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Integrating Open-Source Datasets to Analyze the Transboundary Water–Food–Energy–Climate Nexus in Central Asia

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Abstract: In today's intrinsically connected world, the Water–Food–Energy–Climate Nexus (WFEC Nexus) concept provides a starting point for informed and transparent decision-making based on the trade-offs and synergies between different sectors, including aquatic ecosystems, food security, energy production, and climate neutrality. The WFEC Nexus approach is particularly applicable in regions requiring transboundary water management, such as Central Asia. Unfortunately, this region with unevenly distributed water resources—consisting of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—is characterized by data scarcity, which limits informed decision-making. However, open-source geodata is becoming increasingly available. This paper aims to fill Central Asia's WFEC Nexus data gap by providing an overview of key data. We collected geodata through an integrated survey of stakeholders and researchers, stakeholder consultation, and literature screening. Sixty unique datasets were identified, belonging to one of six thematic categories: (1) climate, (2) hydrology, (3) geography and topography, (4) geomorphology, (5) ecology, and (6) anthropogenic uses. For each dataset, a succinct description, including a link to the online source, is provided. We also provide possible applications of using the presented datasets, demonstrating how they can assist in conducting various studies linked to the WFEC Nexus in Central Asia and worldwide.

Keywords: geodata; GIS; open data; hydropower; biodiversity; conservation

1. Introduction

Today's world is intrinsically connected. Few topics can be considered in isolation from one another. Prevailing issues such as climate change [1], biodiversity loss [2], or social inequality [3] must be tackled by holistic approaches. In this regard, so-called 'nexus' perspectives have been gaining increased acceptance, as they are well suited to better understanding sector interlinkages [4]. A well-known interpretation of the nexus perspective is the Water–Food–Energy–Climate Nexus (WFEC Nexus), which establishes the groundwork for informed and transparent decision-making based on trade-offs and synergies in the sectors of aquatic ecosystems, food security, energy production, and climate neutrality [5]. The WFEC Nexus approach is particularly well-suited to regions characterized by water scarcity, high energy and food demands, and those impacted by climate change. An example is the fast-developing post-Soviet region of Central Asia [6], consisting of Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, and Turkmenistan.

The case of Central Asia adds another layer to the Nexus: transboundary water management tensions. Central Asia has shifted from a centrally governed region to five republic states, with each market economy setting its own priorities, often in conflict with each other [7]. In addition, natural resources are unevenly distributed across Central Asian countries, which are strongly interdependent. While upstream countries with mountainous territories, for example, within the Pamir and Tian Shan Mountain ranges, have abundant water resources, downstream countries are characterized by natural water scarcity but are significant producers of agricultural products and are reliant on water inflows from upstream countries for crop irrigation [8]. In the Soviet era, the region's energy production system was operated as one [9]. Nowadays, five independent countries manage it, resulting in an uneven distribution of energy resources. Countries in the steppes and deserts, such as Kazakhstan and Turkmenistan, are key producers of fossil fuel energies. [8] In contrast, mountainous countries, such as Kyrgyzstan and Tajikistan, have abundant water resources for hydropower production. These water, food, and energy tensions are further exacerbated by climate change, with future water shortages expected in the valleys, steppes, and deserts [10] while increasing runoff in high-mountain Central Asia [11]. Considering the effect of one country's decisions on its neighbors, the WFEC Nexus in Central Asia must not only integrate cross-sectoral considerations but also requires cross-border cooperation from a geographical and political point of view [12]. This integrated approach pertains to planning, management, and assessment [13], all requiring a sound data basis. However, poor data availability within the water, food, energy, and climate topics challenges the Nexus approach.

1.1. Data Scarcity in Central Asia

An inadequate capacity to collect and manage high-quality data, coupled with insufficient monitoring networks, is a major issue that hinders data availability in numerous regions worldwide, especially in developing countries. The transboundary context of Central Asian countries is affected by data scarcity due to the absence of a consolidated and credible platform, as well as the lack of progress on data exchange between countries [14]. As a result, policymakers struggle to make informed decisions about social, economic, water, and environmental issues in the region. Limited resources, including funding and personnel, further challenge data availability. Additionally, natural disasters or conflicts can disrupt data collection systems, impeding the collection of accurate and reliable information. To address these challenges, it is necessary to increase investment in data acquisition and management and improve data exchange mechanisms [15,16].

Data scarcity is particularly apparent in Central Asia's water resources management sector, limiting informed decision-making and effective management strategies, which are especially needed in water-scarce regions [16]. The low density of the hydrometric monitoring network, the deterioration of the quality of the monitoring network after the 1990s, and the limited financial resources available to the hydrometric services in Central Asia constitute a challenge for the management of water resources [17]. Even though hydrometric data is available in hydrological yearbooks, it is not yet widely available in a digital format [18], and little reliable and up-to-date data is available on demand [15]. Data scarcity is also a prevalent problem in environmental research, primarily due to the low reliability of measurements and the high cost of monitoring [19]. For example, the lack of reliable observational data makes it difficult to assess the geomorphological and hydrological impacts of climate change in high-mountain Central Asia, as accurate measurements are needed to downscale global climate models [20]. This, together with limited knowledge of the detailed irrigation scheme and runoff in the artificial canals, negatively impacts forward-looking energy planning in the region. Furthermore, missing detailed data on crop yields, irrigation practices, and climate variability makes it challenging to predict the impact of climate change on agricultural production or to assess soil degradation in the region [21]. The lack of official information on existing infrastructure, such as power plants or transmission lines, further complicates holistic Nexus studies. More generally, data are needed to advance the WFEC Nexus approach in Central Asia and understand and quantify the impacts and interactions of different sectors.

Various studies have emphasized the need for data in Central Asia's water management sector, promoting modern approaches such as remote sensing and prompting data sharing and stakeholder collaboration to fill this gap [15,16]. At the regional level, water information systems may collect, analyze, and share data on water resources and use, including providing up-to-date information on water availability, quality, and use [15]. However, until such systems are more widely established, scientists and stakeholders must rely on other data, such as globally available open-source data.

1.2. Open-Source Data for the Transboundary WFEC Nexus

Open-source data is crucial in diverse fields in today's data-driven world, enabling evidence-based decision-making. Open-source data refer to freely accessible and shareable data that foster transparency, collaboration, and accountability [22]. As the volume of available open-source data grows exponentially, so do the possibilities to utilize it. In this regard, geospatial data is pivotal in understanding and managing various aspects of the WFEC Nexus. It empowers policymakers, scientists, and stakeholders to monitor and analyze changes in land use, vegetation cover, or other environmental factors affecting water resources [23]. By leveraging geospatial data, stakeholders can identify areas facing water scarcity, predict the impact of natural disasters, and formulate effective strategies to mitigate these risks. Moreover, geospatial data supports opportunities for conserving and restoring natural ecosystems, thus improving water quality, supporting biodiversity, and mitigating the impacts of climate change [24] Such data can also support renewable energy development by identifying suitable locations for renewable energy projects [25].

Geospatial data is vital in supporting the implementation of the United Nations Sustainable Development Goals (SDGs). The SDGs encompass a range of environmental concerns, including the development of renewable energy sources or water and natural resource management, where geospatial data is pivotal for tracking progress, ensuring evidence-based policies, and facilitating effective interventions [23].

This paper aims to provide an overview of the most relevant available datasets for WFEC Nexus topics in the data-scarce Central Asian context. A holistic WFEC Nexus approach demands comprehensive data from each sector to understand their complex interactions and ensure sustainable and equitable policy and decision-making. Therefore, this study delivers a detailed and easily accessible data basis for further research activities, discussing the relevance of various open-source datasets in different thematic fields related to the WFEC Nexus. Finally, we demonstrate possible applications of how the presented open-source datasets can be utilized to work on complex and interdisciplinary issues in the Central Asian context.

2. Materials and Methods

The geodata presented in this paper were collected by (i) an integrated survey of researchers and stakeholders, followed by (ii) stakeholder consultation and (iii) a screening of the literature.

In the first step, partners of the Hydro4U project consortium [26], consisting of hydrologists, ecologists, water resources managers, engineers, and spatial analysts from Central Asia and Europe (Table 1), were invited to participate in a data collection survey. The survey aimed to (a) identify relevant datasets and (b) institutions that could provide more data sources, as well as (c) establish a protocol for metadata collection. We identified six data categories into which they could be grouped from a practical point of view to improve their findability by a variety of users: (1) climate, (2) hydrology, (3) geography and topography, (4) geomorphology, (5) ecology, and (6) anthropogenic uses. The interlinkage between the six thematic fields with the four WEFC Nexus categories is shown in Figure 1. The relevance of each group within the WFEC Nexus context is briefly described in each subsection of the results.

Table 1. Stakeholders of the Hydro4U consortium sorted by background, institution, and role in the project and showing their expertise regarding WFEC Nexus elements.

