



OPEN Water-energy-food nexus assessment in the transboundary harirud river basin using the MUSIASEM framework

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Water, food, and energy systems are highly interconnected, and changes in one can have a direct impact on the others. In transboundary basins, these interactions become more complex due to conflicting interests and uneven distribution of resources. In Harirud River Basin, Afghanistan, unsustainable upstream water development plans (e.g., dams and agricultural expansion) have increased water use, resulting in reduced flows downstream to eastern Iran. This reduction, combined with climate variability, has heightened pressure on groundwater and weakened the security of food and energy systems. Using the multi-scale MuSIASEM framework, this study assesses the structural and functional performance of water, food, and energy subsystems on both sides of the Iran–Afghanistan border from 2011 to 2021. Results show that Iran annually produced 2.88 million tons of agricultural outputs with 10,839 terajoules of energy inputs and 1,712 million cubic meter (MCM) of green/blue water, while Afghanistan produced 0.78 million tons with 2,694 terajoules and 692 MCM of water. In the energy sector, Iran generated 11,741 GWh of electricity mainly from fossil fuels, whereas Afghanistan produced only 44 GWh from hydropower. Water withdrawal in Iran reached 2320 MCM/yr, compared to 660 MCM/yr in Afghanistan. These findings highlight the vulnerability of downstream resources and underscore the need for cooperative transboundary basin-level management policies.

Keywords Hydrology, Central Asia, Energy, Sustainable water management

Human well-being depends on reliable access to water, energy, and food (WEF). These resources form an interconnected system in which constraints in the quantity or quality of any component can destabilize the whole across spatial and temporal scales. In transboundary basins, interlinkages intensify because political boundaries rarely align with hydrological ones; scarcity, stakeholder competition, and non-cooperative, power-oriented upstream behaviors in allocation further amplify risks^{1,2}.

Harirud River is shared by Iran, Afghanistan, and Turkmenistan. It supplies Mashhad's drinking water and supports agriculture on Iran's Sarakhs Plain, while in Afghanistan it underpins agriculture and hydropower across Herat and Ghor provinces. Upstream "water control" policies and hydraulic infrastructure expansion have increased abstraction, irrigated area, and hydropower capacity in Afghanistan³. Downstream in eastern Iran, reduced inflows, combined with climate change, have heightened pressure on groundwater, turning water scarcity into a binding constraint on food and energy systems and raising concerns about long-term resource sustainability. These dynamics can exacerbate regional tensions and jeopardize downstream livelihoods⁴.

Addressing such challenges requires identifying key flows and structural parameters within WEF systems to diagnose opportunities and risks under current conditions and assess the impacts of alternative management policies among riparian states. Yet only a limited number of studies have examined these interdependencies in the Harirud River Basin by jointly assessing resource states and demands in both Iran and Afghanistan sides. This motivates an approach that evaluates water, food, and energy together, over a defined time horizon and

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across national borders, while capturing their mutual linkages within integrated resource management. The WEF nexus concept, first highlighted by the World Economic Forum in 2008 and introduced formally at the Bonn 2011 Conference, frames this intersectoral perspective on resource security and sustainability⁵.

Early research often focused on pairwise links, such as water–food⁶, water–energy⁷, or food–energy⁸. Contemporary nexus studies increasingly analyze correlations, dynamics, and feedbacks among coupled systems and environmental drivers, and propose efficiency-oriented strategies^{9–12}. At transnational scales, nexus analyses have also been used to inform cooperative arrangements in shared basins^{13,14}. Implementing the nexus requires both qualitative and quantitative tools: qualitative work addresses institutions and actors¹⁵, policy impacts^{16,17}, and stakeholder behavior¹⁸, whilst quantitative work enables numerical assessment and scenario testing¹⁹. The latter spans accounting with matrices and vectors^{20,21}, computational dashboards such as WEF Nexus Tool 2.0²², indicator-based assessments^{11,23}, and input–output methods^{24,25}. Each has advantages and limits shaped by context and data availability, including extensive data needs, supply-side bias that overlooks demand gaps, and omission of critical consumption flows such as agricultural inputs and water use embedded in power generation.

This study evaluates the performance and adequacy of WEF subsystems in supply and production across the transboundary Harirud Basin at national and transnational scales. We employ MUSIASSEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), a flow-fund, multi-scale accounting framework grounded in socio-ecological metabolism, and develop quantitative indicators to characterize cross-sector relations. Using available statistics, MUSIASSEM is applied to diagnose metabolic patterns and interdependencies among WEF components. Prior applications show its versatility: farm-scale wind-powered desalination in the Canary Islands²⁶; broader territorial scales in Mauritius, South Africa, and Punjab²⁷; village-level charcoal trade-offs²⁸; cross-scale resource mapping in the Nile Basin linking Egypt's energy-intensive desalination to downstream agricultural water in Sudan²⁹; and hydropower–food security trade-offs in the Mekong using metabolic ratios (e.g., m³/MWh)⁵. These studies demonstrate MUSIASSEM's strength in capturing critical linkages via static metabolic accounting and provide a foundation for future dynamic analyses. The analytical components here follow Tovar et al. (2019)²⁶, adapted to the data environment and contextual constraints of Afghanistan.

This work provides the first MUSIASSEM-based WEF nexus assessment for the Harirud River Basin, integrating national and transboundary lenses under severe data and governance constraints. It introduces a tailored indicator set for subsystem adequacy and performance, quantifies cross-scale metabolic ratios characteristic of arid, conflict-affected basins, and links energy and water decisions to food production capacity. The aim is to generate decision-ready evidence to support cooperative, basin-wide resource management and policy design in the Harirud.

Materials and methods

Study area

The Harirud River Basin covers approximately 93,260 km² and spans Afghanistan, Iran, and Turkmenistan. This study focuses on analyzing the Iranian and Afghan sections of the Harirud River Basin. Between 2000 and 2022, the estimated population in the Afghan part averaged 1,780,000 people, while the Iranian part had about 3,747,000^{30–33}. In Iran, parts of the Qareh Qum watershed are in the counties of Sarakhs, Taybad, Torbat-e Jam, Fariman, Quchan, Salehabad, Chenaran, Mashhad, Bakharz, and Golbahar. In Afghanistan, the provinces of Ghor and Herat, located in the western part of the country, are involved. The Harirud River, a key water resource in this basin, originates from the high mountains of Afghanistan. Near Taybad, the river reaches the border between Iran and Afghanistan, and by joining the Kashafrud River, forms the border between the two countries for a length of 259 km³⁴.

Afghanistan has built the Salma Dam upstream, with a capacity of 0.650 billion cubic meters (BCM), to utilize this water resource. In line with economic growth, job creation, and water and energy security, plans for developing water infrastructure, such as the Pashdan earthen dam, are also underway³⁵. Downstream, Iran and Turkmenistan have constructed the Doosti (Friendship) Dam, with a capacity of 1.250 BCM, located 180 km far from Mashhad, to regulate inflow. Figure 1 shows the location of the basin, the flow of the Harirud River, and the dams. Additionally, Turkmenistan covers approximately 20% of the basin's area; however, according to the Iran Ministry of Energy report in 2020³⁶, its contribution to the basin's runoff is only 5%, and the Khorasan Razavi Regional Water Authority report in 2020³³ states that its share of surface water inflow is roughly 13%. The country mainly supplies its agricultural and drinking water needs through the Qareghom Canal. However, the lack of detailed hydrological data for Turkmenistan at the county or provincial level, unlike Iran and Afghanistan, limits comprehensive analysis.

Structure of the MUSIASSEM analytical framework

The MUSIASSEM analytical framework is a type of accounting that uses the concept of metabolism to describe the performance of socio-ecological systems in terms of capital and flow components in a relatively simple manner. This framework was first proposed by Rosen (1958)³⁷. MUSIASSEM, with its simpler structure and lower data requirements, is a more efficient and operational analytical framework than PRIMA (Participatory – Reflective – Integrated – Multi-scale – Assessment) and CLEWS (Climate, Land-use, Energy and Water Systems Models), particularly for large-scale analyses and data-scarce regions. It is suitable for developing countries or transboundary basins with statistical limitations.

MUSIASSEM strengths include the seamless integration of direct and indirect flows in production and consumption chains, the incorporation of local knowledge, and the enabling of stakeholder engagement for future policy scenarios. MUSIASSEM's multi-scale analysis examines subsystems (e.g., agriculture) within broader societal and environmental systems while allowing detailed component analysis. It identifies trade relationships, resource interactions, and the balance of domestic production versus imports, supporting assessments of

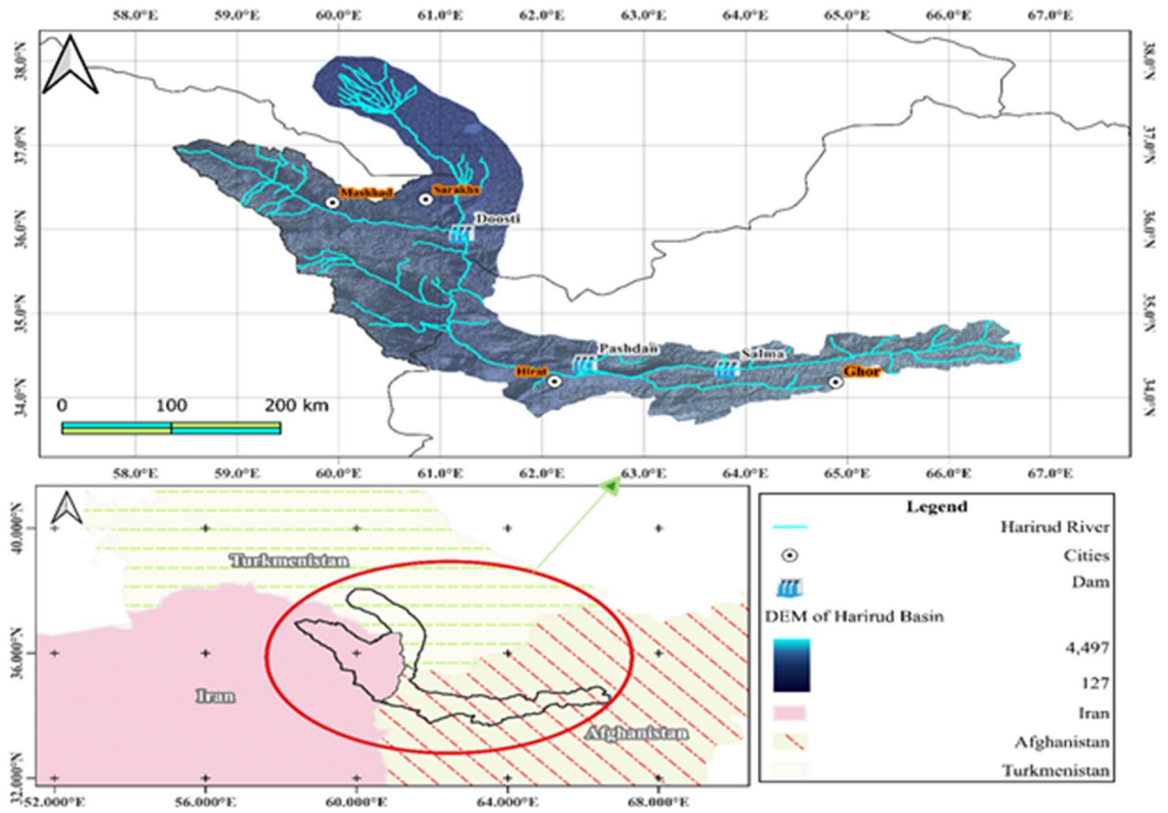


Fig. 1. Location of the Harirud river basin, rivers, and important dams (created by QGIS Desktop 3.32.3; <https://qgis.org/> (last access 21-Feb-2026)).

