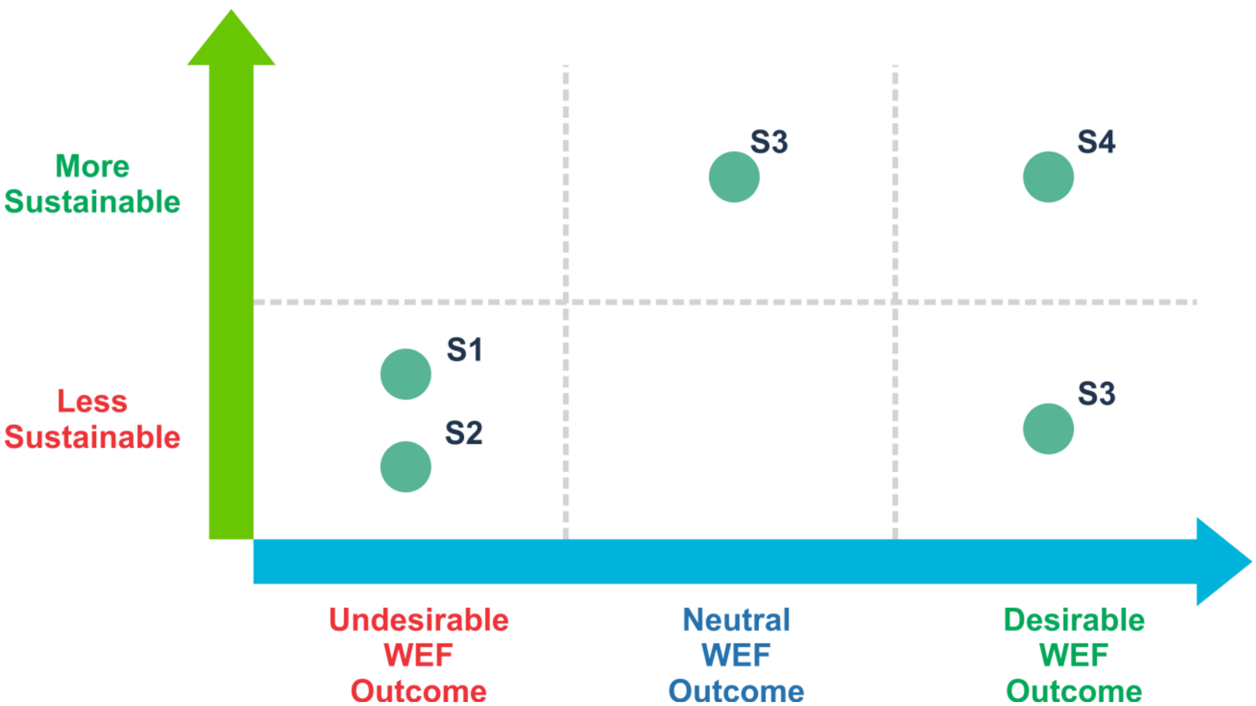

Figure 4.11. Comparisons of INSAF framework results.

Proposed transboundary basin development evaluation framework contributes to the better understanding of the nexus approach and the possibilities of utilizing indicators/assessment frameworks to identify benefits and trade-offs of basin development and different modes of management regarding cooperation, environmental governance, and socio-economic prosperity achievements and define thresholds of sustainability. Yet, further quantification of the results to better understanding of potential risks and trade-offs is encouraged for future research. Since the framework is based on the data from open sources the framework is transferable to other transboundary basins.

Equitable distribution of benefits for the region as a whole and the gains of the individual countries are addressed in the Scenarios 3 ad 4 as an establishment of cooperative relations between the countries as exemplified by the Columbia River Treaty case study. Gains of different actors would be important in defining equitable distribution among groups of people, and would likely be of interest to banks invested in the projects. However, distribution of benefits within the countries among different stakeholders and social groups could be another challenge to be addressed. The losers from the dessication of the Aral Sea are the people whose economy and diet was dependent on the products of the sea. While considering equitable distribution of benefits from development in the region, it will also be important to take into account their sufferings, and the social, health, and economic hardships as well as allocation of water for environmental restoration. Institutionalizing equity and sustainability might contribute in this endeavor.

Institutionalization of equity and sustainability in plans for regional development will require more commitment of the countries to reform IFAS. It will be important to include diverse topics for consideration, including hydropower projects in shared rivers and demand management projects as well. Institutional mechanisms to ensure equitable distribution of the gains could be codified in the agreements and other bilateral and multilateral documents between states.

Additional Limitations of the Research

Efforts to address climate change in the current research were limited, as climate change was not the main focus of the research. Howver, the absence of specific consideration of climate change is one of the limitations of the research presented here. For example, assumptions concerning the amounts of water that will be available for water allocation may not coincide with actual flow in the future because of uncertainties due to impacts of climate change on water resources, such as increased rates of melting and loss of glaciers in upstream countries. AS a result, one caveat to te research presented here is that water allocation should not be done in absolute units but rather as a percentage of the total water available for withdrawal.

Conclusion

Here, a nexus approach is suggested to guide resource use improvement. This thesis explored the potential of an approach that includes both supply and demand management in basin development, evaluated across achievements to WEF security. Results of this thesis indicate that countries in the shared basins might advance in their WEF security achievements in a sustainable manner by employing combined supply-demand strategies in infrastructure development and operation. tThe case study presented here focuses on the Amu-Darya Basin within the Aral Sea Basin, where desiccation of the world's fourth largest sea due to extensive use of water resources for agriculture in unsustainable manner led to "water scarcity"/water allocation driven tensions among states. Thenalysis presented here to evaluate thesustainability of further basin developments contributes to the search for viable options that can promote equitable distribution of benefits and trade-offs in transboundary rivers.

Critics of the depoliticized approach of the nexus concept point to the limited inclusion of environmental concerns and socio-economic dimensions into nexus discussions. The research presented here attempted to address this limitation. The aim of the thesis was to evaluate the gains of riparian states in Water, Energy, and Food security in the Amu-Darya River basin as a result of basin development through construction and different operational modes of reservoirs in the upstream and water conservation strategies with piping and lining of aged irrigation canals throughout the basin. Identifying the Bio-physical, Socio-economic, and Geo-political dimensions of these developments allowed us to make an assessment of the sustainability of potential basin developments.

The assessment tool developed for the purpose of this research – Interdisciplinary Nexus Sustainability Assessment Framework (INSAF) incorporates Water, Energy, and Food security frameworks and an Interdisciplinary Assessment Framework (IAF) that evaluates WEF security achievements by riparian states as a result of infrastructure development and Bio-physical, Socio-economic, and Geo-political dimensions to identify sustainability these achievements. Four proposed alternative scenarios were evaluated to explore different potential resource management, basin governance, and cooperative attitudes of states based on promoting the supply as well as demand management strategies. The results indicate that a supply-demand management perspective in basin planning and development (explored in Scenario 4 as an example of combination of infrastructures) allows the region to achieve improved WEF results for every state more sustainably. Solutions that include both supply and demand management could thus reduce pressure on water resources and bring down the degree of tension between the states, leading to stronger cooperation in the region.

The assessment framework developed here is based on open data sources. As a result, the INSAF framework could help advance research on WEF security and sustainabiliy in other regions, as well, through the use of widely-available indicators that comprise the framework. The transferability of the INSAF assessment framework to other basins, and potential for inclusion of diverse types of infrastructure and measures/tools to basin development through adaptation of the IAF indicators, highlight the strengths and flexibility of this framework and could help promote inclusion of environmental, political, and socio-economic dimensions in the evaluation of basin development projects around the world.

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