Background	Main Institutions *	Role in the Project	n	WFEC Nexus Expertise
Engineering	TUM, BOKU, ILF, SJE,	Hydropower planning and construction, analysis of hydropower potential	14	Energy
Hydrology	HSOL	Modelling of water resources and climate change effects	2	Water (hydrology), climate
Ecology	BOKU, TIIAME, EV-INBO	Fish biodiversity and ecology assessments	9	Water (ecology)
Water and land resources management	IWMI	Cross-border WFEC Nexus analyses with a focus on agricultural aspects	3	Food, water (management)
Spatial analysis	CARTIF, IWMI	Benefits and trade-off analyses in the context of the WFEC Nexus	7	Nexus modelling

Note(s): * Technical University of Munich (TUM), University of Natural Resources and Life Sciences, Vienna (BOKU), ILF Consulting Engineers GmbH (ILF), Ecohydraulic Engineering GmbH (SJE), hydrosolutions GmbH. (HSOL), Tashkent Institute of Irrigation and Agricultural Mechanization Engineers (TIIAME), Institute for Nature and Forest (EV-INBO), International Water Management Institute (IWMI), CARTIF Technology Center (CARTIF).

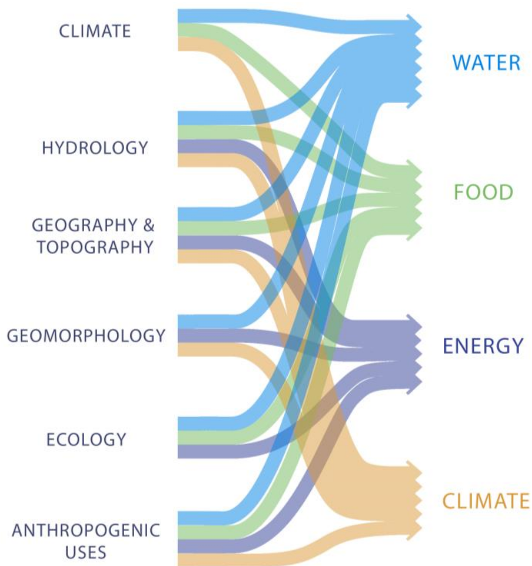

Figure 1. Linking the six categories by which the open-source datasets are classified with the WFEC Nexus elements.

In the second step, we consulted various stakeholders, including scientists, decision-makers, or organizations within the network of the Hydro4U project consortium, to identify additional open-source datasets that may have relevance regarding the WFEC Nexus.

Finally, we searched literature databases using a snowball approach and investigated data sources used by applied WFEC Nexus studies.

Each dataset was assigned to one of the six data categories (Figure 1), and key metadata was extracted to assist data findability and usability. This paper presents a non-exhaustive list of open-source datasets, including key metadata, such as the spatial and temporal extent, resolution, data creation/publication date, and type of data (e.g., vector, raster, tables, or time series). Each listed dataset carries a unique ID and a reference to the data origin and provider, including a link to the online source. A succinct data description provides an overview of the data's purpose and content.

The aim of the data collection within the Hydro4U project was to provide a solid base for working on WFEC-related issues in Central Asia, e.g., assessing the sustainable hydropower potential, performing climate change modelling, or conducting trade-off analysis between hydropower and agricultural water needs. We demonstrate the relevance of each thematic field's data in the context of the WFEC Nexus by linking key datasets with assessing the sustainable hydropower potential as a case study application.

3. Results

3.1. Climate

Water availability in a basin is driven by precipitation. In contrast, evaporation—water uptake by the atmosphere—is driven by temperature, solar radiation, wind speed, crop and soil type, and water availability in the uppermost soil layers [1,27]. Rising temperatures and precipitation intensity and frequency changes will, therefore, impact future water availability, affecting water-dependent economic sectors such as agriculture and putting additional pressure on domestic water supplies and ecosystems [1].

An overview of climate variable products is provided in Table 2. Weather station data shared publicly (C01–C02) can be complemented by gridded weather data products (C03–C11). Station data may further be used to correct biases in gridded data products. Evaporation is typically given as potential evaporation (C12) or actual evaporation (C13). Potential evaporation is the amount of water that would evaporate in a given time interval, subject to no limitation. Actual evaporation is the amount of water evaporating under natural, often sub-optimal, conditions. It can be estimated from remote sensing products or potential evaporation using correction factors for plant growth stage and land cover. These values are relevant for water availability studies.

When looking at the WFEC Nexus, projections of future climate are also relevant. We suggest selecting the four general circulation models (GCM) with the highest priority according to the ISIMIP3b protocol [28] in the Coupled Model Inter-comparison Project (CMIP) phase 6, namely, GFDLESM4 (C14), IPSL-CM6A-LR (C15), MRI-ESM2.0 (C16), and UKESM1.0-LL (C17), for a first assessment of the WFEC Nexus.

Table 2. Open-source data related to climate.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
C01	GHCN-daily V3	Daily records of precipitation and temperature station data	Global	At least 30 years of data for each station	Daily	2012, 2023	Time series (csv)	Menne et al. [29,30]	NOAA	https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00861/html (accessed on 26 April 2023)
C02	Central Asia temperature and precipitation data	Monthly records from station data	Central Asia	Variable length time series between 1879–2003	Monthly	2003	Time series (tab-delimited ASCII)	Williams et al. [31]	NSIDC	https://nsidc.org/data/g02174/versions/1#anchor-1 (accessed 26 April 2023)
C03	CHELSA v2.1	Monthly precipitation and temperature time series	Global	1979–2018, projected climatologies for selected GCM models for 1981–2010, 2011–2040, 2041–2070, and 2071–2100	30 arc-seconds, data quality should be validated prior to use.	2021	Raster (tif)	Karger et al. [32–34]	WSL	https://chelsa-climate.org/ (accessed on 22 May 2023)
C04	WorldClim	Historical monthly weather data downscaled from CRU-TS-4.03	Global	1960–2018	2.5 arc-minutes/monthly		Raster (tif)	WorldClim [35,36]	WorldClim	https://www.worldclim.org/data/monthlywth.html (accessed on 22 May 2023)
C05	ERA5-Land	Single-level precipitation sum and air temperature at 2 m above ground	Global	1950–present	6 arc-minutes/from hourly to monthly	2023	Raster (GRIB)	CDS [37]	CDS	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview (accessed on 26 April 2023)
C06	CRU-TS-4.06.01	High-resolution gridded data of month-by-month variation in climate	Global	1901–2021	30 arc-minutes/monthly	2023	Raster (netCDF)	University of East Anglia Climate Research Unit [38]	CEDA	https://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.06/data/ (accessed on 26 April 2023)

Table 2. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
C07	GPM IMERG	Daily precipitation L3 (the successor product of TRMM).	Global	2000–present	6 arc-minutes/daily	2023	Raster (netCDF)	Huffman et al. [39]	NASA GES DISC	https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_06/summary (accessed on 26 April 2023)
C08	APHRODITE v1801 R1	Daily precipitation analysis product	Monsoon Asia (incl. Central Asia)	1998–2015	15 arc-minutes/daily	2018	Raster (netCDF)	Yatagai et al. [40]	APHRODITE	http://aphrodite.st.hirosaki-u.ac.jp/download/data/search/ (accessed on 26 April 2023)
C09	GPCC Full Data Daily Version 2022	Daily gridded precipitation data	Global	1982–2020	60 arc-minutes/daily	2022	Raster (netCDF)	Ziese et al. [41,42]	GPC	https://opendata.dwd.de/climate_environment/GPCC/full_data_monthly_v2022/025/ (accessed on 26 April 2023)
C10	CHIRPS	Quasi-global satellite and observation-based precipitation estimates over land	Quasi-global	1981–near present	3 arc-minutes/pentad to monthly	2014	Raters (netCDF)	Funk et al. [43,44]	Climate Hazard Center, UC Santa Barbara	https://www.chc.ucsb.edu/data (accessed on 26 April 2023)
C11	PERSIANN-CDR V1	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks	Global	1982–present (note large data gaps until 1999)	2.4 arc-minutes/subdaily to annual	2014	Raster (netCDF)	Sorooshian et al. [45,46]	NCEI, NOAA	https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00854/html (accessed on 23 May 2023)
C12	Global aridity and PET database v3	Potential evaporation and aridity index	Global	Average data from 1970–2000	30 arc-seconds	2022	Vector (shp)	Zomer et al. [47,48]	CGIAR	https://cgiarcsi.community/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v3/ (accessed on 23 May 2023)

Table 2. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
C13	SSEpop	Actual evaporation	Global	Annual data from 2003–2021	Suitable for regional focus	2020	Raster (tif)	Senay et al. [49]	USGS	https://earlywarning.usgs.gov/fews/product/466 (accessed on 23 May 2023)
C14	GFDLESM4	Projections of future precipitation and temperature for shared socio-economic pathways	Global	Daily data from 1980 to 2100	100 km resolution	2018	Raster (netCDF)	Krasting et al. [50]	NOAA	https://www.wdc-climate.de/ui/cmip6?input=CMIP6.CMIP.NOAA-GFDL.GFDL-ESM4 (accessed on 13 September 2023)
C15	IPSL-CM6A-LR	Projections of future precipitation and temperature for shared socio-economic pathways	Global	Daily data from 1980 to 2100	250 km resolution	2018	Raster (netCDF)	Boucher et al. [51]	IPLS	https://www.wdc-climate.de/ui/cmip6?input=CMIP6.CFMIP.IPSL.IPSL-CM6A-LR (accessed on 13 September 2023)
C16	MRI-ESM2.0	Projections of future precipitation and temperature for shared socio-economic pathways	Global	Daily data from 1980 to 2100	250 km resolution	2019	Raster (netCDF)	Yukimoto et al. [52]	MRI	https://www.wdc-climate.de/ui/cmip6?input=CMIP6.CMIP.MRI.MRI-ESM2-0.historical (accessed on 13 September 2023)
C17	UKESM1.0-LL	Projections of future precipitation and temperature for shared socio-economic pathways	Global	Daily data from 1980 to 2100	250 km resolution	2019	Raster (netCDF)	Tang et al. [53]	MOHC	https://www.wdc-climate.de/ui/cmip6?input=CMIP6.CMIP.MOHC.UKESM1-0-LL.esm-piControl (accessed on 13 September 2023)