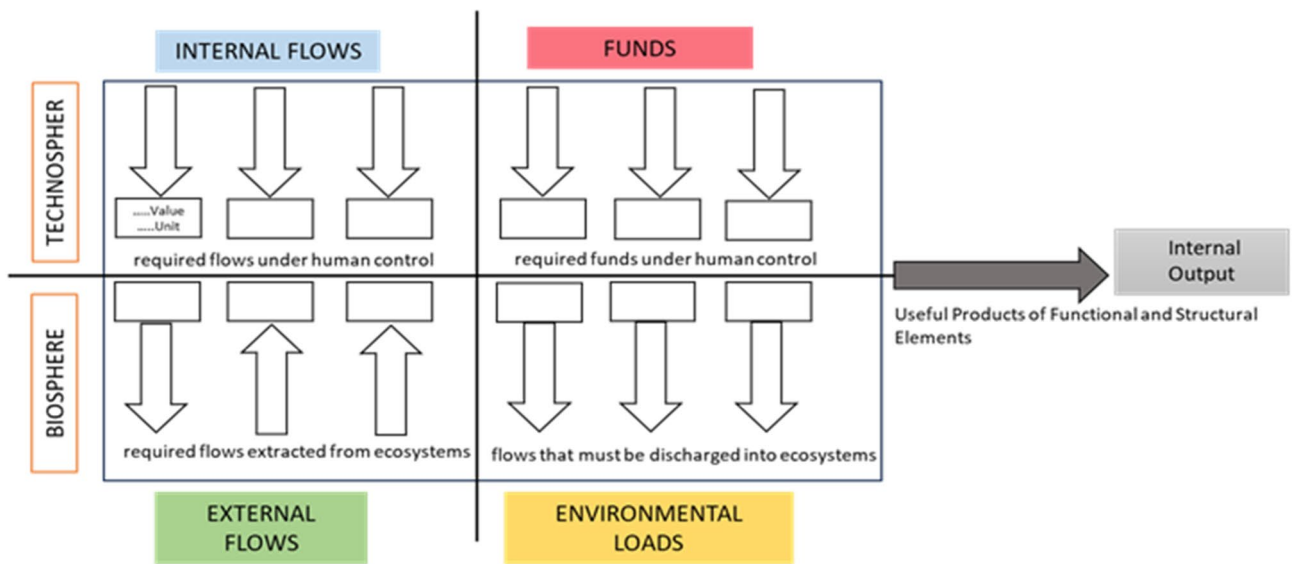


Fig. 2. Graphical representation of processor’s components.

metabolic security in water, food, and energy. This framework comprises processors that represent the structural and functional components of a system across multiple scales. Since the inherent characteristic of natural systems is their open boundaries, this framework enables the definition and analysis of trade relationships and interactions between each system and others. With such capability, based on the relative share of a system in using its domestic production versus using imported flows, part of the metabolic security in supplying WEF can be examined²⁹. Figure 2 illustrates the components of a processor, generally consisting of four parts. The upper part relates to inputs entering from the Technosphere (processes under human control). These inputs

include flows and capital. Flows are materials and energy consumed during the process (such as fuel, fertilizer, and electricity), but capital elements are not consumed; rather, they are maintained over time (such as turbine capacity, labor force, and land) and convert inputs into outputs. The lower part of the processor pertains to the system's interaction with the biosphere (the natural environment outside human control), where the left side includes all flows entering from the environment outside the system during the process (like green water, soil, and wind), and the right side relates to loads returned to the surrounding environment during the metabolic process (like waste, greenhouse gases, and sewage). The processor's output indicates the number of product(s) produced with a specific quantity of required flows and capital and a certain level of interaction with the biosphere.

The WEF nexus system

The MUSIASSEM framework enables analysis across various spatial and temporal scales. These spatial levels can encompass global, regional, national, local, and even subsystem scales. In this study, the WEF nexus will be analyzed at two spatial levels: national and transnational. At the national level, functional parameters of WEF supply processes within the borders of Iran and Afghanistan, specifically in the Harirud River Basin, have been quantified separately to identify priorities and constraints related to resource management in each country. Each functional processor aggregates its subordinate structural processes, detailed in Fig. 3. The water processor includes extracting water from aquifers and surface flows. The food processor involves producing agricultural products from key cultivated areas (300 ha). Within the study area, the only energy source considered is electricity, as fuel for Iran is supplied from the national system outside the basin, and for Afghanistan through imports. Afghanistan's electricity comes solely from the renewable Salma hydropower plant, while Iran relies on non-renewable gas, steam, and combined cycle power plants within the area. At the transnational level, along the Harirud River Basin border, the representation will be quantified through the analysis of potential trade in food products, energy trade, and the inflow of the transboundary Harirud River from Afghanistan into Iran, to examine the connection and dependency between the two countries. Figure 4 illustrates a local nexus system comprising processors and its boundary. There is a dynamic, interdependent relationship among WEF systems, where changes in one component inevitably impact the others. Increased energy availability can boost food production capacity, while expanding food production demands more water and energy resources. Similarly, large-scale water use, especially for agriculture or desalination, requires a significant energy input. This intricate interconnection highlights the complexity and feedback-driven nature of the WEF nexus, emphasizing the need for integrated, holistic management approaches to ensure long-term sustainability and security across all three sectors.

We represent the Harirud's WEF system using MUSIASSEM's flow–fund accounting. Funds are capacity elements that persist over the analysis window and enable metabolism, such as population, labor time, irrigated land, machinery and irrigation infrastructure, installed power capacity, conveyance and distribution networks, and where observable proxies for aquifer or reservoir storage. Flows are the throughputs consumed or produced within the window, including water abstractions and deliveries, energy and fuel use, agricultural inputs, and the production of potable water, electricity, and marketable crops. Outputs denote the useful goods and services supplied to society (e.g., treated water delivered, electricity supplied, crop tonnage or calories), while Environmental Loads capture the biophysical pressures generated by WEF activities, such as depletions relative

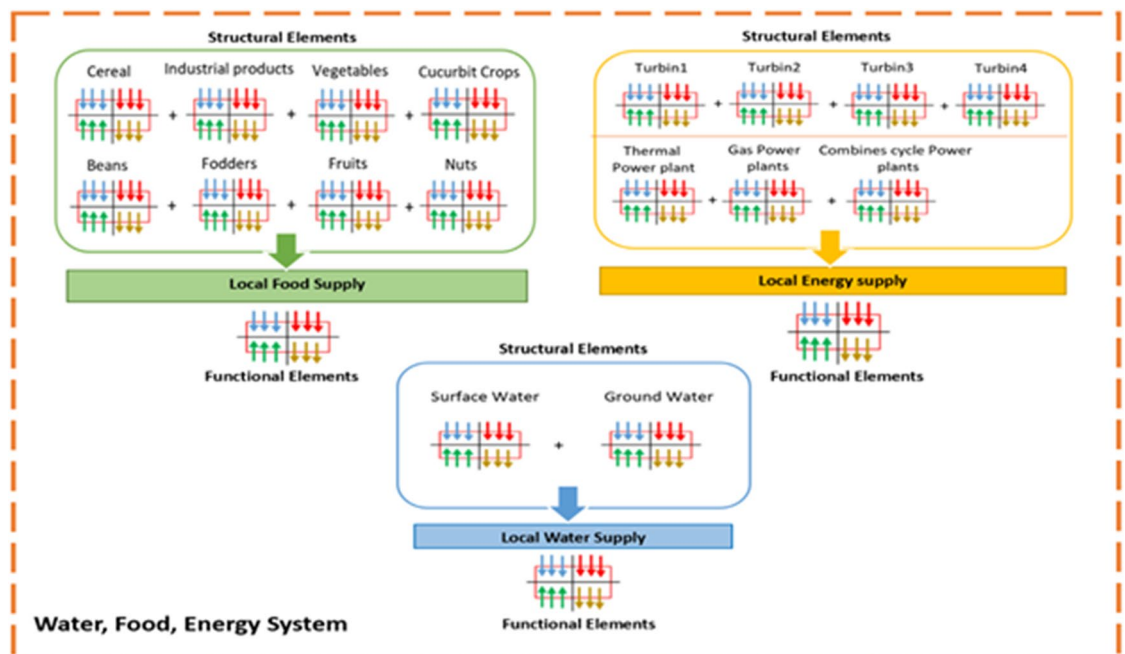


Fig. 3. Hierarchical relationships between processors and their structural components.

