

Review

Use of Remote Sensing Data to Study the Aral Sea Basin in Central Asia—Geoscience and Geological Hazards

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Abstract

The Aral Sea Basin (ASB), situated in Central Asia, serves as a prime example of a man-made environmental disaster. The practice of irrigation can be traced back to ancient times. However, the substantial water withdrawals that have occurred since the second half of the 20th century appear to have led to the irreversible drying up of the Aral Sea and the disruption of the flow of the Amu Darya and Syr Darya rivers. This study conducts a comprehensive review of satellite data from the past sixty years, drawing upon a selection of peer-reviewed papers available on Scopus. The selection of papers is conducted in accordance with a methodology that is predicated on the combination of keywords. The study focuses on geoscientific aspects, including the atmosphere, water resources, geology, and geological hazards. The primary sensors employed in this study were Terra-MODIS, NOAA-AVHRR, and the Landsat series. It is evident that certain data types, including radar data, US or Soviet archives, and very-high-resolution data such as OrbView-3, have seen minimal utilisation. Despite the restricted application of remote sensing data in publications addressing the ASB, remote sensing data offer a substantial repository for monitoring the desiccation of the Aral Sea, once the fourth largest continental body of water, and for the estimation of its water surface and volume. Nevertheless, the utilisation of remote sensing in publications concerning the Aral region remains limited, with less than 10% of publications employing this method. Sentinel-2 data has been utilised to illustrate the construction of the Qosh Tepa Canal in Afghanistan, a project which has been the subject of significant controversy, with a particular focus on the issue of water leakage. This predicament is indicative of the broader challenges confronting the region with regard to water management in the context of climate change. A comparison of the Aral Sea's case history is drawn with analogous examples worldwide, including Lake Urmia, the Great Salt Lake, and, arguably more problematically, the Caspian Sea.

Keywords: bibliometry; remote sensing; Central Asia; water; irrigation; climate change; Qosh Tepa Canal



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1. Introduction

The Aral Sea disaster is regarded as one of the most remarkable illustrations of the profound impact that human activity has had on the natural world [1–7]. The region provides a compelling case for examining the consequences of water-related development interventions and their impact on human population, settlement and migration [8,9]. For instance, Uzbekistan recorded approximately 100,000 internally displaced persons, with this figure anticipated to rise to 200,000. Before 1960, the Aral Sea was a vast expanse of saltwater covering approximately 68,000 km², the fourth largest continental body of water (Figure 1). The term ‘Aral Lake’ would therefore be more appropriate than ‘Aral Sea’.

In 1870 and 1895, the surface area was of the same order of magnitude, estimated at 65,781 km² and 67,769 km² respectively [10,11]. The endoreic depression, with its 1100 km³ of water, was fed by the Syr Darya and Amu Darya, two rivers originating in the Tien Shan and Pamir mountains, respectively (Figure 1). As early as the end of the 19th century, scientists pointed to the vulnerability of the Aral Sea and the risk of its drying up, as the Amu Darya and Syr Darya basins “showed clear signs of gradual drying up over their entire surface” [10]. The area was mapped by Russian military topographers following the conquest of Central Asia in the late 19th century. Most of the major work began after the Russian Revolution. The priority was to create a modern irrigation network in the Amu Darya delta (Khorezm region). The Syr Darya was not developed at that time, except in the upper Fergana Valley. In the upstream part of the basin, work began on the tributaries of the Amu Darya and Syr Darya to produce hydroelectric power and irrigate land that had been fertile in ancient times. These works, which drew little water from the main rivers, had no real impact on the Aral Sea. The major changes that led to the Aral Sea disaster occurred mainly in the period after the Second World War, when major works were carried out in the Khorezm, with the creation of a new regional capital at Nukus. The various developments led to the complete irrigation of the Fergana, the Tashkent region, the Ili valley in the Tien Shan mountains of Kyrgyzstan and the Zeravshan valley. The Kara Kum Canal (KKC, Figure 1) was built between 1954 and 1988 to serve the cotton monoculture promoted by the USSR and to provide a major source of water for Ashgabat, the capital of Turkmenistan. After the heavy rains of the 1950s, water extraction from the rivers became unsustainable for the Aral Sea Basin (ASB). The overuse of river water for irrigation has led to severe losses of natural ecosystems in the delta regions.