Several precipitation and temperature datasets covering Central Asia are available in the literature. We selected the products reported to perform well in Central Asia [54–57]. A thorough comparison of all precipitation products is unavailable but would be extremely helpful for practitioners. The CHELSA v2.1 weather data (C03) presents one of the newest data products and was recently used to assess projected climate change impacts on surface runoff in mountainous catchments of Central Asia [11]. The CHELSA dataset is based on a downscaling of ERA5 data with orographic correction and is bias-corrected using the GHCN station dataset (Figure 2). This bias correction works well in regions with high weather station density or few changes in weather station density and measurement quality. In mountainous regions with low and changing station densities (e.g., the parts of the Alai Mountain range), the bias correction algorithm can lead to erroneous trends in the CHELSA dataset [18]. Depending on the application, different weather datasets may be more suitable than others. Therefore, it is recommended to validate a weather data product before use.

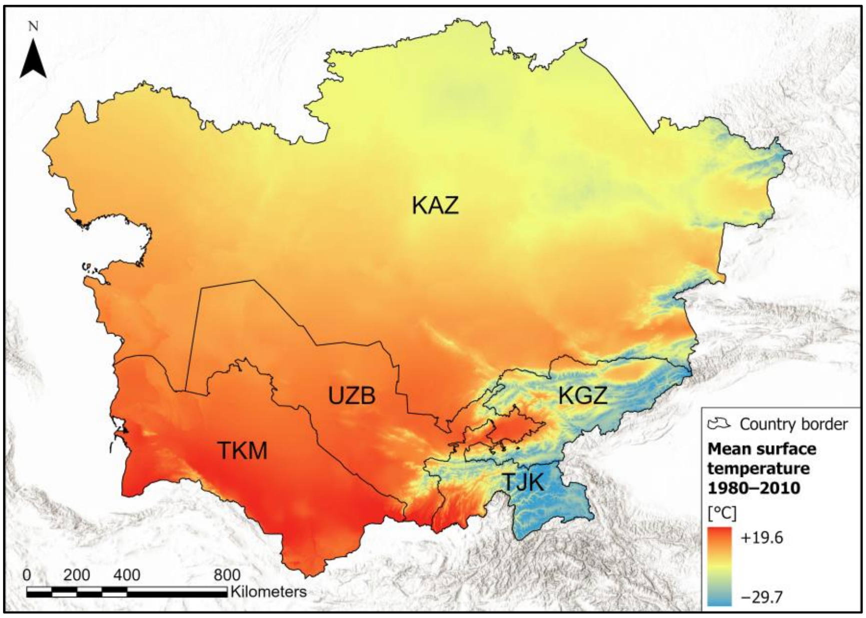

Figure 2. The long-term average of annual surface temperature between 1980 and 2010 (data sources: [33,34,58]; background map: [59]).

3.2. Hydrology

Hydrology plays a crucial role in the Water–Food–Energy–Climate Nexus. Hydrological processes and variability significantly impact water resources planning and other aspects of the Nexus, including agriculture, ecosystem dynamics, food security, or energy production. Lakes and rivers are essential for aquatic and riparian ecosystems [60], providing income from fisheries and supplying water for agriculture and industry [61]. Lakes act as storage reservoirs, dampening a river runoff signal, thus providing flood protection and water in the low flow season [62], and recharging groundwater reservoirs [60]. Soil hydraulic properties are an essential driver for water transport and storage in the uppermost soil layers, which are relevant for agricultural production. Snow melt is the most significant contributor to seasonal river discharge in many basins in Central Asia. Snow melt data can be used to calibrate and validate snow modules of hydrological models in the absence of local data. Adequate representation of snow melt processes in hydrological models is essential for assessing climate change's impact on a shift from solid to liquid precipitation [63]. Permafrost is a highly under-researched topic in Central Asia, with a high-risk potential for cascading events involving rockfalls, landslides, lake dam breaches, and debris flows [64].

The data relating to hydrology presented in Table 3 covers a wide range of spatial, temporal, and qualitative properties: from global data to regional data, processed satellite observations to model simulation results, and point data to time series data.

The first group of data pertains to rivers and includes river networks (H01), basin outlines (H02, H04), gauge locations on rivers (H04), mean river discharge (H04, H13), and time series of river discharge (H04). The data can be used to assess past and current water availability for various uses (notably for irrigation and hydropower production) and to calibrate and validate water balance models [65]. This can subsequently be used for scenario analysis to plan viable infrastructure projects [66], to optimize the operation of hydraulic infrastructure [67], to design climate change mitigation strategies [11,68], and for the allocation of water for different uses [69]. Combined with a topographical layer, river runoff data can be used to estimate the theoretical hydropower potential [70].

The second group of data refers to glaciers, specifically, to glacier geometry (H05, H07) and current and projected glacier melt (H07, H08, H09, H10, H11). Data related to glacier melt is characterized by large uncertainties of 50% to 150%. Because of the glacier data scarcity in the high mountainous region of Central Asia [64], these uncertainties have to be accepted. Glacier melt provides a critical water supply in late summer [71] when precipitation in the downstream water use zone is minimal. The expected decline in glacier melt contributions to discharge will impact hydropower production, agricultural production, and water availability for households and industries.

Further geospatial layers in the hydrology section pertain to lake outlines (H03), soil hydraulic properties (H12), a reanalysis product of snow water equivalents (H06), and a permafrost extent probability map (H14). Finally, the data list delivers a real-time dataset regarding soil moisture (H15). Such information can be valuable for various applications such as weather and climate modelling, predicting and monitoring droughts and floods, or estimating crop productivity [72].

Table 3. Open-source data related to hydrology.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
H01	HydroRIVERS V1.0	River network	Global	NA	Suitable for regional focus	2013	Vector (shp)	Lehner et al. [73]	WWF HydroSHEDS	https://www.hydrosheds.org/products/hydrorivers (accessed on 6 September 2023)
H02	HydroBASINS V1.0	Basin outlines consistent with river network	Global	NA	Suitable for regional focus	2013	Vector (shp)	Lehner et al. [73]	WWF HydroSHEDS	https://www.hydrosheds.org/products/hydrobasins (accessed on 6 September 2023)
H03	HydroLAKES V1.0	Lake outlines	Global	NA	Suitable for regional focus	2013	Vector (shp)	Messager et al. [74]	WWF HydroSHEDS	https://www.hydrosheds.org/products/hydrolakes (accessed on 6 September 2023)
H04	CA-discharge data set	Geolocations of river gauges in mountainous Central Asia, including basin outlines, discharge, and basin characterization	Mountainous parts of the drainage basins Issy Kul, Chu, Talas, Syr Darya, Amu Darya, Murghab, Harirud	Time series of various lengths between 1915–2012	Suitable for water balance modelling at basin scale	2023	Vector as geopackage (shp/gpkg)	Marti et al. [18]	Zenodo.org	https://www.doi.org/10.5281/zenodo.7743778 (accessed on 24 July 2023)
H05	Randolph Glacier Inventory V6.0	Glacier outlines	Global	2014	Suitable for regional focus	2017	Vector (shp)	RGI Consortium [75]	Global Land Ice Measurements from Space Initiative (GLIMS)	https://www.glims.org/RGI/ (accessed on 3 April 2023)
H06	High Mountain Asia Snow ReanalysisV1	Snow cover and snow water equivalents	High mountain Asia	1 October 1999–30 September 2017	16 arc-second	2021	Raster (netCDF)	Liu et al. [76]	National Snow and Ice Data Center (NSIDC)	https://nsidc.org/data/hma_sr_d/versions/1 (accessed on 3 April 2023)
H07	Glacier thickness Farinotti	Glacier thickness on RGI based on inverse modelling	Global	2014	Suitable for regional focus	2019	Raster (tif)	Farinotti et al. [77]	ETH Zurich	https://www.research-collection.ethz.ch/handle/20.500.11850/315707 (accessed on 3 April 2023)