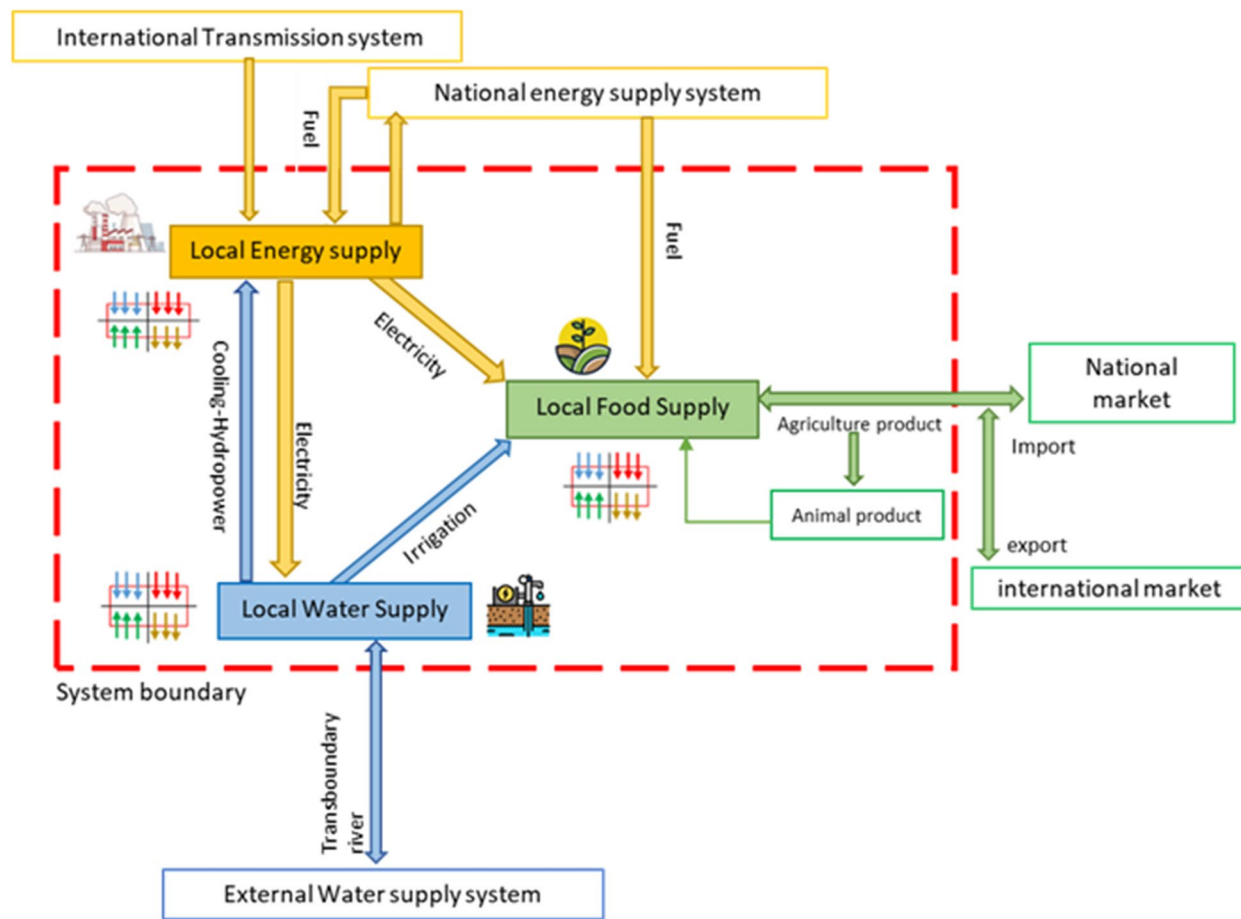


Fig. 4. Performance of a metabolic system under the WFE NEXUS approach.

to renewable water, water for power-plant cooling, transmission and distribution (T&D) losses, fuel use and associated CO₂ emissions, and post-harvest losses.

In the water subsystem, we distinguish inflows (upstream river inflow, local runoff, groundwater withdrawals, return flows, and technosphere transfers if any), storage-related funds (reservoirs, aquifer proxies, conveyance capacity), and uses (municipal, irrigation, industrial, environmental flows). Treatment processes for drinking water and wastewater are included where data permit. The water transmission system comprises bulk canals and pipelines, pumping stations, and municipal distribution; we track conveyance loss, non-revenue water, and specific energy for transport. Water outputs are measured as volumes effectively delivered to end uses, and loads include consumptive use, depletions, and quality-related proxies where available.

In the energy subsystem, generation technologies (thermal, hydropower, and other renewables where present) are characterized by installed capacity, output, and input requirements, including fuels and process water for cooling or steam generation. The electricity transmission system includes high-voltage transmission and medium/low-voltage distribution; we report technical and commercial losses and cross-border imports/exports. End uses are disaggregated to highlight agriculture's electricity demand for groundwater pumping and pressurized irrigation. Energy outputs are electricity supplied to end users, and Environmental Loads include CO₂ from generation and on-farm pumping, plus water intensity of power.

In the food subsystem, funds include cultivated area (rainfed and irrigated), irrigation infrastructure, and machinery. Flows comprise agricultural inputs, blue/green water applied, and on-farm energy use. We track primary production by crop group, processing and storage capacities, and loss rates along the chain. Trade flows are represented to distinguish basin-internal availability from imports/exports and to infer virtual water and embodied energy where applicable. Outputs are marketable production and, when relevant, dietary availability; loads include water and energy intensity per ton and post-harvest loss fractions.

Cross-sector couplings are explicit. Energy-for-water is measured as electricity per unit of water delivered for supply and irrigation. Water-for-energy is measured as cooling/process water per unit of electricity and as flow dependence for hydropower. Water-for-food and energy-for-food capture irrigation water and energy use per ton produced. We report adequacy ratios (output/demand) for each subsystem, fund productivities (e.g., t·ha⁻¹·yr⁻¹; MWh·MW⁻¹·yr⁻¹), and sustainability stresses (withdrawals/renewables, T&D loss fractions, CO₂e/MWh, non-revenue water, and post-harvest loss).

Evaluating the WEF system

In this study, to quantify the functional elements of the processors, a wide range of observational data was used. These data were obtained from global databases, reputable scientific articles, and yearbooks and reports received from official authorities of both Iran and Afghanistan, such as the Ministry of Energy, Ministry of Agriculture Jihad, Regional Water Authority, and Khorasan Razavi Electricity Distribution Company for Iran, and the Ministry of Agriculture, Irrigation and Livestock, the National Statistics and Information Authority, and the Ministry of Energy and Water for Afghanistan, as well as from international organizations such as FAO, USAID, and DACCAR. The details are provided in Appendix b, in addition, some of the functional elements were calculated using mathematical equations and formulas, which are explained in detail for each processor in Appendix a.

In addition, analytical indicators were used in this study to provide a complementary assessment of the water–food–energy nexus. These indicators and their calculation methods are presented in Table 1.

Results

In this section, the Nexus concept is first examined in the context of processors for local WEF supply, demonstrating the dependency and interactions between natural and human systems within the borders of both countries. The values of their constituent components are the annual averages of parameters over the 2011–2021 period, based on the calculations and available data presented in the previous section. Additionally, using a graphical-numerical framework based on the nexus concept, the relationships between each processor and others within the border, as well as the dependency on meeting demand from outside the border at the Harirud River Basin level, will be examined. Finally, by calculating the numerical indicators introduced in Table 1 the status of some components of the processors and their outputs in Iran and Afghanistan will be assessed.

Local water supply

Iran

The local water supply processor encompasses the process from the point of water abstraction from surface and groundwater sources, from abstraction to delivered withdrawals for various uses. The water processor has the most interaction with the biosphere. Figure 5 shows the implementation of the local water supply processor in Iran. As observed, precipitation and evapotranspiration, as the main natural inputs and outputs in the water system, were estimated based on the corrected GLDAS data. Accordingly, during the period 2011–2021, the average annual precipitation volume was estimated at 2.7 BCM, equivalent to an average annual precipitation of 206 mm in the basin. This amount, compared to the 40-year long-term average precipitation up to 2008 (7.8 BCM), indicates an approximate 8% decrease in rainfall.

Of the total precipitation volume, 5.6 BCM was evapotranspiration from natural lands, accounting for 78% of the total precipitation. The remaining contributed to runoff or infiltration into surface and groundwater resources. Based on the difference between precipitation and evapotranspiration, the average annual renewable water resources available in the Iranian part of the basin were estimated at 1.6 BCM.

Food indicators		
Indicator	Formula	Description
Water Use productivity	$WUP = \frac{\text{Crop yield (kg/ha)}}{\text{Crop evapotranspiration (m}^3\text{/ha)}}$	The (WUE) index in agriculture measures how effectively water is used to produce crops.
Land productivity	$LP = \frac{\text{Crop production (Kg)}}{\text{Land area (Ha)}}$	indicator used to measure the amount of agricultural production per unit of land. It is essential for evaluating farm efficiency.
Energy use efficiency	$EUE = \frac{\text{Crop yield (kg/ha)}}{\text{Energy input (Mj/ha)}}$	It represents the amount of crop produced per hectare in relation to the consumption of energy-intensive inputs such as chemical fertilizers, seeds, water, fuel, and electricity, as well as the use of machinery and labor per unit area.
Water indicators		
Falkenmark indicator	$FI = \frac{\text{Renewable water resource (m}^3\text{)}}{\text{Population}}$	It calculates the annual freshwater availability per person, and it is typically expressed in cubic meters per capita per year (m ³ /capita/year). Classification Range: < 500 m ³ /capita: Severe water scarcity 500–1,000 m ³ /capita: Water scarcity > 1,000 m ³ /capita: Water stress or adequate water
Water withdrawal index	$WWI = \frac{\text{Total withdrawal water (m}^3\text{)}}{\text{Renewable water resource (m}^3\text{)}}$	The index helps assess the pressure on water resources and is used to monitor the sustainability of water consumption in different regions. Classification Range: < 20%: Stable situation 20–40%: low Water scarcity > 40%: Sever water stress
Ground water withdrawal	$GWR = \frac{\text{Groundwater withdrawal (m}^3\text{)}}{\text{Total water withdrawal (m}^3\text{)}}$	It is used to evaluate the extent to which groundwater is being withdrawn relative to total water withdrawals in region.
Food water scarcity	$FWSI = \frac{\text{Total water withdrawal for agriculture (m}^3\text{)}}{\text{Total renewable water resource (m}^3\text{)}}$	It is useful for assessing the sustainability of freshwater resources. It helps identify regions under high water stress

Table 1. Indicators used in evaluating components of the WEF system processors.

Sized processor of the Functional Elements Local Water Supply (2011-2021), Iran-Harirud Basin

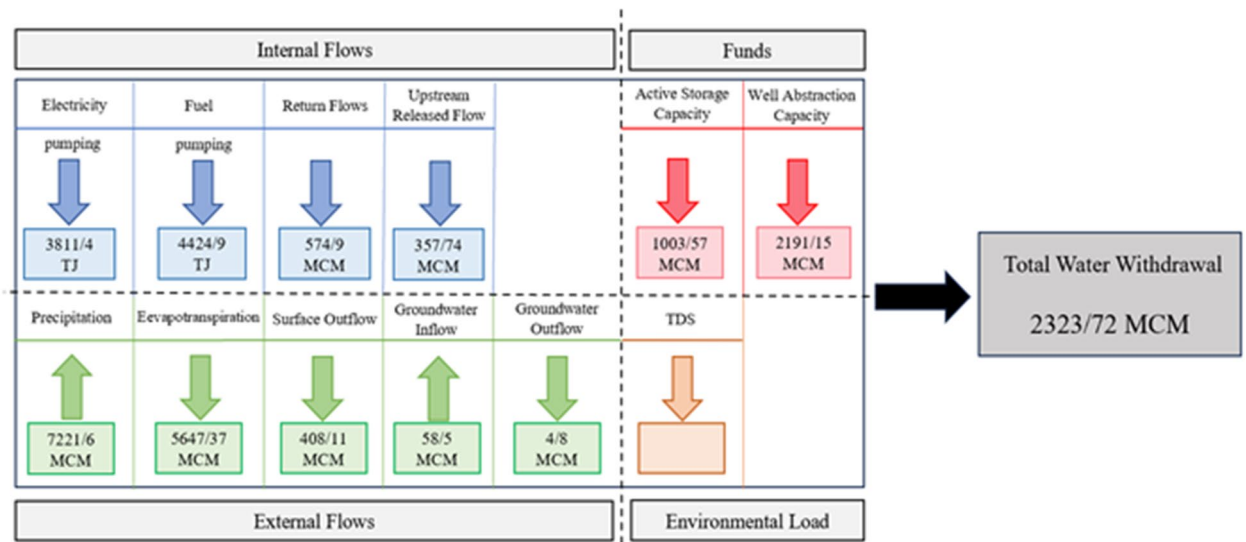


Fig. 5. Sized processor of the functional element for local water withdrawal (Iran).