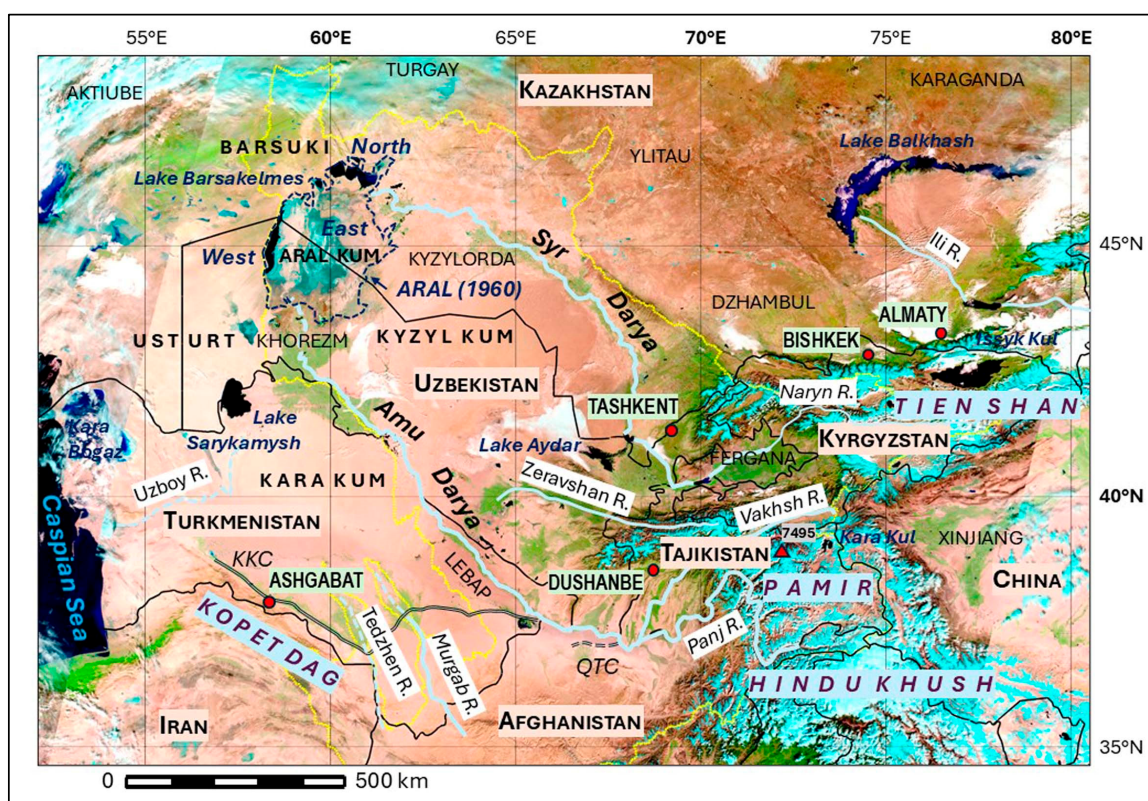


Figure 1. The Aral Sea Basin. The ASB is marked by the yellow line. The shapefile is available at <https://mrb.grdc.bafg.de/> (accessed on 20 February 2025). Background: Terra MODIS. KKC: Kara Kum Canal; QTC: Qosh Tepa Canal. Black solid lines: national borders; light blue solid lines: major rivers. Vegetation is green, water bodies are dark blue or black, soil and mineral surfaces are yellow to brown, snow and ice are cyan, and clouds are white.

Since the 1960s, the surface area and volume of water has been steadily decreasing [12], while the salinity of the water has increased significantly [13]. The average annual flow of the two main rivers into the Aral Sea was 56 km³ in the 1950s, which was reduced to less than 10 km³ in 2002. It is clear that the Soviet Union's disastrous management of irrigation is the main cause of the problem [14–22]. However, this does not negate the fact that climate change is particularly acute in this region, making attempts to solve the problem much more difficult [23–27]. Since the collapse of the Soviet Union in 1991, the Central Asian countries of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan have faced a range of problems, including soil salinisation, rising water tables in heavily irrigated areas and the abandonment of land that has become infertile. Numerous studies have already shown the negative effects of insufficiently diversified and adapted agriculture, and the low water use efficiency associated with the dilapidated irrigation system and reduced agricultural diversification.