Table 3. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
H08	Glacier thickness Millan	Glacier thickness on RGI based on inverse modelling	Global	2014	~50 m	2022	Raster (tif)	Millan et al. [78]	SEDOO	https://www.sedoo.fr/theia-publication-products/?uuid=55acbdd5-3982-4eac-89b2-46703557938c (accessed on 3 April 2023)
H09	Glacier thinning rates	Glacier thinning rates on RGI	Global	Average rate of change between 2000–2019	Suitable for regional focus	2021	Table (csv)	Hugonnet et al. [79]	SEDOO	https://doi.org/10.6096/13 (accessed on 3 April 2023)
H10	Glacier ablation rates	Glacier ablation rates for many of the glaciers with area >2 km^2 in High Mountain Asia	High Mountain Asia	Average ablation rate between 2000–2016	Suitable for regional focus in basins dominated by glacier melt from larger glaciers	2021	Table (csv)	Miles et al. [80]	ZENODO	https://doi.org/10.5281/zenodo.3843292 (accessed on 24 July 2023)
H11	Projections of glacier melt	Projections of glacier melt under CMIP 6 climate projections	Global	2000–2100	Suitable for regional focus	2023	Raster (netCDF)	Rounce et al. [81]	National Snow and Ice Data Center (NSIDC)	https://nsidc.org/data/hma2_ggp/versions/1 (accessed on 24 July 2023)
H12	HiHydroSoils V2.0	High resolution (250 m) soil maps hydraulic properties	Global	NA	~250 m	2020	Raster (tif)	FutureWater [82]	FutureWater	https://www.futurewater.eu/projects/hihydrosoil/ (accessed on 24 April 2023)
H13	FLO1K	Map of average mean, minimum and maximum river runoff	Global	Averages between 1960–2015	30 arc-seconds. Suitable where discharge measurements are unavailable	2018	Raster (netCDF)	Barbarossa et al. [83]	Figshare	https://doi.org/10.6084/m9.figshare.c.3890224.v1 (accessed on 3 May 2023)

Table 3. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
H14	Northern Hemisphere Permafrost–Ground Temperature Map (2000-2016)	Provides modeled mean annual ground temperatures at the top layer of the permafrost	Northern Hemisphere	Based on average temperatures between 2000–2016	30 arc-seconds	2018	Raster (netCDF)	Obu et al. [84,85]	Arctic Permafrost Geospatial Center	https://doi.org/10.1594/PANGAEA.888600 (accessed on 3 April 2023)
H15	Soil Moisture Active Passive (SMAP)	Two datasets (near real-time as well as historic data) providing estimates of global land surface moisture measured by a passive microwave radiometer	Global	Near real-time data, as well as from 2015–today	36 km^2	2021/2022	Raster (HDF5)	O'Neill et al. [86,87]	National Snow and Ice Data Center	https://doi.org/10.5067/NCTT8THPWRTL (accessed on 6 September 2023) https://doi.org/10.5067/LPJ8F0TAK6E0 (accessed on 6 September 2023)

The gauge locations (H04) and basin outlines (H04) are presented in Figure 3. This dataset focuses on the zone of runoff formation, i.e., the mountainous region of Central Asia. The dataset H04 has been used in a stochastic soil water balance model to estimate the impact of the projected future climate on river runoff in Central Asia [11] and validate a hydrological model (H13). The dataset has further been used to calibrate semi-distributed hydrological models to estimate the impact of climate change on the flow duration curve of specific demonstration sites and plan for sustainable small hydropower production under a changing climate [88].

3.3. Geography and Topography

Geographic and topographic data constitute the basis for various WFEC Nexus analyses, including delineating different administrative areas and information on elevation and surface cover (Table 4).

The first dataset (T01) provides an overview of Central Asia's administrative areas. Aside from country borders, T01 contains subdivisions such as subnational regions (oblasts) and districts (tuman) for each country. The subsequent datasets (T02, T03) deliver information on Central Asia's topography through digital elevation models (DEM) and products derived from them. For example, HydroSHEDS (T03) is a DEM derived from elevation data of the Shuttle Radar Topography Mission (SRTM) (T02) [89] and is best suited for hydrological applications. Several post-processing techniques like deepening open water surfaces, weeding of coastal zones, stream burning, filtering, molding of valley courses, sink filling, or carving through barriers have been applied. In addition to a DEM, it includes further information such as flow direction and accumulation data, which is highly relevant for many hydrological applications such as flow network modelling. Such pre-computed products can significantly reduce computational efforts in large areas like Central Asia.

The last set of data is related to land cover. Copernicus Global Land Service (T04) provides yearly information between 2015 and 2019 on land coverage categorized into 23 classes at a 100 m resolution. In addition, Copernicus Climate Change Service [90] delivers global land cover maps at 300 m spatial resolution annually between 1992 and 2020 (T05). Such information is critical for assessments dealing with water [91] or food availability [92], especially given that land cover can strongly affect local climate conditions [93]. In addition to being valuable within the climate-modelling communities, these datasets serve a wide range of applications, including land accounting, forest monitoring, and combatting desertification.

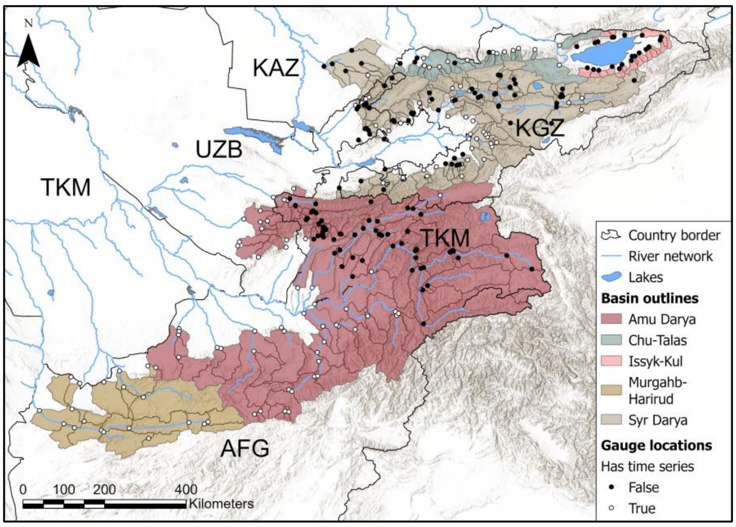

Figure 3. Gauge locations and basin outlines used for modelling the impact of climate change on future water availability in the mountainous river basins of Central Asia (data sources: [18,58], background map: [59]).

Table 4. Open-source data related to geography and topography.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
T01	Global Administrative Areas (GADM)	Delineation of country and administrative boundaries	Global	NA	Suitable for regional focus	2022	Vector (shp/gpkg)	GADM [58]	GADM	https://gadm.org/data.html (accessed on 22 May 2023)
T02	Digital Elevation—Shuttle Radar Topography Mission (SRTM)	Void-filled and non-void-filled options obtained by radar from space	Global	NA	1 arc-seconds or 3 arc-seconds	2000/2018	Raster (tif)	Earth Resources Observation and Science Center (EROS) [94]	United States Geological Survey (USGS)—Earth Resources Observation and Science (EROS) Center	https://doi.org/10.5066/F7PR7TFT (accessed on 22 May 2023)
T03	HydroSHEDS V1.0	Hydrological conditioned DEM and other DEM-based products (flow direction, flow accumulation, land mask grid)	Global	NA	3, 15, 30 arc-seconds and 5, 6 arc-minutes	2007/2008	Raster (tif)	Lehner et al. [95]	WWF HydroSheds	https://www.hydrosheds.org/downloads (accessed on 22 May 2023)
T04	Copernicus Global Land Service	Land cover data of 23 classes, including transitions of land cover classes over time capturing land cover changes	Global	Annual between 2015—2019	~100 m (Mapping accuracy is just over 80%)	2020	Raster (tif)	Buchhorn et al. [96]	Copernicus Global Land Service	https://land.copernicus.eu/global/products/lc (accessed on 6 September 2023)
T05	Land cover classification gridded maps	Global maps categorizing the land surface into 22 classes, defined by the FAO Land Cover Classification System	Global	Annual between 1992—2020	~300 m	2019	Raster (netCDF4)	Copernicus Climate Change Service [90]	Copernicus Climate Change Service	https://doi.org/10.24381/cds.006f2c9a (accessed on 17 May 2023)

A possible application of the data by HydroSHEDS (T03) is shown in Figure 4. The overall river network was calculated using the flow direction and accumulation raster presented in T03. Comparing the modelled runoff scheme between regular DEMs and the HydroSHEDS data, the benefits of the hydrologically conditioned HydroSHEDS data become evident. The geographic location of the scheme is consistent with the rivers displayed in topographic maps [97]. The slope of the channel in the generated river network was derived from the underlying DEM.

3.4. Geomorphology

Understanding the landscape characteristics of one's study area is crucial for water-related planning. Data on geology and geomorphology are helpful for acquiring basic information on dominant rock types to understand the ground's specific characteristics. The data in this section include the fields of lithology, geology, soil erosion, and landslide hazards (Table 5). These aspects are directly or indirectly related to the WFEC Nexus. The geomorphological characteristics of the catchment influence the hydrological processes, such as infiltration and associated groundwater recharge. They, therefore, influence the spatial and temporal availability of water and its geochemical composition. Soil properties result from geomorphological processes and, together with water availability, impact the agricultural use of land, directly affecting food production. Information on the potential risk of soil loss on agricultural land and the risk of landslides are highly relevant in the WFEC Nexus. Soil loss negatively affects the productivity of agricultural areas and the water quality of associated surface water where the sediments deposit. Landslides threaten human lives or infrastructure (e.g., in this context, especially power plants) but also account for local soil movements affecting agricultural areas and surface waters. As geomorphology directly influences water processes and food production, and the risk related to geomorphology can affect critical infrastructure, it is highly relevant to be considered in the WFEC Nexus.