The Iranian section, as the downstream part of the Harirud Basin, depends partly on the flow released from Afghanistan. During the 11-year study period, an average of 357.74 MCM/yr of water was released by Afghanistan in the upstream and entered the Doosti Dam on the Iran-Turkmenistan border. The actual flow volume discharged from the border city of Sarakhs, Iran, to Turkmenistan was reported as 408.11 MCM³⁷. This amount includes Turkmenistan's share of the Doosti Dam storage as well as the outflows from the Kashafrud River within Iran.

According to reports from the Khorasan Razavi Regional Water Authority during the study period, an average of 58.5 MCM of groundwater flow entered the Sarakhs aquifer from Turkmenistan annually, while 4.8 MCM of groundwater from the Sarakhs and Salehabad–Jannatabad aquifers flowed into the aquifers of Turkmenistan and Afghanistan. In the 40-year long-term balance, the inflow from Turkmenistan to Iran was estimated at 101 MCM, and the outflow from Iranian aquifers to neighboring aquifers at 22 MCM, showing a 42% and 84% reduction, respectively, compared to the study period.

The structural components of the water utilization system include the effective storage capacity of dams and the wells constructed to exploit groundwater resources. In Khorasan Razavi Province, a total of 12 dams has been constructed for the utilization of surface water resources, including the transboundary Harirud River and the Kashafrud, Rusrud, and Jamrud Rivers. The total effective storage capacity of these dams is 1,003.57 MCM, and their total regulated water volume is 442.5 MCM. Among these, the joint Doosti Dam, with an effective capacity of 980 MCM and an annual regulated water volume of 342 MCM, is the largest dam in the basin. The other dams are relatively small, with a combined effective capacity of only about 100.5 MCM.

To exploit groundwater resources in the basin, 5,931 deep wells with a maximum discharge of 19.5 L per second and an average annual operation of 4,841 h, and 6,140 semi-deep wells with a maximum discharge of 3.75 L per second and an average annual operation of 2,118 h have been drilled⁴⁰. Based on the technical data of the wells, the total extraction capacity of all wells in the region is estimated at 2,191.15 MCM/yr.

According to the output components of the water supply system, the total water withdrawal from surface and groundwater resources was 2.32 BCM, which is approximately 1.5 times the annual renewable water volume (1.6 BCM). Nearly 78% of the total withdrawals (1.78 BCM) were supplied from groundwater resources, including 1.73 BCM from wells and 141 MCM from springs and qanats. The share of surface water resources from total withdrawals was estimated at 452.7 MCM.

For groundwater extraction through well pumping, 3,811.4 terajoules of electricity (equivalent to 1,059 gigawatt-hours) were consumed for pumping water from 7,693 electric wells, and 4,424.9 terajoules of fuel (equivalent to 78.6 million liters of diesel) were used for pumping from 4,378 diesel wells. The agricultural sector, with an annual withdrawal of 1.67 BCM (72% of total withdrawals), had the largest share. Of this amount, 15% (250 MCM) was supplied from surface water, and 85% (1,419 MCM) from groundwater.

According to the Khorasan Razavi Regional Water Authority (2021)⁴⁰, the return flow from agricultural use accounted for 15%, equivalent to 218 MCM, during the study period. Therefore, the actual agricultural consumption was 1.45 BCM. Domestic water use ranked second, based on per capita consumption and population. The total water withdrawn for domestic use was 397.6 MCM/yr, comprising 30% from surface water and 70% from groundwater³². Of this amount, 278.3 MCM returned to water sources, resulting in an actual domestic consumption of 119.3 MCM.

Except for the metropolitan area of Mashhad, all other cities within the basin rely on groundwater for drinking water. Meanwhile, Mashhad's dependence on surface water increased from 7% in 2007 to 24% in 2021.

Water withdrawals for industry and services were entirely supplied from groundwater, totaling 256.3 MCM. Considering a return rate of 15% for services and 70% for industry, a total of 78.5 MCM were returned to water resources. Accordingly, the actual water consumption in these two sectors averaged 177.8 MCM/yr.

Based on the assessment of withdrawals from the water subsystem, out of the total 2.4 BCM of annual withdrawals, approximately 588 MCM were returned to water sources, and the total actual water consumption in the Iranian part of the Harirud Basin was estimated at an average of 1.83 BCM/yr.

Afghanistan

As shown in Fig. 6, the inflow volume from precipitation into the water subsystem in the Afghan part of the basin during the 11-year study period was estimated to be an average of 10.45 BCM, equivalent to 266.8 mm of annual rainfall. Compared to the Iranian part of the basin, the precipitation volume was 45% higher. Of the total inflow generated by precipitation in the basin, 80%, equivalent to 8.39 BCM, was lost through evapotranspiration from natural lands. Based on the amount of precipitation and evapotranspiration, the average renewable water resources available in the Afghan part of the basin were estimated at 2.06 BCM, which is 29% higher than that of the Iranian part.

As mentioned in the Iranian subsystem, Afghanistan, as the upstream country of the Harirud River Basin, annually releases an average of 357.8 MCM of water to the downstream. In terms of groundwater exchange, only a very small amount, about 1.31 MCM flows from Iran's Salehabad–Jannatabad aquifer into Afghanistan's aquifers.

For the utilization of surface and groundwater resources, the only operational reservoir dam in the Afghan part of the basin is the Salma Dam, with a total capacity of 640 MCM and an effective capacity of 633 MCM, constructed on the Harirud River³⁵. Regarding groundwater resources, the lack of reliable and up-to-date data remains one of the main limitations in this region. Consequently, there are no credible reports on the total number of drilled wells; only 644 deep and hand-dug wells were recorded in the Zarghoon Pashtun and Karukh districts up to 2004³⁸.

According to the output of the water balance system, the total water withdrawal from the Afghan part of the Harirud River Basin was estimated at an average of 659.5 MCM/yr, which is 73% less than in the Iranian part. However, unlike Iran, Afghanistan has a high dependence on surface water resources, about 520.2 MCM, equivalent to 79% of total withdrawals, came from surface water. Accordingly, the agricultural sector, with an annual withdrawal of 612 MCM, is the region's primary water consumer. Of this amount, about 80 MCM returned to the water system, resulting in an actual agricultural consumption of 532.17 MCM.

The domestic sector ranks second, with a withdrawal of 34.5 MCM from groundwater resources³⁸. Of this amount, approximately 27.82 MCM returned to water resources, and 12 MCM were consumed. The industrial sector in this region consists of only 200 production units located in the Herat Industrial Zone, which collectively withdraw 7.8 MCM of groundwater. Of this amount, 70%, equivalent to 5.46 MCM, returned to water sources, and the actual industrial consumption was estimated at 2.34 MCM.

It should be noted that due to the lack of specific data on return flow rates from different uses in Afghanistan, the same coefficients as in Iran were assumed. Therefore, the reported figures on water withdrawals and actual consumption in Afghanistan are subject to uncertainty and should be interpreted as approximate estimates.

Sized processor of the Functional Elements Local Water Supply (2011-2021), Afghanistan-Harirud Basin

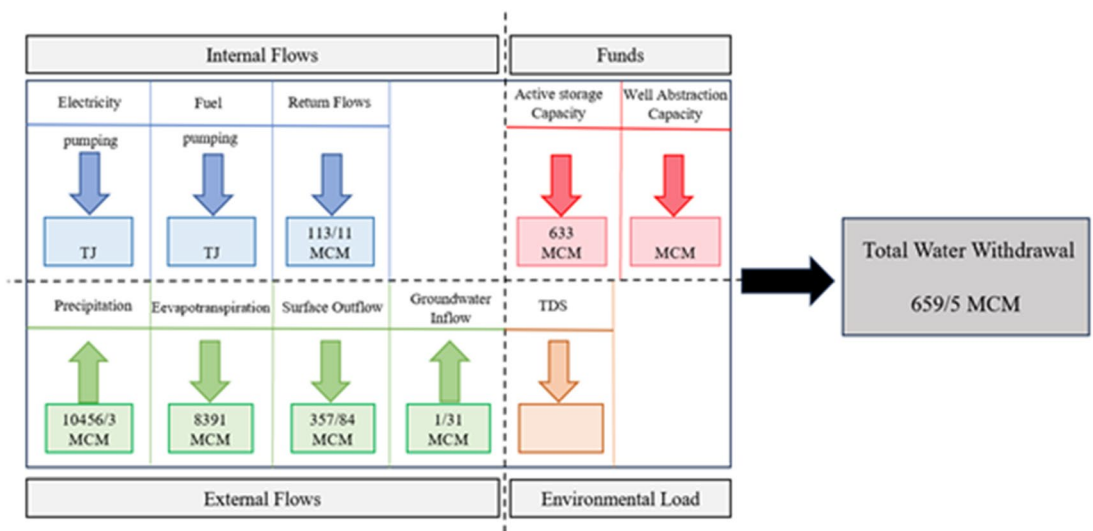


Fig. 6. Sized processor of the functional element for local water withdrawal (Afghanistan).

Local food supply

Iran

As shown in the study period, on average, 365,453 hectares of land were cultivated with agricultural and horticultural crops. According to the cropping pattern derived from the Khorasan Razavi Agricultural Jihad Organization, 19% of the total cultivated area was dedicated to horticultural crops and 81% to field crops. Furthermore, 30% of the cultivated land was rainfed, mainly consisting of grains (96%) and legumes (4%). Among irrigated field crops, with a total cultivated area of 267,000 hectares, the largest share belonged to grains (61%), followed by vegetable–melon crops (15%), while vegetables (6.7%) and industrial crops (6.2%) had the smallest shares. In the category of horticultural crops, saffron and cumin (28%) and pome fruits (24%) had the largest cultivated areas, while stone fruits (10%) had the smallest share (Khorasan Razavi Agricultural Jihad, 2011–2021). One of the main inflows into the food subsystem is water. Since irrigated cultivation is more common in the region, most of the agricultural water demand is supplied from blue water resources (surface and groundwater), and only a small portion depends on green water (precipitation). The estimation of agricultural water consumption was based on the average net irrigation requirement (blue water) and effective rainfall (green water) for crops during the study period, obtained from the Soil and Water Research Institute. The share of surface and groundwater resources was also determined using the annual water reports of the Khorasan Razavi Regional Water Authority.

Accordingly, total agricultural water consumption was estimated at 1.712 BCM, of which 1.451 BCM (85%) came from blue water sources (surface and groundwater), and 260 MCM (15%) from green water. About 90% of irrigation water demand for fields and orchards was supplied from groundwater, including 260 MCM from springs and qanats and 1.032 BCM from wells.