2. Methods

2.1. Principle

Remote sensing information has become essential for land monitoring and management [28]. As early as 1987, a Special Issue of the Soviet scientific journal *Problemy Osvoeniya Pustyn* (Problems of Desert Development) was devoted to remote sensing applications and model development in Central Asia. In this context, it seemed important to produce an up-to-date summary of the use of different types of satellite data for the various environmental problems that arise at the scale of a vast watershed such as the ASB. The focus is on the geoscientific aspects, i.e., water resources, the nature of soils and bedrock, and the associated risks such as floods, desertification, landslides, earthquakes, and the atmosphere (temperature, precipitation, dust). Land cover, land use, crop type differentiation, vegetation assessment, locust infestation mapping or abandonment mapping are all excluded from the study. This approach has rarely been considered [29–31]. A review of scientific publications dealing with remote sensing applications for agricultural monitoring in ASB was carried out by Conrad et al. [21] and part of their methodology was adopted in our approach. A review of remote sensing applications for landslides in Central Asia has also been conducted [32]. It is also noteworthy that the evolution of remote sensing from space, dating back to the 1960s, coincided with the Aral Sea disaster, which has been and continues to be monitored by various generations of satellite data.

The present literature search was chiefly based on the Scopus database (<https://www.scopus.com> (accessed on 27 July 2025)) from 1977 to 2025. The title, abstract and keywords were searched for different key terms. The search was initiated with the term 'Aral' alone according to (i), thus defining the primary subject areas of the scientific papers (Scopus documents) pertaining to the area.

(i) TITLE-ABS-KEY ("Aral")

The search yielded 2768 documents, comprising 2064 journal articles, 299 conference papers, and 188 book chapters. As stated in (ii), the search has been restricted to remote sensing applications in the Aral area.

(ii) TITLE-ABS-KEY ("Aral") AND TITLE-ABS-KEY ("remote sensing")

The search has yielded a total of 183 documents, constituting 6.6% of the total number of documents in the initial series. As indicated in (iii), 126 articles have been identified as being of a peer-reviewed nature (6.1% of the articles concerning 'Aral').

(iii) TITLE-ABS-KEY ("Aral") AND TITLE-ABS-KEY ("remote sensing") AND (LIMIT-TO (DOCTYPE, "ar"))

Given that the Aral Sea Basin encompasses regions situated at considerable distances from the sea itself, the search was expanded by the incorporation of two search terms. The initial term pertained to the domain of remote sensing (RS), while the subsequent term was associated with the geographical extent, that is, Central Asia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan or Uzbekistan. In the concluding step of the process, the primary satellite sensors employed for various geoscience and geohazard studies in Central Asia were identified using the same methodology (number of documents and subject areas covered). On this occasion, it was solely articles that were selected, on the basis that this particular list constitutes the source of the papers which were analysed for thematic purposes in Section 4.

The review's objective is to establish a comprehensive definition of the role of remote sensing in the primary thematic applications within the Aral Sea Basin, with particular emphasis on the following aspects: data (scale, revisit time, spatial and spectral resolution, etc.), methods, integration into models or association with exogenous data. The present study has facilitated the observation of the evolution of satellite data usage over the past 60 years. Moreover, the present study has enabled the identification of a number of research directions that merit exploration in future studies. This review is being conducted as part of the Erasmus+ programme "Strengthening Higher Education in the Water Sector for Climate Resilience and Security in Central Asia (HWCA)", which forms part of the European Union's Green Deal. The Green Deal recognises that climate change and environmental degradation pose an existential threat to Europe and the world. The main objective is to contribute to the training of a new generation of Central Asian experts ready to tackle the challenges facing the water sector. A total of 17 universities and research institutes (3 from Europe, 13 from Central Asia) are participating in the programme.

2.2. Main Statistical Trends

The quantitative analysis of the Scopus database reveals that there are 4993 documents corresponding to the term 'Aral'. The two primary subject areas are closely balanced, with "Environmental Sciences" and "Earth and Planetary Sciences" each accounting for approximately 21% of the total number of documents (Figure 2). The two other subject areas under scrutiny account for approximately 11% of the total, with the specific percentages allocated to "Agricultural and Biological Sciences" and "Social Sciences" being around 11% each. The subject area "Engineering", which accounts for more than 5% of the total, is also well-represented. Nine other subject areas of lesser quantitative importance are listed in Figure 2. It is imperative to note that solely those subject areas which represent more than 1% (i.e., 50 documents) are to be considered.