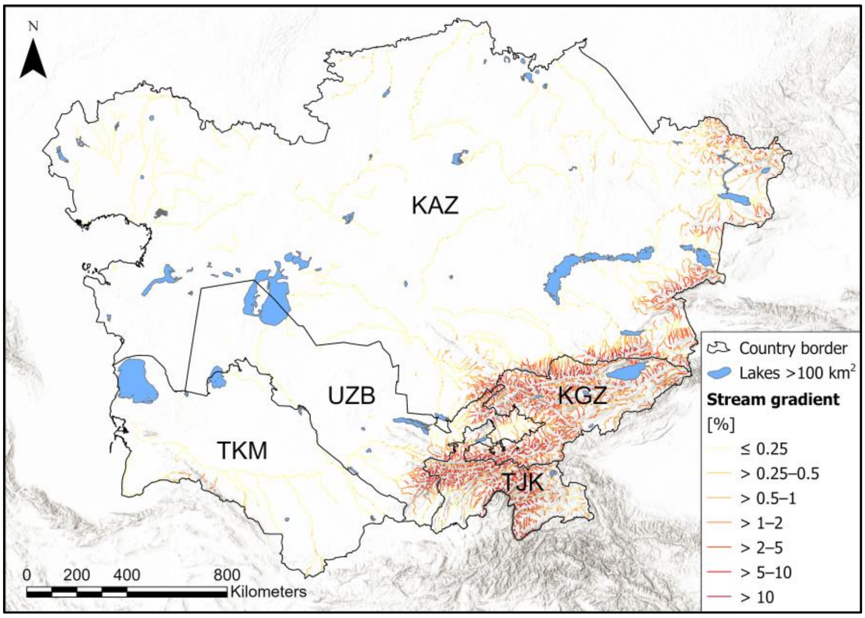

Figure 4. Computed slope of the Central Asian river network. Note: Only rivers with a mean annual flow >1 m^3/s are represented in the map; discharge information was obtained from dataset H13 (see Chapter 3.2) (data sources: [58,74,83,95], background map: [59]).

Lithological information describes the rock's geochemical, mineralogical, and physical properties [98]. More broadly, it also provides information on the sediments transported in the river system, affecting water quality, river type, and river morphology. This lithological data is available as a global dataset (G01), classifying rock types (including unconsolidated sediments). It uses a three-level classification system, providing information on the main lithological class (level 1), more specific rock attributes (level 2), and the presence of other rock types (level 3) [98]. Geological data describing the geological periods of the local rock types are available for the former Soviet Union (G02). The widely used RUSLE approach [99] estimates soil erosion per unit area by a simple multiplication of six factors available globally (G03) but shows some data gaps, especially in the high mountain region. It represents soil loss due to inter-rill and rill erosion but does not account for gullying or tillage erosion [99]. The globally available landslide hazard map (G04) indicates six hazard classes from medium to high risk, differentiating between rainfall- and earthquake-induced landslides.

In WFEC Nexus applications, the geomorphology data can provide insights into primary rock type and soil movement characteristics, such as the example shown for the upper part of the At-Bashy River catchment, Kyrgyzstan. This geomorphological data was, for example, used to assess the hydromorphological processes within the basin as part of the planning process for a small hydropower plant by using the landslide hazard data (S04) to estimate the planned hydropower plant's susceptibility to landslides. For the At-Bashy hydropower site [88], the hazard of landslides from rainfall or earthquakes is moderate and moderate to medium, respectively (Figure 5). In the catchment upstream of the planned hydropower plant, however, the hazard for earthquake-triggered landslides is classified as high for most of the area. Therefore, the At-Bashy River riverbed may be affected by landslides due to high sediment inputs, which needs to be considered for the operation of the plant and can, therefore, affect energy production.

Table 5. Open-source data related to geomorphology.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
G01	Global lithological map (GLiM)	Lithological map with three-level classification system for rock types	Global	-	Suitable for regional focus	2012	Vector (shp)	Moosdorf and Hartmann [98,100]	Commission for the Geological Map of the World	https://ccgm.org/en/product/world-lithology-map/ (accessed on 24 July 2023)
G02	Generalized Geology of the Former Soviet Union	Geological map showing geology, oil and gas fields, and geologic provinces	Former Soviet Union	-	Suitable for regional focus	1999	Vector (shp)	Persits et al. [101]	United States Geological Survey (USGS)	https://certmapper.cr.usgs.gov/data/apps/world-maps/ (accessed on 5 May 2023)
G03	Soil Erosion	Assessment of global soil erosion using the RUSLE method	Global	2001, 2012	~25 km	2017/2019	Raster (tif)	Borrelli et al. [102,103]	Joint Research Centre of the European Commission	https://esdac.jrc.ec.europa.eu/content/global-soil-erosion (Available upon request) (accessed on 5 May 2023)
G04	Landslide Hazard	Global landslide hazard map containing rainfall and earthquake-induced landslide hazards	Global	-	~1 km	2020/2021	Raster (tif)	The World Bank [104]	The World Bank	https://datacatalog.worldbank.org/search/dataset/0037584 (accessed on 5 February 2023)

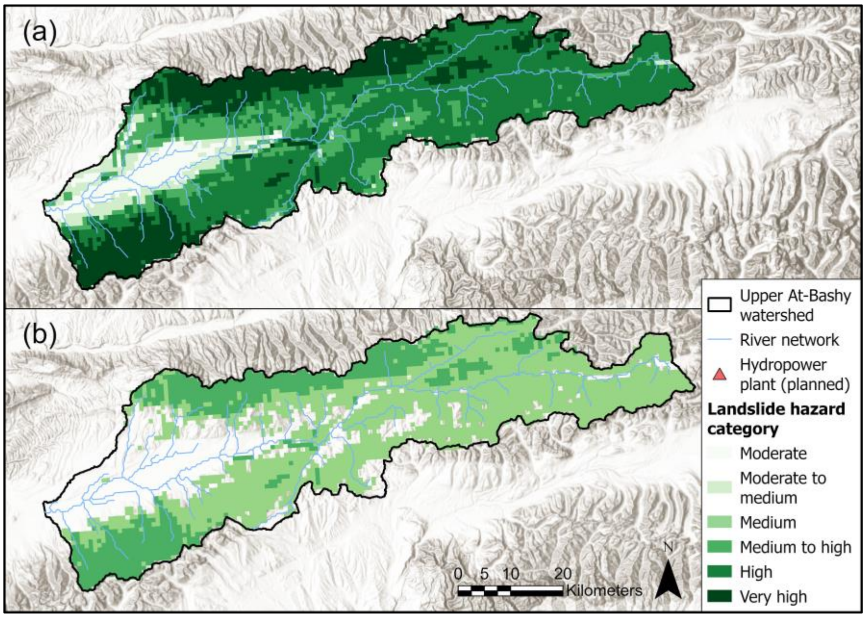

Figure 5. Landslide hazard divided into (**a**) earthquake- and (**b**) rainfall-induced landslides in the upper At-Bashy catchment (Kyrgyzstan); categories corresponding to representative annual frequency of landslide events per km^2: moderate: 0.1–0.29%; moderate to medium: 0.3–0.64%; medium: 0.65–0.9%; medium to high: 1–2.9%; high: 3–9.9%, very high: $\geq$ 10% (data sources: [73,104]; background map: [59]).

3.5. Ecology

Water is essential for life. Therefore, settlements, infrastructure, and production facilities are often found near freshwater ecosystems. River landscapes provide water for drinking, cooling, energy production, and irrigation, as well as offer fish for food supply and areas for flood protection. However, such uses often entail significant modifications (e.g., channelization and flow alterations), affecting ecological functions [105] and the ability of nature to contribute to society [106]. Degraded ecosystems often have reduced biodiversity and may no longer provide fundamental services, so conservation and restoration efforts are imperative [107,108]. In this regard, geodata provide the fundamental information needed to assess the ecological status quo [109–111] and, based thereupon, derive prioritization frameworks for conservation and restoration [112,113] at various spatial levels [114]. To this aim, Table 6 presents key data related to freshwater ecology.