By crop type, field crops accounted for 75% of total blue water use, and horticultural crops for 25%. On average during the study period, blue water consumption by crop groups was as follows: grains (491 MCM), forage crops (220.2 MCM), vegetable–melon crops (178 MCM), vegetables (105.5 MCM), and industrial crops (97.3 MCM). Among horticultural crops, the highest blue water consumption belonged to stone fruits (108 MCM) and pome fruits (103.5 MCM), while the lowest belonged to saffron and cumin (36.2 MCM) and small-seed fruits (37.3 MCM). Considering a 15% return flow in the basin (Toos Ab, 2012), the volume of return flow from cultivated lands to surface and groundwater was estimated at 218 MCM, and the total withdrawal from surface and groundwater resources was calculated at 1.67 BCM. Other major inputs in the agricultural sector include chemical fertilizers, seeds, fuel, and electricity (used for water pumping from wells). The average consumption of chemical fertilizers in the agricultural sector of this region was estimated at 3,714.16 terajoules, which represents the largest share among agricultural inputs. This corresponds to 96,321 tons of fertilizers, including nitrogen (50%), phosphate (31%), and potassium (19%).

Due to the high dependence of agriculture on groundwater resources and the large number of wells, a significant portion of inputs is also attributed to fuel and electricity consumption for pumping. On average, 2,138.62 terajoules of fuel (equivalent to 44.6 million liters of diesel) and 2,087.73 terajoules of electricity (equivalent to 518 GWh) were consumed annually for groundwater extraction in the agricultural sector. Seeds accounted for 2,131.41 terajoules (19%) of the total input energy, equivalent to 121,000 tons of seed. Human labor and machinery are also considered agricultural inputs that remain fixed during the production process; therefore, they are categorized under Funds. Together, they accounted for 7% of the total input energy, equivalent to 767.18 terajoules. The machinery-to-labor energy ratio (2.38) indicates a semi-mechanized system. The highest labor use was recorded in the production of horticultural crops, particularly saffron, pome fruits, and dried fruits, while grains had the highest share of mechanized operations in the region. The food production subsystem of Iran, with a total consumption of 10,839 terajoules of inputs and 1.712 BCM of blue and green water, produced an average of 3.1 million tons of gross agricultural products annually. Of this amount, 2.8 million tons were main crops, and 300,000 tons were grain straw. From the total production, 2.778 million tons, valued at 21,196.27 billion rials, reached final consumption. About 13.6% of the total main crop production was lost along the supply chain and did not reach final use.

Based on the estimated loss ratios from the FAO food balance and Mirzaei (2021)³⁹, of the 338,760 tons of lost products, 80% belonged to field crops and 20% to horticultural crops. The highest losses were recorded for vegetables, vegetable–melon crops, grains, and fresh fruits. The net irrigation requirement for these lost products indicates that approximately 173 MCM of blue water were consumed to produce them, equivalent to 12% of total agricultural water use. Of the total net agricultural products, 80% were directly consumable without processing, including vegetable–melon crops, vegetables, legumes, forage crops, and horticultural products. The forage group (including alfalfa, forage maize, barley, and grain straw) totaled around 700,000 tons and was used for livestock feed. The remaining 70% of this category, equivalent to about 2.209 million tons, was distributed to meet local demand, domestic markets, and exports to neighboring countries (Fig. 7).

Conversely, wheat and industrial crops, averaging 577,792 tons annually, required processing. After processing, 67% of these products entered the supply chain to meet the demand for flour, sugar, vegetable oils, and fibers, while about 102,000 tons were converted into by-products such as oilcake, pulp, and bran, used for livestock feed and concentrate production. About 16% of the raw materials were lost or turned into by-products during processing, which are often reused in industry or fertilizer production. It should be noted that the differentiation between main and by-products for crops requiring processing was made based on the references provided in the Appendix II.

Afghanistan

As shown in the processor's fund elements in Fig. 8, during the study period, based on agricultural reports from the Ministry of Agriculture, Irrigation, and Livestock of Afghanistan (2018–2021) and land use maps extracted from ESA, approximately 191,000 hectares of agricultural land in the Afghan part of the Harirud basin

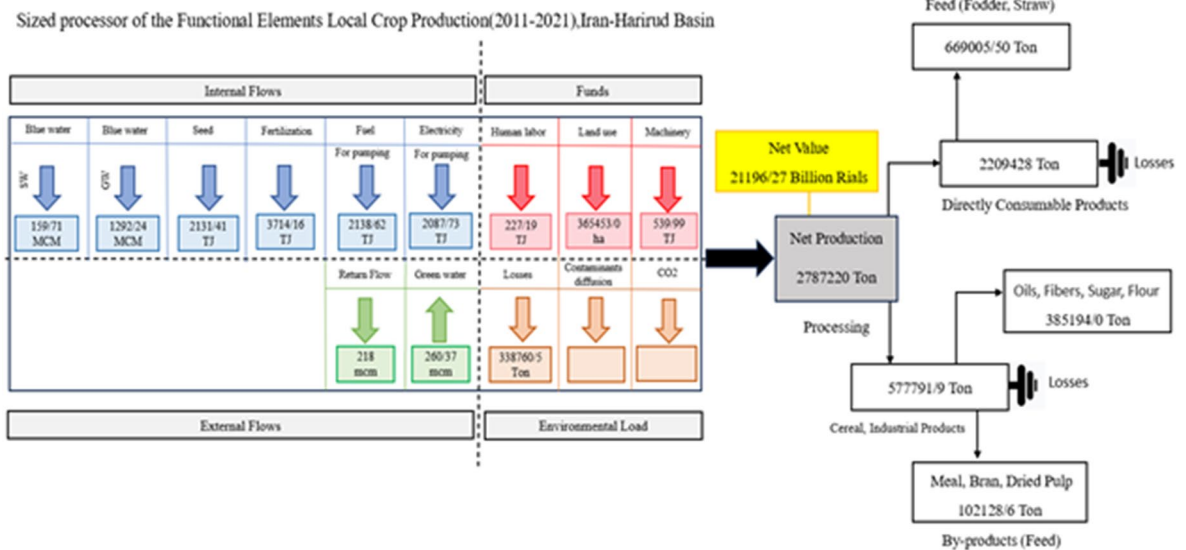


Fig. 7. Sized processor of the functional element for local crop production (Iran).

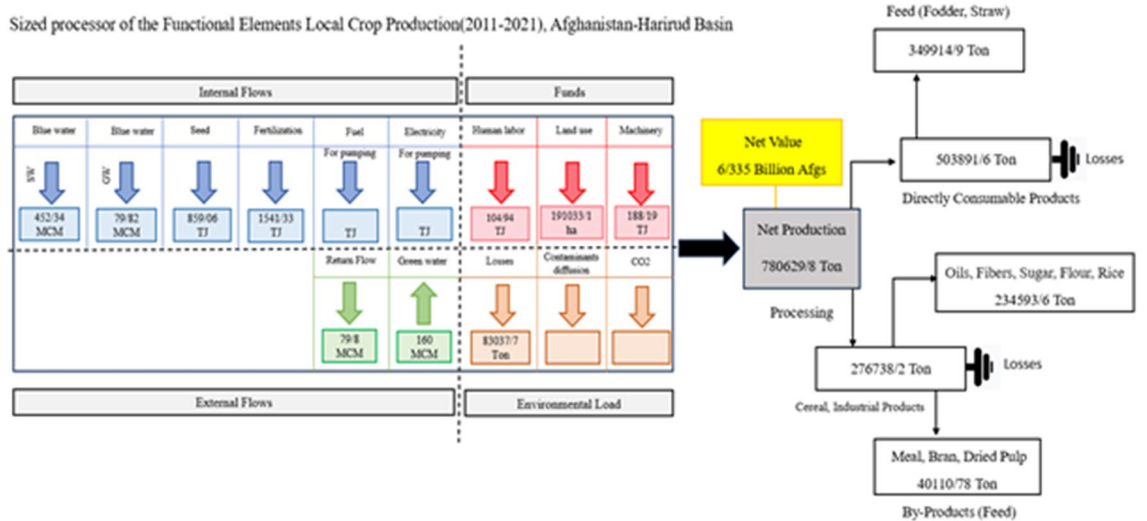


Fig. 8. Sized processor of the functional element local crop production (Afghanistan).

were cultivated. The cultivated area in Afghanistan was 47% smaller than that of Iran. Of this total area, 94% was allocated to field crops and only 6% to orchards. According to the Ministry of Agriculture, Irrigation, and Livestock of Afghanistan (2019), wheat was the dominant rainfed crop, covering 80,000 hectares (42% of the total cultivated area). In irrigated farmland, cereals (wheat, barley, rice, and maize) were the dominant group, accounting for 91%, followed by legumes (3%), while other crop types each occupied less than 3% of the total cultivated area. In the orchard category, stone fruits (such as mulberries and grapes) made up 39%, saffron 32%, pome fruits 16%, seed fruits 7%, and dry fruits 6% of the total orchard area.

The average annual water consumption in the Afghan part of the Harirud River Basin’s agricultural sector was estimated at 692 MCM, supplied from both blue water (surface and groundwater) and green water (rainwater). Of this total, 77% (532 MCM) originated from blue water and the Technosphere, while 23% (160 MCM) came from green water and the biosphere. Compared with Iran, blue water consumption in Afghanistan was 64% lower, while irrigated farmland was 58% smaller. This difference is primarily due to the predominance of low-water-demand crops, such as wheat and barley, in the Afghan cropping pattern. The distribution of blue water sources between surface and groundwater was estimated based on previous studies and reports^{41–43}. Accordingly, 85% (452.34 MCM) of irrigation water was supplied from surface water, and 15% (80 MCM) from groundwater. Studies (e.g., Hosseini, 2018) indicate that irrigation in this region mainly relies on traditional systems such as canals directly or indirectly connected to the Harirud River and its tributaries. Groundwater is mostly extracted

through qanats and karezes, while well-based irrigation remains limited. Assuming a 15% return flow rate similar to Iran, the total water withdrawal from all sources to meet agricultural demand was estimated at 612 MCM.

Among irrigated crops, cereals had the highest water consumption, accounting for 420 MCM (79% of total agricultural demand), followed by legumes (22.5 MCM) and vegetables (10 MCM). In the orchard category, stone fruits (24 MCM) and pome fruits (14 MCM) had the highest water demands. Conversely, industrial crops and melons consumed 9 and 10 MCM, respectively, while dry and seed fruits used 4 and 5 MCM, respectively the lowest among all groups. Due to the limited contribution of groundwater irrigation (especially from wells) and the lack of reliable data on groundwater use in Afghanistan, fuel and electricity consumption for pumping could not be evaluated. Therefore, agricultural inputs in the Afghan subsystem were limited to chemical fertilizers and seeds among internal flows, and labor and machinery among fund elements. Estimates of these agricultural inputs were gathered from key studies^{45–47}.