It is noteworthy that a mere 3.7% of the documents pertaining to 'Aral' also contain the key word 'remote sensing' (i.e., 183). In order to facilitate a more profound comprehension of the subject matter, Figure 3 provides a visual representation of the distribution of documents incorporating the term 'remote sensing' and various regional geographical entities, which constitutes the second key term (e.g., Central Asia, Aral Sea, one of the five Central Asian countries). In contrast to the prevailing trend in general statistics, 'remote sensing' appears to be more frequently associated with the subject area 'Earth and Planetary Sciences' than 'Environmental Science' in the context of Central Asia. If we now consider the number of documents relative to the country's population, Kazakhstan (20.5 millions) and Kyrgyzstan (7 millions) appear to be overrepresented, with 16.5 and 14.6 documents per million inhabitants, respectively. On the other hand, Turkmenistan (7.5 million inhabitants, or 6.8 documents per million inhabitants), Tajikistan (10.5 million inhabitants, or 4.9 documents per million inhabitants) and, above all, Uzbekistan (36.6 million inhabitants, or 2.9 documents per million inhabitants) are clearly under-

represented. The subject area of ‘Environmental Sciences’ is well represented in Uzbekistan. It is also interesting to note that the number of papers in ‘Agricultural and Biological Sciences’ is low, especially in Kyrgyzstan, Uzbekistan, and Tajikistan. The field of ‘Social Sciences’ is conspicuously absent from the statistical data pertaining to Turkmenistan. It is important to note that only a small part of Kazakhstan is located within the Aral Sea Basin, and as such, it is likely that the region is overrepresented in the general statistics (see Section 3 for further details).