Identifying exceptionally biodiverse and imperiled systems is indispensable for water management decisions [115]. In this context, the first five datasets provide insights into the distribution of freshwater species. As a starting point, the ecoregion concept describes the large-scale distribution of biodiversity [116]. The Freshwater Ecoregions of the World (FEOW) dataset (E01) complements the terrestrial [117] and marine classification approaches [118]. Aside from providing multiple measures of species diversity (e.g., share of endemic species), the FEOW delineation constitutes a fundamental conservation planning unit [119] and may aid in identifying priorities at the continental scale [120,121], particularly in combination with the Key Biodiversity Areas (E02), a dataset on areas that are globally the most important for biodiversity. At the regional scale, ecoregions can sub-divide major basins [122] or identify rare river types. Conservation planning at the sub-regional scale will benefit from including other freshwater biodiversity data [123]. These data may include the International Union for Conservation of Nature's (IUCN's) spatial data of the Red List of Threatened Species (E03), the global EPTO (E04), or the Living Planet Index database (E05). The IUCN provides datasets on mammals, amphibians, reptiles, fishes, marine groups, plants, and freshwater groups. Particularly, the freshwater group (E03), including crabs, crayfishes, fishes (i.e., *Actinopterygii*), mollusks, *Odonata* (i.e., dragonflies and damselflies), and others, is relevant for WFEC Nexus assessments. The data contains taxonomy, distribution status, and IUCN Red List Category information. Also, the EPTO dataset (E04), containing global georeferenced records of four major macroinvertebrate taxa groups (i.e., *Ephemeroptera*, *Plecoptera*, *Trichoptera*, and *Odonata*), may be used for such approaches. The four insect genera recorded in dataset E04 not only constitute a proxy measure of the overall richness of macroinvertebrate assemblages [124,125], but they exhibit different sensitivities to water pollution and habitat degradation [126], thereby helping to assess human pressure gradients at various spatial levels.

From a temporal perspective, the Living Planet Index database (E05) provides a time series of population abundance data for amphibians, birds, fishes, mammals, and reptiles on the species level. Dataset E06 presents the connectivity status of 8.5 million river reaches, showing the extent to which these rivers are free-flowing based on the Connectivity Status Index (CSI). The CSI integrates five central pressures: river fragmentation, flow regulation, sediment trapping, water consumption, and infrastructure development. The global Free-Flowing Rivers dataset can aid in identifying protection and restoration priorities on global or supra-regional scales. The dataset must be used cautiously at smaller scales since it is based upon global dam databases [127,128] and is, therefore, missing countless small dams. Consequently, national or basin-scale decisions must incorporate higher-quality data [129].

The next two datasets include information on protected areas. The first (E07) encompasses the World Database on Protected Areas (WDPA) and the World Database on Other Effective Area-based Conservation Measures (WD-OECM). These datasets illustrate the status (proposed, inscribed, adopted, designated, established, and the respective year of enactment) and designation type (national, regional, international) of protected areas, among others. At the international level, the Ramsar sites, Wetlands of International Importance, and World Heritage Sites are listed. In contrast, sites of Community Importance [130] or Special Protection Areas [131] are listed at the regional level. The associated IUCN categories (Ia, Ib, II, III, IV, V, and VI) are provided where applicable. Even though Ramsar sites are also included in dataset E07, it might be worthwhile to use the Ramsar Sites Information Service (RSIS; E08), which does not only provide up-to-date point information (and in some cases also boundaries) on Ramsar sites but further details on each site. On a global or regional scale, the coarse information on the presence of a Ramsar site might be sufficient, but especially at smaller scales, the exact delineation of Ramsar areas might be required. Dataset E09 includes the statistically derived Global Environmental Stratification (GEnS). By distinguishing 125 strata with relatively homogeneous bioclimatic conditions, it provides a novel global spatial framework for integrating and analyzing ecological and environmental data. This robust spatial analytical framework can be used to interconnect local observations, identify gaps in current monitoring efforts, and systematically design new monitoring and research efforts [132,133].

Figure 6 shows the number of endangered (CR, EN, and VU) freshwater fish species per basin (H02—HydroBASIN, see Section 3.2). It was generated based on the IUCN Red List dataset (E03), focusing on endangered freshwater fish species classified as native and extant in Central Asia. The map highlights the areas that are potentially inhabited by multiple endangered fish species (e.g., Ural, Amu-Darya, and Syr-Darya) and can therefore be considered to be sensitive to future developments (e.g., the construction of hydropower plants) and their associated pressures (e.g., impoundments, water abstraction). Ideally, areas with a high frequency of endangered species should not be subjected to further pressures and, therefore, should be excluded from new hydropower development. Consequently, such maps are indispensable for conservation planning at the global or regional scale.

Table 6. Open-source data related to ecology.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data created/Published	Type of Data	Data Source	Data Provider	Online Link
E01	Freshwater Ecoregions	Delineation of 426 freshwater conservation units with distinct freshwater communities	Global	NA	Suitable for global and regional focus	2008	Vector (shp)	Abell et al. [123]	The Nature Conservancy and World Wildlife Fund 2019	www.feow.org (accessed on 2 May 2023)
E02	Key Biodiversity Areas	Areas contributing significantly to biodiversity	Global	Updated regularly	Suitable for global, regional, and national focus	2016	Vector (shp)	IUCN [134]	Bird Life International (2022)	www.keybiodiversityareas.org/kba-data (Available upon request) (accessed on 2 May 2023)
E03	IUCN Red List of Freshwater species	Distribution ranges of freshwater species	Global	Updated regularly	Suitable for global and regional focus	2021	Vector (shp)	IUCN [135]	IUCN	www.iucnredlist.org/resources/spatial-data-download (accessed on 2 May 2023)
E04	Global EPTO Database	Comprehensive table of *Ephemeroptera*, *Plecoptera*, *Trichoptera*, and *Odonata* (EPTO) occurrence records	Global	1951–2021 (94% with complete date)	Suitable for global, regional, and national focus	2023	Table (csv) with coordinates and catchment IDs	Grigoropoulou et al. [136]	IGB Leibniz-Institute of Freshwater Ecology and Inland Fisheries	https://fred.igb-berlin.de/data/package/829 (accessed on 2 May 2023)
E05	Living Planet Index Database	Time-series of population abundance data for vertebrate species (public version)	Global	1970–2021	Varying	2022	Table (csv) of species with yearly abundance metrics and site coordinates	Living Planet Index [137]	Zoological Society of London and WWF 2022	www.livingplanetindex.org (accessed on 2 May 2023)

Table 6. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data created/Published	Type of Data	Data Source	Data Provider	Online Link
E06	Free-Flowing Rivers	Global river network including a connectivity status assessment on the reach scale	Global	NA	Suitable for global and regional focus	2019	Vector (gdb)	Grill et al. [129,138]	Grill and Lehner (2019)	https://doi.org/10.6084/m9.figshare.7688801 (accessed on 2 May 2023)
E07	World Database on Protected Areas	Global Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM)	Global	Updated regularly	Suitable for global, regional, and national focus	2023	Vector (shp)	UNEP-WCMC and IUCN [139]	Protected Planet	www.protectedplanet.net (accessed on 2 May 2023)
E08	Ramsar sites	Global point information of Ramsar Sites	Global	NA	Suitable for global and regional focus	2021	Table (csv) with coordinates or Vector (shp)	Ramsar [140]	Ramsar Sites Information Service	https://rsis.ramsar.org (accessed on 2 May 2023)
E09	Global Environmental Stratification (GEnS)	High-resolution bioclimate map of the world	Global	NA	30 arc-seconds	2018	Raster, Vector (tif, shp)	Metzger [132,133]	M. Metzger	https://datashare.ed.ac.uk/handle/10283/3089 (accessed on 2 May 2023)

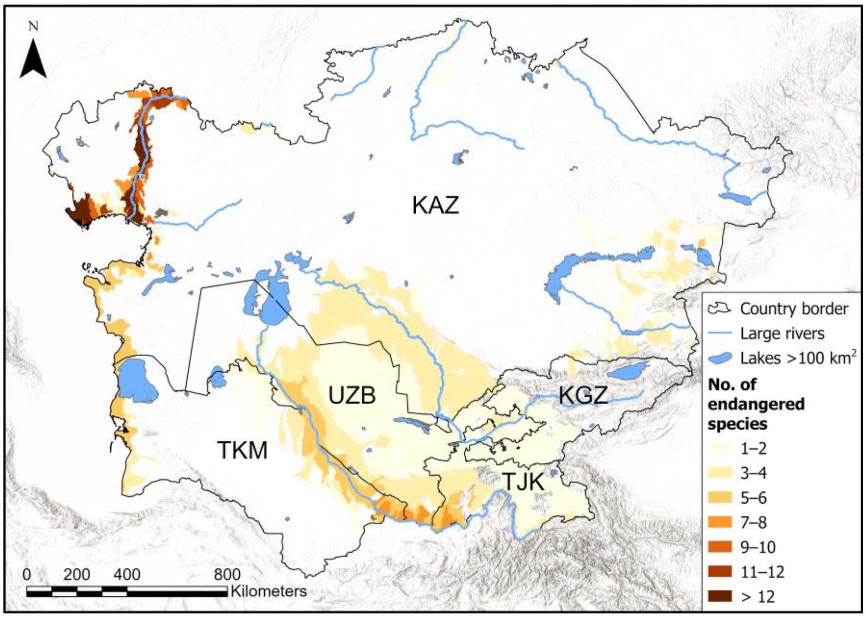

Figure 6. Number of endangered (CR, EN, and VU) freshwater fish species per HydroBASIN (level 8, H02) considering only (probably) extant and native species (E03) (data sources: [58,74,135,141]; background map: [59]).