Among inputs, the total consumption of chemical fertilizers was 1,541.3 terajoules, equivalent to 38,986 kg of fertilizers. The share of each type was 51% urea, 42% diammonium phosphate, and 7% potassium fertilizer. Irrigated and rainfed cereals, followed by stone fruits and saffron, had the highest fertilizer consumption, while pome fruits and legumes had the lowest. Seeds were the second major input, with an average annual consumption of 859 terajoules, equivalent to 47,740 tons. Compared with the Iranian part of the Harirud basin (121,000 tons), seed consumption in Afghanistan was about 60% lower. This discrepancy is due to the smaller scale of agricultural land and the more limited cropping pattern in Afghanistan. Other contributing factors include dependency on imported seeds, limited availability, and inefficient distribution networks in rural areas. Labor and machinery, as fixed inputs, together accounted for 9% of all inflows into the Afghan agricultural production subsystem. The total energy input of these two factors was estimated at 105 terajoules for labor and 188 terajoules for machinery. The energy ratio of machinery to labor (1.79) indicates a semi-mechanized system, although the level of mechanization remains lower than in Iran (2.38), reflecting higher dependency on human labor.

Based on the processor's output and loss assessment, the food production subsystem in the Afghan part of the Harirud basin, with total energy inputs of 2,693.5 terajoules and 692 MCM of blue and green water, produced an annual gross agricultural yield of 863,666 tons. This included 487,563 tons of main products and 385,103 tons of cereal straw. Of the main products, 18% (83,037.7 tons) were lost during the production chain and did not reach final consumption. Among field crops, cereals and vegetables, and among orchard crops, pome and stone fruits, recorded the highest post-harvest losses.

Accordingly, the annual net production of main and by-products in the Afghan part of the Harirud basin (2011–2021) was 780,630 tons, with a net value for local farmers of approximately 6.5 billion Afghanis, equivalent to 8,573 billion Iranian Rials, which is 60% lower than the net value of agricultural production in the Iranian part of the basin.

Of this total, main field crops (409,412 tons) constituted 86%, and orchard crops (69,151 tons) made up 14% of total production. By subsystem elements, cereals (282,595 tons; 60%), stone fruits (31,553 tons; 6.5%), vegetables (27,691 tons; 6%), and melons (27,137 tons; 5.5%) were the dominant groups, while all other crops accounted for less than 1% of total production. Of the total net agricultural output, 503,891.6 tons (60%) were directly consumable without processing, including 349,915 tons of cereal straw, barley, and maize for livestock

Sized processor of the Functional Elements Local Electricity Power Plants Production(2011-2021), Iran-Harirud Basin

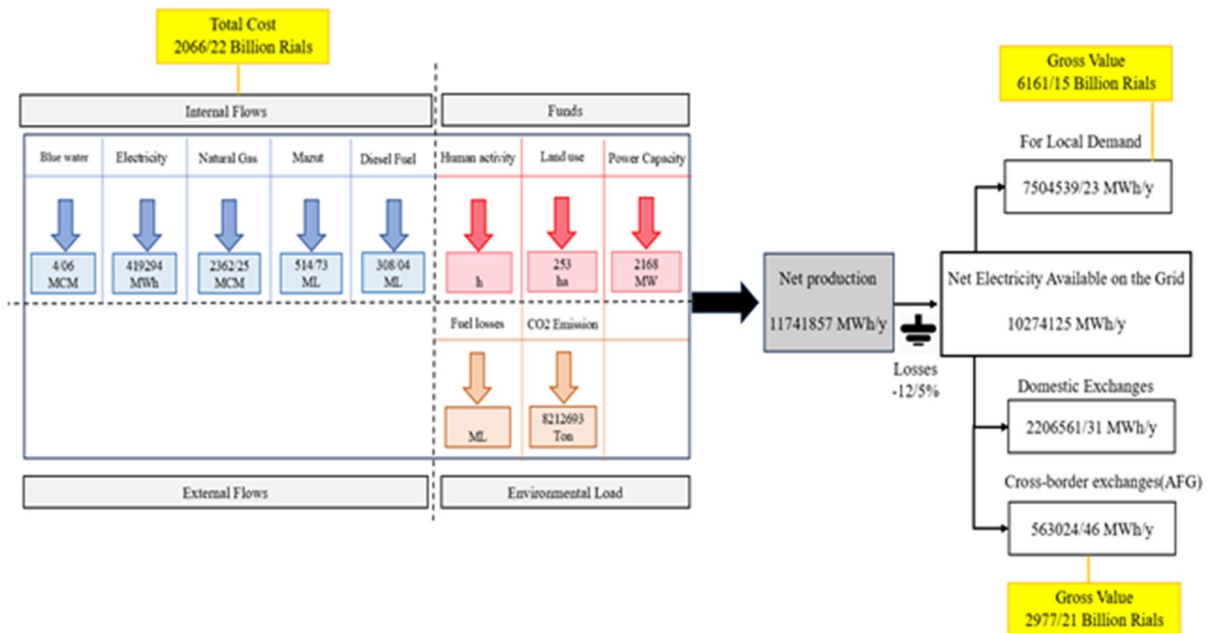


Fig. 9. Sized processor of the functional element local electricity supply (Iran).

feed, and 153,977 tons of melons, vegetables, legumes, and fruits for local human consumption. The remaining 40% (276,738 tons) consisted of wheat, rice, and industrial crops, which required processing before reaching the market. After processing, 234,593 tons of food products such as flour, rice, sugar, oil, and fibers were produced for final consumption, along with 40,111 tons of by-products used for livestock feed.

Local energy supply

Iran

The local electricity production subsystem of Iran within the Harirud River basin, shown in Fig. 9, consists of non-renewable thermal power plants, including steam, gas, and combined cycle plants (structural elements). This system includes the Tous, Mashhad, Shams, Ferdowsi, and Shariati power plants, which together occupy a total area of 253 hectares. Electricity generation in these plants relies primarily on fossil fuels. During the period 2011–2021, an annual average of 2,362 million cubic meters of natural gas (89,765.7 terajoules) was used as the main fuel, along with 515 million liters of fuel oil (20,589.4 terajoules) and 308 million liters of diesel (17,342.7 terajoules) as alternative fuels. These figures correspond to a specific fuel consumption of approximately 194 m³ of natural gas, 42 L of fuel oil, and 25 L of diesel per megawatt-hour (MWh) of electricity produced. The substantial use of fossil fuels in the electricity generation process has led to significant CO₂ emissions. According to the Ministry of Energy's energy balance report (2021), these plants emit approximately 2.8 million tons of CO₂ per year, equivalent to 675 kg of CO₂ per MWh of electricity produced. This indicates the high environmental pollution load of this subsystem in the region.

Water is another vital flow in the electricity generation subsystem. According to the Ministry of Industry, Mine, and Trade, an average of 4 MCM of water is consumed annually for steam production and cooling systems. In other words, producing one MWh of electricity requires approximately 334 L of water. From an economic perspective, based on the official selling prices of petroleum derivatives for power plants and the regional water tariff book of Khorasan Razavi, the total cost of consumable inputs (fuel and water) for these plants was estimated at 2,066 billion Iranian rials. It should be noted that this value represents only a portion of the total production costs, as other expenses such as maintenance, labor, and infrastructure investment were not included due to data limitations. Overall, the local electricity production subsystem in the Iranian part of the Harirud basin generated a gross output of 12.1 million MWh (43,780.14 terajoules) annually, relying heavily on fossil fuels and water resources. This system also contains an autocatalytic flow, meaning that part of the electricity produced is consumed internally for operating and maintaining equipment.

In total, 3.5% of the electricity generated (approximately 419,000 MWh per year, equivalent to 1,509.4 terajoules) was used for technical and operational consumption within the plants. After deducting this internal use, the net electricity production was 11.7 million MWh (42,270.7 terajoules) per year. According to the Khorasan Razavi Regional Electricity Company (2023), these power plants are connected to the national power grid, where approximately 1.47 million MWh (12.5%) of the net electricity is lost in transmission and distribution networks. After accounting for these losses, the available electricity for final consumption amounted to 10.27 million MWh annually.

Based on consumption data and the number of local subscribers obtained from the Khorasan Razavi Electricity Distribution Company and Mashhad County Power Department (2011–2022), about 73% of the total electricity generated was consumed locally, indicating 100% self-sufficiency of the subsystem in meeting regional demand. The gross value of electricity sales to local consumers, based on the Ministry of Energy's average retail electricity price, was estimated at 6,161 billion rials, equivalent to 820 rials per kilowatt-hour across all sectors.

In addition to meeting local demand, approximately 2.77 million MWh of surplus electricity were available annually for exchange. Of this amount, about 563,000 MWh (20%) were exported to Afghanistan via the Torbat-e Jam and Taybad transmission lines to the Herat substation, while the remaining surplus was transmitted to

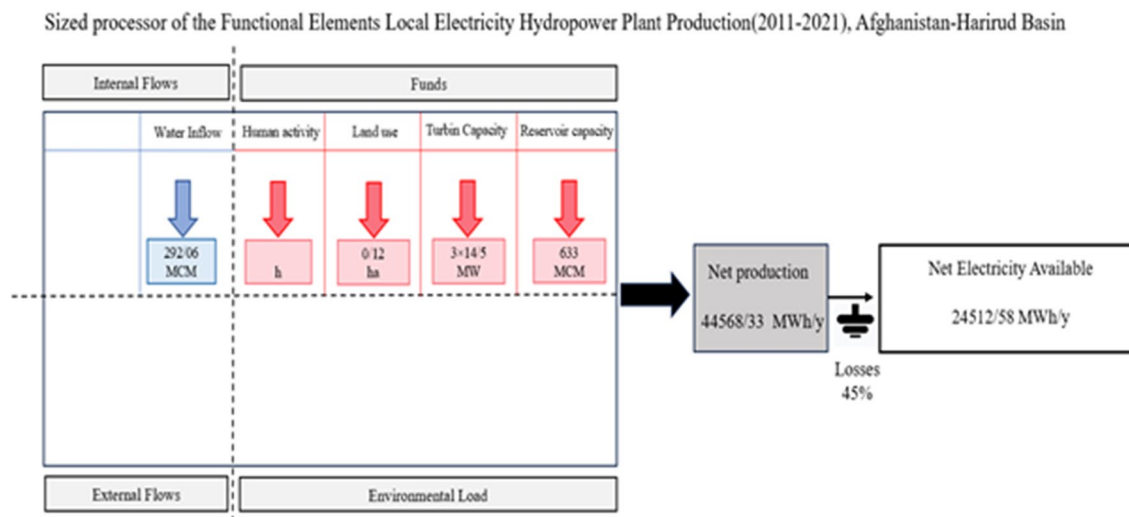


Fig. 10. Sized processor of the functional element local electricity supply (Afghanistan).

neighboring provinces during peak consumption months. The gross export value of electricity to Afghanistan, based on the Statistical Yearbook (2014–2020) and the average exchange rate during the study period, was estimated at 2,977 billion rials. On average, Iran received 5,288 rials (equivalent to 4.5 Afghani) per kilowatt-hour of exported electricity.

Afghanistan

The structure of the local electricity supply subsystem in the Afghan part of the Harirud basin, shown in Fig. 10, is simpler compared to that of Iran. The Salma Hydropower Plant is equipped with three Francis turbines, each coupled with a generator of 14.5 megawatts, giving a total installed capacity of 43.5 megawatts. This power plant has been operational since 2016, and during the first five years of the study period, local electricity generation was zero.