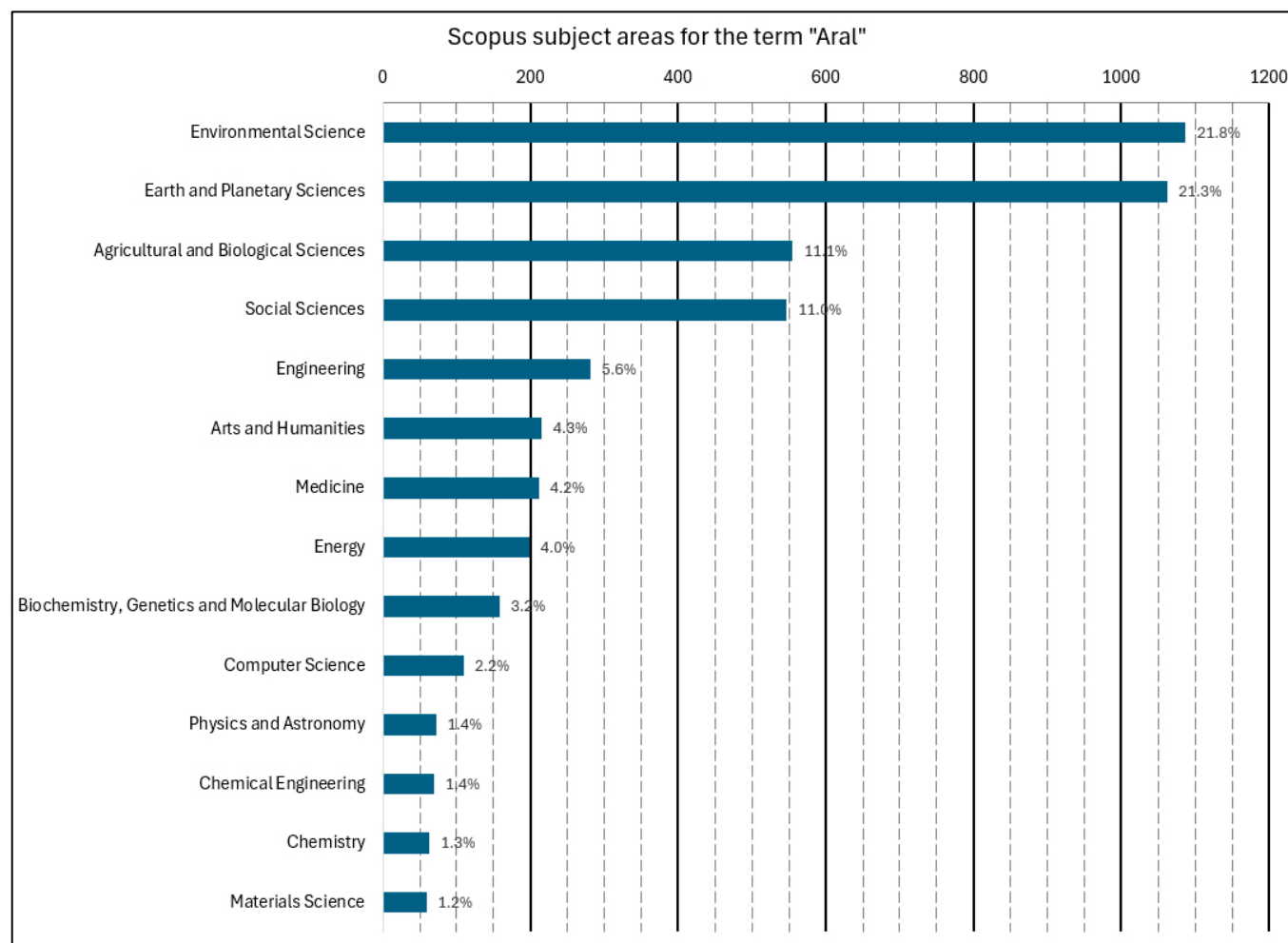


Figure 2. Subject areas of the documents found on Scopus using the term ‘Aral’. As more than one subject area can be attributed to a document, the total number is 4993 and not 2768 as previously indicated. Please note that the subject areas are limited to those accounting for more than 1% of the total number of documents.