3.6. Anthropogenic Uses

The Nexus approach holistically connects different thematic areas and balances human activities such as energy production or agriculture. Irrigation or land use changes, as well as energy production, significantly impact water availability and quality. Both, energy and food production and consumption patterns impact greenhouse gas emissions and, therefore, the climate on a global scale. Human activities intensify the interconnection of WFEC Nexus-related topics further due to growing water, food, and energy demands. The data presented in Table 7 cover a wide range of spatial, temporal, and qualitative properties related to human activities: from global to regional data, processed satellite observations to model simulation results, and point data to time series. The data have been classified into three sub-groups covering infrastructure, agriculture, and social development.

Different types of infrastructure are needed to facilitate the efficient and sustainable management of these interconnected systems. The first set of data includes different uses of water management, including the location of dams for hydropower production (A01) and other purposes, such as irrigation, industry, or domestic use (A02). These two previous datasets can be highly relevant when defining effective transboundary water management strategies or developing national and regional hydropower development plans. Large reservoirs leading to natural flow regime shifts can cause multiple conflicts for the WFEC Nexus [142,143]. The location of different types of canals is accessible through Open Street Maps (A03) [144]. When applying hydrological models (e.g., H13) to estimate the flow in a river system, it is critical to consider the canal system and, particularly, the irrigation scheme. However, working with the data has shown that the dataset must be used cautiously, as completeness and detail vary from region to region. The final dataset in this group is OpenStreetMaps' Electricity Network (A04), which includes substations, towers, power lines, and underground/underwater cables. Such information is essential when discussing energy development in a region.

Agriculture provides the basis for food production but can also affect the natural water balance. About 80% of the water used to irrigate agricultural land in Central Asia comes from surface water [145,146], affecting the downstream water availability. AQUASTAT (A05), provided by the Food and Agriculture Organization of the United Nations (FAO), provides information on irrigation and drainage development, including irrigated crop yield, irrigated area, cropping intensity, and drainage development—all on a national, annual basis. The data presents a chronological overview of the development within these themes of the different countries without providing spatial information at a sub-national level. Similar data within sub-national boundaries or river basin scales are rarely available. The Crop Calendar dataset (A06), developed by FAO in collaboration with the United States Department of Agriculture (USDA), provides spatial information on the crop planting and harvesting dates of 19 major crop types. In addition, the MapSPAM model (A07) provides detailed patterns of crop harvested area (rainfed and irrigated) and crop yields annually for 2000, 2005, and 2010. The FAO has also delivered the Harmonized World Soil Database (HWSD), including agroecological zones (A08).

The last group relates to the social developments affecting the WFEC Nexus, such as a gridded population count (A09). These data can be used to evaluate critical information, such as food, water, or energy demand at different spatial scales. Finally, the Human Development Index (A10) can provide information on vulnerability to water scarcity, energy shortages, and food insecurity. By comparing the changes in the HDI over time, it is possible to assess the impact of WFEC Nexus-related policies on human development.

In the absence of official statistical data at the sub-national level in Central Asia, agricultural data can be assessed using the MapSPAM model (A06). This open-access and georeferenced information makes it possible to evaluate the total agricultural water withdrawal at the sub-national level (Figure 7). Each pixel in the region is associated with a harvested irrigated area and a specific crop yield. The latter can be transformed into agricultural water withdrawals by means of the water requirements for each crop type, which are identified in relevant publications [146,156–158]. For most crops, the literature provides water consumption intervals depending on the type of irrigation system, the geographical area, and the climate. In the case of the example shown in Figure 7, the mean value of each interval was selected for the calculation of agricultural water use. Given that water withdrawal for agricultural activities affects water availability downstream, such analyses are a critical element of WFEC Nexus studies, as upstream water consumption affects food production, domestic water availability, hydropower generation, and local climate conditions downstream.

Table 7. Open-source data related to anthropogenic uses.

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
A01	Global Energy Observatory—Hydro PowerPlants	Consolidated and processed dataset of hydropower plants	Global	NA	Suitable for regional focus	Varied, modified in 2018	Vector (shp) and table (xls)	Global Energy Observatory [147]	Global Energy Observatory (GEO)	https://globalenergyobservatory.org/list.php?db=PowerPlants&type=Hydro (accessed on 19 May 2023)
A02	Global Georeferenced Database of Dams (GOODD)	Location of >38,000 dams and associated watersheds	Global	NA	Suitable for regional focus. Older structures are mostly complete, newer ones are incomplete	2020	Vector (shp)	Mulligan et al. [148]	Global Dam Watch	https://www.globaldamwatch.org/ (accessed on 19 May 2023)
A03	Irrigation canals by OpenStreetMap (OSM)	Location of OSM irrigation channels	Global	--	Suitable for regional focus (incomplete)	2020	Vector (shp)	OpenStreetMap contributors [149]	OpenStreetMap	https://www.openstreetmap.org/#map=6/40.388/68.994 (accessed on 20 November 2023)
A04	Electricity network by OpenStreetMap	OpenStreetMap electricity network	Global	--	Suitable for regional focus (incomplete)	2020	Vector (shp)	OpenStreetMap contributors [149]	OpenStreetMap	https://www.openstreetmap.org/#map=6/40.388/68.994 (accessed on 20 November 2023)
A05	AQUASTAT	Data on harvested area, crop yields, renewable water resources, and agricultural water withdrawal	Global	1964–2020	Suitable for regional and national focus	1993	Table (xls)	FAO [146]	FAO	https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y (accessed on 20 May 2023)
A06	Crop Calendar	Global crop planting/harvesting dates for 19 major crops; combined data from Food and Agriculture Organization (FAO) and United States Department of Agriculture (USDA)	Global	NA	5 arc-minutes or 0.5 arc-degrees	2010	Raster (netCDF, ArcINFO ASCII)	Sacks et al. [150,151]	Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, USA,	https://sage.nelson.wisc.edu/data-and-models/datasets/crop-calendar-dataset/ (accessed on 21 June 2023)

Table 7. *Cont.*

ID	Name	Description	Spatial Extent	Temporal Extent	Resolution (Accuracy)	Data Created/Published	Type of Data	Data Source	Data Provider	Online Link
A07	MapSPAM	Crop production indicators for 42 crop types, including physical area, harvest area, production, and yield	Global	2000, 2005, 2010	5 arc-minutes	2010	Raster (csv)	MapSPAM (CGIAR, FAO, World bank etc.) [152]	Harvard database	https://www.mapspam.info/data/ (accessed on 19 February 2023)
A08	Harmonized World Soil database (HWSD) v 1.2	Dataset of harmonized soil properties	Global		30 arc-seconds	2009	Raster (mdb)	FAO, IIASA, ISRIC-World Soil Information, Institute of Soil Science-Chinese Academy of Sciences (ISSCAS), and the JRC [153]	FAO	https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on 19 May 2023)
A09	Gridded Population of the World (GPW) v4	Gridded population counts aggregated from national and sub-national levels	Global	2000, 2005, 2010, 2015, 2020	30 arc-seconds	2018	Raster (tif, ASCII; netCDF4)	Center for International Earth Science Information Network—CIESIN—Columbia University [154]	Center for International Earth Science Information Network (CIESIN)-Socioeconomic Data and Applications Center (SEDAC)	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11 (accessed on 19 May 2023)
A10	Human Development Index (HDI)	An index for assessing human developments considering three dimensions: (i) a long and healthy life, (ii) the status of knowledge, and (iii) the standard of living	Global	1990–2021	Suitable for regional focus	2020	Table (csv, xls)	United Nations Development Programme (UNDP) [155]	UNDP	http://hdr.undp.org/en/content/download-data (accessed on 19 May 2023)

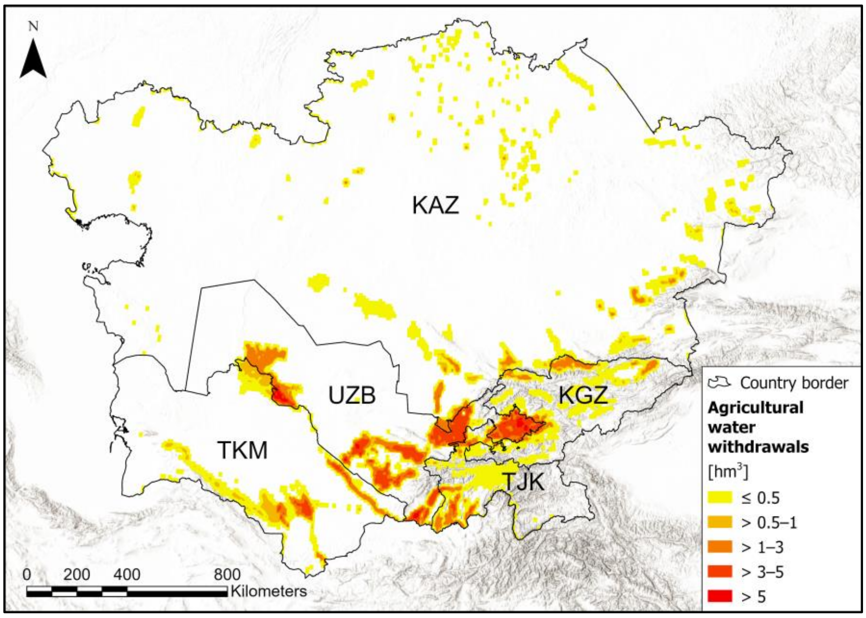

Figure 7. Agricultural water withdrawals in Central Asia in 2010 (data sources: [58,146,152,156–158], background map: [59]).