According to the National Statistics and Information Authority Yearbook (2016–2021), during the first five years of operation, the plant produced an average of 44,568 megawatt-hours (MWh) of electricity per year. However, the Asian Development Bank's Afghanistan Power Sector Master Plan estimated the plant's average annual generation potential at 197,000 MWh. This means that Afghanistan has utilized only 23% of the plant's potential capacity. To generate this amount of electricity, water flows through the turbines at a discharge rate of 9.26 cubic meters per second, equivalent to an annual volume of 292 MCM. The Salma Dam reservoir, with a storage capacity of 633 MCM, supports this operation. Although a small amount of evaporation occurs from the reservoir surface, the internal water flow in this subsystem does not represent actual water consumption; it is merely required for power generation and subsequently continues downstream to meet other water demands.

Although the plant's electricity generation is relatively low and insufficient to balance regional demand, its environmental impact is minimal. Unlike the thermal power plants in the Iranian part of the basin, which have a significant environmental load, the electricity generation process in Afghanistan does not emit greenhouse gases, and its environmental footprint is mainly associated with the construction and operation stages. Moreover, its land footprint is very small; excluding the dam reservoir, the powerhouse occupies only about 0.12 hectares of land. According to the output of the energy subsystem processor in Afghanistan, the electricity generated by the Salma Hydropower Plant is directly supplied to Herat and Ghor provinces, since these regions are not connected to Afghanistan's national power grid. One of the main challenges is the very high transmission and distribution loss rate, amounting to 45%. Consequently, of the total electricity generated, approximately 20,055.7 MWh are lost annually, leaving only about 24,512 MWh available to meet the demand in Herat and Ghor provinces.

According to the Asian Development Bank, as of 2013, the electrification rate was 78% in Herat and only 4% in Ghor. Assuming the realization of the projected development scenario, these rates were expected to increase to 95% and 38%, respectively, by 2021. Based on this, the net electricity demand in the two provinces during the study period was estimated at 679,340 MWh per year, and the gross demand at 955,640 MWh per year. Accordingly, the self-sufficiency level of local electricity production in the Afghan part of the Harirud basin is only about 3.6%, highlighting the region's strong dependence on electricity imports.

WEF nexus system of the harirud river basin

In the previous section, the performance of the social–ecological metabolism-based processors of each subsystem were quantified and evaluated separately for the Iranian and Afghan parts of the Harirud River Basin. This assessment included an analysis of inflows and exchanges from the technosphere and biosphere, the use of structural resources, pollutants and environmental loads, economic parameters, and finally, the net outputs and final products of each processor. In this section, a summary of the cross-border and intra-basin interactions among the processors of the three subsystems WEF is presented in an integrated framework at the Harirud basin boundary.

As shown in Fig. 11, the subsystems in both the Iranian and Afghan parts of the Harirud River Basin not only have complex internal interactions within their operational boundaries but also engage in external exchanges beyond the basin through resource trade and the transboundary Harirud River. The external interactions of the Iranian part indicate that, in order to supply fuel for non-renewable power plants and diesel pumps used for groundwater extraction, a significant amount equivalent to 132,123 terajoules of diesel, natural gas, and fuel oil is imported from other parts of the country. In return, the surplus electricity generation of local power plants—amounting to 2,206,561 megawatt-hours is transmitted to the national power grid to meet peak demand in other regions. At the transnational level, Iran exports part of its locally generated electricity to Afghanistan. Meanwhile, Afghanistan, as the upstream country, plays a key role in supplying water to the downstream parts of the basin by releasing the flow of the Harirud River toward the Doosti Dam.

In the food subsystem of the Iranian part of the basin, agricultural surpluses totaling 291,420 tons are exported beyond the basin. It should be noted that Iran's export products include vegetables and horticultural crops, while in Afghanistan they include wheat flour, vegetables, horticultural crops, and animal feed concentrate. Conversely, to fully meet local demand and compensate for the shortage of strategic crops, significant imports amounting to 1,355,000 tons are made from domestic markets and international sources. Although there are no precise statistics on agricultural product exchanges between the Iranian and Afghan parts of the basin, national data indicate the existence of reciprocal trade relations in agricultural commodities between the two countries.

From an intra-basin perspective, the interconnections among the water, food, and energy subsystems are clearly evident in both regions. Approximately 10% of the total locally generated electricity is used to power electrical pumps, with 55% of these pumps installed on agricultural wells. This demonstrates the direct dependency of the water subsystem on energy and the indirect dependency of the food subsystem on energy. On the other hand, thermal power plants in the region require about 4 MCM of water annually for cooling processes, a relatively small share of total water withdrawal, yet one that underscores the water–energy nexus at the local scale. In contrast, in the Afghan part of the basin, since the energy subsystem relies on hydropower

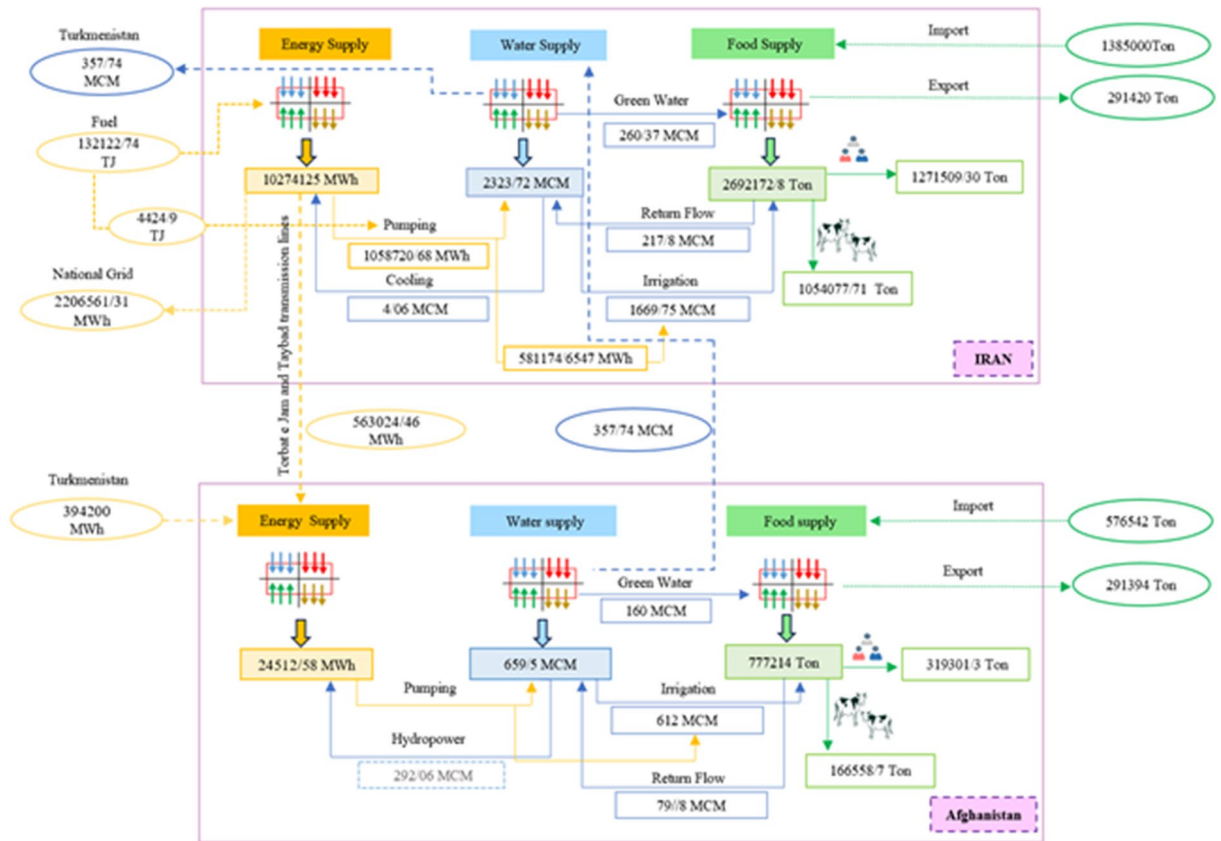


Fig. 11. A summary of the nexus interactions among water, food, and energy subsystems in the Harirud River Basin.

generation, the dependency of energy on water is significantly higher, indicating a greater vulnerability of this resource to climate change and reductions in water storage.

Across both the Iranian and Afghan parts of the Harirud Basin, over 70% of total surface and groundwater withdrawals are used to meet agricultural water demand for irrigation of farms and orchards. In addition, part of the crop water requirements is met through green water derived from precipitation. A portion of the water withdrawn for irrigation also returns to surface and groundwater bodies, contributing to their recharge. This pattern indicates that agricultural production in the basin is highly dependent on the availability of irrigation water and annual rainfall, and the balance between these two sources plays a crucial role in the sustainability of the region’s water and food resources.

Assessment of the status of some processor components based on numerical indicators at the country level

Table 2 evaluates the values of key indicators related to the food processor, broken down by agricultural product categories, and for water for the Iranian and Afghan sections.

Food sector indicators

An analysis of food-related indicators in Table 2 reveals that the yield of agricultural crops (L_p) in Iran is, on average, higher than in Afghanistan, whereas the yield of horticultural products in Afghanistan exceeds that of Iran. However, water use efficiency for most Iranian crops is higher, whereas energy use efficiency (EUE) in Afghanistan shows higher values across many crop groups. In Afghanistan, the level of mechanization is lower and there is a greater reliance on manual labor. Moreover, the consumption rate of energy-intensive inputs such as chemical fertilizers and seeds per unit area is lower in farms and orchards in Afghanistan compared to those in Iran. In addition, unlike Iran, Afghanistan’s agriculture relies on surface water resources and traditional irrigation canals, which has significantly reduced the use of fuel and electricity for pumping systems. As a result, energy efficiency has been estimated to be greater than one for most products. Nevertheless, the lower levels of technology and farm management result in reduced crop yield (L_p) in Afghanistan. Therefore, it can be concluded that Afghanistan performs better in terms of energy efficiency, whereas Iran holds a superior position in terms of final food production productivity.

	Food indicators					
	LP(Kg/ha)		WUP (kg/m ³)		EUE(KG/MJ)	
Products	Iran	Afghanistan	Iran	Afghanistan	Iran	Afghanistan
Cereals	3579.62	3031.63	0.88	0.65	0.1	0.13
Industrial Products	24607.1	3018.9	2.45	0.5	0.35	0.21
Legumes*	325.5	1433.3	-	0.18	0.09	0.13
Vegetables	38527.7	19,826	4.88	2.2	0.63	0.79
Cucurbit Crops	18269.5	16380.9	3.28	3.44	0.4	1.25
Forage	26,763	-	3.51	-	0.5	-
Fruits	8814.7	10402.34	2.2	1.9	0.3	0.39
Nuts	762.56	2255.8	0.16	0.35	0.02	0.1
Saffron	3.4	2.08	0.0019	0.0014	0.000019	0.000015
	Water Indicators					
	Iran		Afghanistan			
Water Withdrawal Index	1.45		0.32			
Falkenmark indicator	362		1327			
Groundwater withdrawal	0.76		0.21			
Food water scarcity	1.04		0.3			

Table 2. The calculated values of indices for iran and afghanistan in the harirud section.

Water sector indicators

The results of the water-related indicators in Table 2 show that Iran, with a Water Withdrawal Index of 1.45 and a Falkenmark indicator of about 362 cubic meters per capita, is experiencing a condition of severe water stress. In contrast, these values in Afghanistan are approximately 0.3 and 1327 cubic meters per capita, respectively, indicating lower water pressure and relatively better access to renewable water resources. Furthermore, the Groundwater Withdrawal Index in Iran is around 0.76, reflecting the country's high dependence on aquifers to meet agricultural demands, while in Afghanistan this index is only about 0.21, signifying a greater reliance on surface water resources. This difference leads to significantly higher energy costs and pressure on groundwater reserves in Iran, thereby reducing the long-term sustainability of water resources. On the other hand, the Food Water Scarcity Index in Iran, with a value of 1.04, indicates that the country is on the verge of a severe limitation in water availability for food production. In Afghanistan, this index is around 0.3, suggesting that the country is still within a mild water stress range. Therefore, from the perspective of water resource sustainability, Afghanistan currently enjoys a more favorable situation than Iran; however, increasing water demand and climate change trends may threaten this balance in the future.

Overall, the results of the water indicators highlight that demand management, reducing dependency on groundwater, and improving water use efficiency in Iran's agricultural sector should be prioritized in the policy framework of the Harirud basin.

Sensitivity analysis of water-energy efficiencies

Given the uncertainties inherent in large-scale data aggregation, particularly in the Afghan section of the basin where primary data is scarce, a sensitivity analysis was conducted to assess how variations in key efficiency parameters influence the system's metabolic performance. We focused on two critical parameters: irrigation efficiency (impacting water withdrawals) and pumping/turbine efficiency (impacting energy consumption and production).

Irrigation efficiency and water withdrawal

Irrigation efficiency is a critical determinant of total water withdrawal. In the baseline scenario, standard efficiency coefficients derived from regional averages were applied. A sensitivity analysis varying irrigation efficiency by $\pm 10\%$ reveals significant impacts on water security. For the Iranian sector, a 10% decrease in overall irrigation efficiency would require an increase in water withdrawal of approximately 160–180 MCM/yr to maintain the same crop production levels. Given that 85% of agricultural water is supplied by groundwater, such a decrease would directly exacerbate aquifer depletion, increasing the energy demand for pumping and accelerating the decline of groundwater tables. Conversely, a 10% improvement in efficiency could alleviate stress on the Sarakhs aquifer, though rebound effects (expanding cultivated area) must be managed.

Pump and turbine efficiency

Energy consumption for groundwater extraction is highly sensitive to electromechanical efficiency. In the Iranian sector, where agricultural pumping consumes over 1,000 GWh annually, a $\pm 10\%$ variation in pump efficiency results in a fluctuation of approximately 100 GWh in energy demand. This highlights that maintaining pump efficiency is as critical as managing water volumes for the water-energy nexus. Regarding energy production, the Salma Dam in Afghanistan (44 GWh/yr) is sensitive to turbine performance. A degradation in turbine efficiency of 5–10%—plausible due to aging infrastructure or maintenance gaps—would proportionally reduce renewable energy supply, potentially forcing a reliance on less sustainable energy alternatives. These results underscore

that “technical coefficients” in the MUSIASSEM framework are not merely static numbers but dynamic leverage points for policy intervention.

Discussion

This study used MUSIASSEM to quantify the WEF nexus across the Iranian and Afghan sections of the Harirud River Basin. The results confirm strong interdependencies alongside asymmetric vulnerabilities, providing quantitative backing to prevailing conceptual nexus arguments for arid and semi-arid transboundary basins^{5,13}.

Downstream pressures and feedbacks in Iran

Iran's water withdrawals are $\approx 1.5\times$ the annual renewable volume, with $\approx 78\%$ supplied from groundwater. This over-abstraction links directly to higher non-renewable energy use for pumping and associated environmental externalities⁴⁷. Despite dependence on upstream releases, observed surface outflows from Iran exceed inflows, pointing to management gaps in downstream flow control. Mashhad's growing reliance on Harirud inflows, coupled with a prohibited status for its aquifer⁴⁸, indicates rising risk of supply deficits and a tightening water–energy feedback as demand grows.

Upstream contrasts in Afghanistan

The Afghan section has $\sim 29\%$ more renewable water and a smaller population, yet remains within water-stress ranges on a per-capita basis. Its agriculture relies mainly on surface water and traditional canals, resulting in low irrigation efficiency, but substantially lower non-renewable energy use compared to Iran. Net production of $\sim 777,000$ tons with a 28% surplus dominated by cereals and feed suggests scope for complementary trade that could relieve Iranian deficits.

Food system imbalances and trade

In Iran, a portion of the surplus suitable for export (\approx approximately 10.5%, primarily horticulture and vegetables) is water-intensive and difficult to justify under conditions of absolute scarcity and groundwater pressure. Simultaneously, ~ 1.38 million tons of products are imported to meet demand, reflecting a misalignment between cropping patterns and local needs, as well as sizable chain losses tied to pest control, quality, storage, transport, and processing constraints. On the Afghan side, lower mechanization and conflict-related losses in processing and storage imply opportunities for cross-border cooperation; Iran's more advanced irrigation, machinery, and technical capacity could help reduce post-harvest losses.

Energy subsystem disparities

Iran meets local electricity demand, powers water-supply pumping, and exports surplus to Afghanistan, but high T&D losses waste non-renewable energy and water embedded in power production. Heavy fossil reliance raises costs and CO₂ emissions, while ≈ 4 million m³·yr⁻¹ of cooling and steam water underscores power–water interdependence. Afghanistan's system is simpler and less polluting but supplies only $\approx 3.6\%$ of demand domestically via Salma; $\approx 45\%$ of imports originate from Iran. The dependency of this limited generation capacity on the highly variable flows of the Harirud River creates significant energy security risks, sensitive not only to natural hydrological fluctuations but also to upstream management decisions and downstream demands. High loss rates, lack of a national grid, and underuse of Salma's potential sustain chronic shortages. Priority actions include boosting Salma's effective capacity, scaling solar and wind, and modernizing local networks to cut losses.

Transboundary dynamics and governance

Internal WEF pressures amplify cross-border tensions. For Iran, scarcity plus energy-intensive groundwater pumping elevates the stakes of reliable upstream inflows. Afghanistan's prospective infrastructure, including Pashdan^{35,44}, could alter flow regimes, affecting Iranian supplies and even Salma's performance. These findings quantify the cross-sector, cross-border feedbacks often described qualitatively in nexus and transboundary studies^{5,49,50}. They support a shift from siloed IWRM practice toward integrated WEF governance with explicit trade-off handling^{5,13}.

Policy implications

In Iran: prioritize water- and energy-efficiency in irrigated agriculture, curb groundwater pressure, and reduce T&D losses. In Afghanistan: raise agricultural water productivity, diversify renewables, and strengthen grid and management capacity. Jointly: establish hydrometeorological data exchange, co-design infrastructure with explicit WEF trade-offs, and implement equitable benefit-sharing. MUSIASSEM's standardized quantitative lexicon can anchor these dialogues and improve accountability across scales.

Limitations, uncertainty, and future work

A primary challenge in transboundary nexus assessment is the asymmetry in data availability and quality. While the Iranian sector benefits from relatively robust datasets (e.g., registered well metering and updated dam statistics), the Afghan sector suffers from significant data scarcity. This study relied on global remote sensing products (e.g., GLDAS for precipitation/evapotranspiration) and the transposition of technical coefficients (e.g., return flow rates) from similar hydrological zones in Iran to Afghanistan. This introduces epistemic uncertainty. For instance, assuming identical return flow rates may underestimate or overestimate actual aquifer recharge in Afghanistan, depending on local soil properties and irrigation technologies. Furthermore, informal water withdrawals in conflict-affected zones are difficult to quantify. Consequently, the results for the Afghan subsystem should be interpreted as “best available estimates” rather than precise measurements. Future research

should prioritize ground-truthing these remote data and establishing joint monitoring mechanisms to reduce these uncertainties, as accurate data is the prerequisite for effective transboundary cooperation.

The present assessment is static; future analyses should employ dynamic models, such as system dynamics or agent-based models, to test scenarios spanning climate change, demographics, technology, and policy [51]. Deeper integration of socio-economic variables and explicit treatment of water quality and land-use/land-cover change would broaden environmental scope and sharpen policy relevance.

Contribution

By applying MUSIASSEM to both national sections of the Harirud, this study delivers a comparative, cross-scale WEF diagnosis that links quantified subsystem performance to concrete transboundary governance needs, advancing evidence for integrated management in arid, conflict-affected basins.

Based on the metabolic analysis of the WFE nexus in the Harirud River Basin, three practical policy actions are recommended:

- (1) For Iran, immediate investment in solar-powered irrigation systems can reduce electricity used for groundwater pumping. This not only lowers carbon emissions but also reduces pressure on overstressed aquifers. A targeted subsidy scheme for farmers in the Mashhad–Sarakhsh corridor could incentivize the transition.
- (2) For Afghanistan, given the low agricultural water productivity and limited mechanization, a pilot project on drip irrigation in Herat province backed by international donors or a bilateral Iran–Afghanistan fund can improve output while conserving water.
- (3) At the transboundary level, establishing a joint water–energy monitoring committee under the supervision of regional organizations (e.g., ECO or ESCAP) is crucial. This platform can facilitate exchange of flow and demand data, coordinate dam operations (e.g., Salma–Doosti), and design trade mechanisms (e.g., electricity-for-water swap scenarios).

Conclusion

This study applied the MUSIASSEM framework to analyze the interdependencies and vulnerabilities of WFE systems in the transboundary Harirud River Basin, covering both Iran and Afghanistan. The results reveal asymmetric pressures: Iran is facing severe water stress due to over-extraction of groundwater for agriculture, accompanied by high energy consumption for pumping, while Afghanistan struggles with low agricultural productivity and critical dependence on imported energy and food.

The findings highlight the need to shift from traditional sectoral planning to integrated WFE nexus governance. For Iran, priority must be given to reducing groundwater dependency through improved irrigation efficiency and renewable energy integration, such as solar-powered water pumping systems. For Afghanistan, increasing agricultural water productivity and addressing energy transmission losses are critical for improving food and energy security.

At the transboundary level, results emphasize the necessity of establishing a joint Iran–Afghanistan WFE coordination platform. Such a platform could support data exchange, harmonize infrastructure planning (e.g., dam operation), and promote mutually beneficial trade mechanisms (e.g., electricity-for-water swap arrangements). These practical and actionable recommendations can significantly reduce tensions, increase resilience, and foster sustainable development across the Harirud Basin.

Despite data limitations, particularly on Afghanistan's side, this study offers a robust metabolic diagnosis of system performance. Future research should incorporate dynamic modeling and socio-political dimensions to deepen understanding of long-term scenarios under climate change, demographic pressures, and policy shifts.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

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Competing interests

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