4. Discussion

4.1. Data Updates and Integration

The presented datasets cannot be seen as static since new datasets are constantly being released, and existing ones are continuously updated and improved with more recent and more accurate data. For instance, HydroSHEDS [95], a set of hydrological products, announced an updated version for 2023 (HydroSHEDS V2). The underlying DEM will be replaced with a more detailed one, increasing the spatial extent and improving the raster resolution from 3 arc-seconds to 1 arc-second [159]. Another example is the French–U.S. SWOT mission (Surface Water and Ocean Topography), which started in 2022 and will provide an unprecedented view of the globe's water. The SWOT mission aims to measure the surface water heights of lakes, rivers, flood zones, and the deep and coastal oceans based on a wide-swath Ka-band radar measurement from space. When the project reaches its goal, the results and digital terrain models could, for example, be used globally for hydrodynamic modelling to improve river discharge estimates [160].

Freely available satellite data with high spatial and temporal resolution (e.g., multispectral Sentinel2 data) already offer the possibility of obtaining crucial spatial information on land use, topography, or the availability of different resources. These datasets can be integrated with cloud-computing systems such as Google Earth Engine (GEE), thereby facilitating data analysis for large areas and extended periods. This data integration can provide vital information to fill existing data gaps, such as identifying areas of deposition and erosion in surface waters [161] or alterations of the river course [162].

In addition to new or updated datasets, more recent developments in Artificial Intelligence (AI) and Machine Learning offer significant potential in generating global datasets. Case studies and developed AI tools already exist, which point to possible applications. Examples include recent advances in Machine Learning applications in algal bloom and shellfish contamination forecasting [163], evapotranspiration estimation for agricultural water management in semi-arid environments [164], and the prediction of Arsenic exceeding permissible thresholds in drinking water [165]. Machine Learning is considered a key tool in data analysis, classification, and prediction of the increasing volume of environmental data [166]. AI techniques are decreasing model development costs and prediction errors, leading to more accurate models [167]. The accuracy claimed by model creators is often impressive. However, such statements must be handled cautiously. Spatial and environmental data can be highly affected by autocorrelation, and the results of testing accuracy can therefore be misleading [168]. Also, the availability of sufficient data is fundamental to form the baseline necessary to develop AI applications. Training, validation, and testing datasets are required to ensure rigorous model training, optimization, and validation processes [169]. In areas like Central Asia, where minimal data exists, local conditions may differ from the training data. Therefore, models might deliver less accurate results in data-scarce regions [168].

4.2. Real-Time Applications

Adaptive management practices based on real-time information will become increasingly important in a region such as Central Asia, which is highly water-stressed and where summer shortages are predicted to increase due to climate change [10]. Indeed, there has been development in this area in Central Asia. One such example is the web application tool 'Count4D', designed for irrigation and water resources management in Central Asia. The application has separate components intended for administrators, districts, and water user associations and a tool allowing field observers to send water level measurements, which are automatically converted to discharge values [170]. Another successful case study in this area is an Integrated Water Resources Management project in the Fergana Valley. Among other interventions, an automated water monitoring system (updated every 10 min) and a management information system were employed. The system was designed to plan, assess, and correct water distribution between different water user associations. The project has led to a dramatic decrease in conflicts between the governing administration and water user associations and a reduction of common water delivery by 12–25% [7].

4.3. WFEC Nexus Application in Central Asia: The Case of Hydropower

Hydropower is a highly relevant issue within the WFEC Nexus [171], particularly in Central Asia. Several Central Asian governments have set ambitious targets for increasing the share of renewable energies and developing the region's hydropower sector, as energy demand continues to rise and electricity supply in many rural areas is still highly unstable [172]. However, hydropower development in the region needs to be approached with caution as it is closely linked to all WFEC-related issues. Hydropower operations can affect the daily, seasonal, and annual flow regime through reservoir operations, e.g., reducing water availability downstream [105,143]. Such changes in water availability can affect food production in Central Asia [173], which relies heavily on surface water irrigation [145,146]. In addition, hydropower can negatively impact aquatic ecosystems, lowering fish stocks [174] and thus putting pressure on the fisheries sector. At the same time, existing irrigation infrastructure, such as non-powered dams in the complex canal system, can be electrified, and careful operation could lead to synergies between energy production and agriculture [175]. Hydropower has a high potential to cover the increasing energy demand, replacing fossil energy sources and consequently contributing to tackling climate change on a global scale [173].

Identifying a region's existing hydropower potential [70,97] is an essential step in formulating holistic, sustainable hydropower development plans. The examples of data applications shown in the results provide essential information for determining the sustainable hydropower potential of the region. The climate information shown in Figure 2 can be used to develop a climate change model that estimates future changes in discharge to ensure long-term sustainability. The hydrological data on discharge at the gauging station shown in Figure 3 are essential input data for climate change modelling. However, they are also necessary to validate hydrological models, which are needed to assess flow conditions in ungauged basins. The calculated river network and slopes displayed in Figure 4 provide information on the available head within specific river reaches. Besides the discharge, the hydraulic head is the primary determinant of the technical hydropower potential [70,97]. Therefore, the map displayed in Figure 4 depicts areas best suited for hydropower generation concerning topography. In order to consider sustainability aspects in hydropower potential assessments, it is necessary to also consider geomorphological processes in mountainous regions, such as landslides (Figure 5), to exclude hazard zones. In addition, including ecological criteria, such as the presence of endangered fish species (Figure 6), is essential to preserve the aquatic ecosystem, as hydropower can negatively affect aquatic flora and fauna. Finally, the proportion of the flow required for irrigation (Figure 7) must be assessed to avoid conflict between hydropower production and other Nexus components, ensuring food security. This example demonstrates the practical relevance of the database for applications directly related to the WFEC Nexus.

4.4. Data Limitations

The quality of the datasets holds significant potential for various fields and regions, but their availability and quality also face limitations. Open-source data can be used in various applications at the regional scale or serve to substitute point data of hydrological stations. Using these datasets to assess the sustainable hydropower potential or conduct a tradeoff analysis between water needs for agricultural irrigation and hydropower production, we validated the data used to work on Nexus-related issues at a regional level (Section 4.3). In this regard, the results of the hydropower potential study fit well with detailed site-specific studies of hydropower plants currently under construction in the project Hydro4U [176]. However, these datasets, which are often of global scope, are too coarse for detailed planning, such as the sizing of a hydroelectric plant. In many cases, local measurements, which are rarely available in Central Asia, are needed to validate model results or refine the spatial or temporal resolution. Nevertheless, the database can serve as a starting point for such detailed studies, providing information on where and which additional or more detailed data is needed. In general, an overall validation of the dataset for all kinds of applications has not been conducted in this study. The user must always consider the data resolution specified for each dataset and decide whether it is sufficient for a particular application. Understanding and accepting the potential limitations and accuracy described in the dataset references for the specific application is also essential.

Open datasets and the ability to access these remotely allow individuals and organizations worldwide to work on solutions to pressing societal issues. On the one hand, this allows the necessary democratization of innovation, but, especially with further development of Artificial Intelligence and Machine Learning, it also leads to the development of even more data and tools with regional or global coverage [177], which may not be validated for all regions, including Central Asia. Screening open datasets for their suitability for regional Nexus-type modelling is essential but neither scientifically nor commercially rewarding. Funding periodic benchmarking studies of open data and tools would improve their useability for the benefit of society.

4.5. Promoting Data Sharing and Fostering Collaboration

There is a high dependency on globally available, open-source data when studying Nexus-related issues in Central Asia. To date, local measurements are rarely available due to outdated infrastructure, resource constraints, and data protection regulations. To overcome these challenges and bridge data gaps, promoting open data initiatives and fostering collaborations among local authorities, academic institutions, civil society organizations, and private entities is necessary. Standardizing data collection methods, developing data-sharing agreements, and leveraging emerging technologies can enhance data quality and accessibility. Additionally, political will is needed to invest in modernizing outdated infrastructure, including data collection and dissemination systems, which can improve data availability and accuracy. By addressing these issues, effective decision-making, transparency, and accountability can be fostered in Central Asia and beyond. Recognizing the interdependence of water, energy, food systems, and climate, the WFEC Nexus approach highlights the need for integrated data collection and management strategies.

5. Conclusions

This paper presents a synopsis of open-source geodata grouped into six data categories that can be used for transboundary WFEC Nexus analysis. Such data are particularly relevant for Central Asia, where the availability of regional geodata is still scarce. The data sources presented in this article allow researchers and decision-makers to integratively consider topics such as water resources (management), biodiversity, climate change, anthropogenic uses, and development scenarios [97,178,179], thereby providing an invaluable foundation to conduct a variety of assessments linked to the WFEC Nexus. The datasets are insufficient for every site-specific application where high data resolution is required. More data must be collected and published to ensure the sustainable development of WFEC-related issues in Central Asia.

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