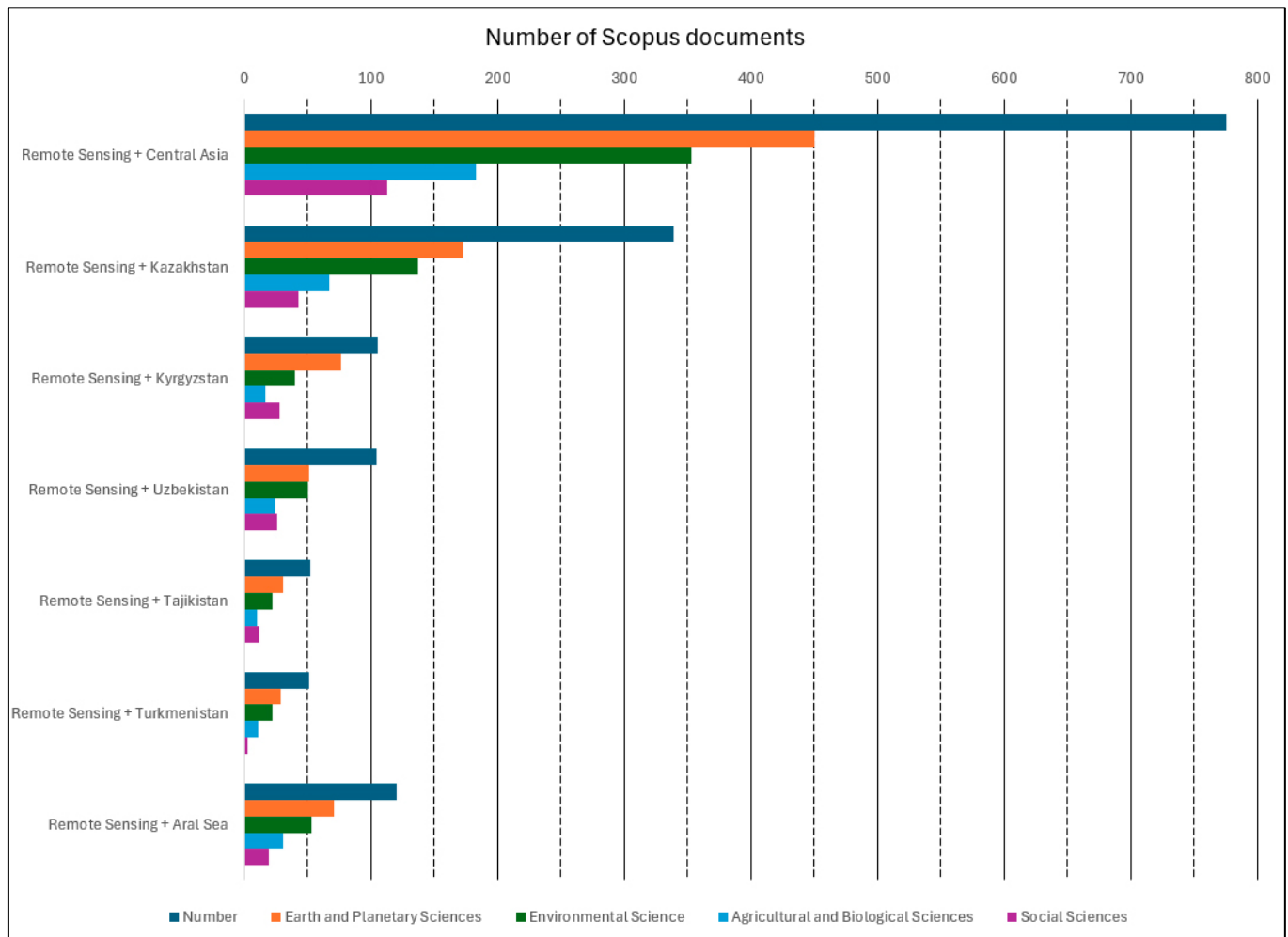


Figure 3. Distribution according to the four main Scopus subject areas for documents corresponding to the combined terms ‘remote sensing’ and ‘Central Asia’, ‘Aral Sea’, or ‘one of the five Central Asian countries’.

3. Study Area

3.1. Geography

The ASB in Central Asia encompasses an area of approximately 1.7 million km², comprising the states of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. The region has a population of 82 million, with a very uneven geographical distribution, 45% of whom live in Uzbekistan (36.5 million). The ASB spans almost all of Tajikistan, Turkmenistan and Uzbekistan, as well as Kyrgyzstan’s Osh, Jalal-Abad and Naryn provinces, Kazakhstan’s Kyzylorda and South Kazakhstan provinces, Afghanistan’s northeastern provinces, and a small part of Iran. Geoscientific challenges are encountered in the downstream countries of Uzbekistan, Turkmenistan and Kazakhstan. These include water availability, irrigation and the disappearance of the Aral Sea in the downstream countries, and glacier melt, landslides, seismicity and hydropower plants in the upstream countries. The ASB has a wide variety of topography. The Turan lowlands of Kyzyl Kum (or the Black Desert) and Kara Kum (or the Red Desert) are mainly flat plains and deserts (about 40%). High mountains are found at the western end of the Himalayas in the south-east of the ASB (about 30%), while hills and small mountains are found in the transition zone (also about 30%). Altitudes range from −15 m at the Aral Sea to 7495 m at the peak of Ismail Samani in Tajikistan. The main water sources are two rivers. The Amu Darya and

its upstream tributaries, the Vakhsh and Panj rivers (1 million km²), originate from the glaciers of the Pamir and Hindu Kush in Tajikistan and Afghanistan. The Syr Darya and its main upstream tributary, the Naryn, originate from the glaciers of the Tien Shan in central and western Kyrgyzstan (0.5 million km²). The two rivers are of a similar length, with the Amu Darya measuring 2525 km and the Syr Darya measuring 2212 km. The ASB also includes the Tedzhen and Murghab rivers, which originate in Afghanistan and flow into Turkmenistan, where they disappear into the sands of the Kara Kum. Mountains to the southeast block moisture-rich winds from reaching Central Asia's inland areas. As a result, precipitation is low and erratic over much of Central Asia, particularly towards the Aral Sea where high solar radiation leads to low humidity and arid conditions [33]. Therefore, the climate of the ASB is arid to semi-arid, and is characterised by the cold desert (BWk) and cold steppe (BSk) as defined by Köppen [27,34,35]. In recent decades, the region has experienced an increase in mean annual temperature, precipitation, and potential evapotranspiration [36,37], especially in the high mountain ranges [38]. All simulations indicate a warming trend, with snowmelt in the upper reaches leading to increased runoff and more floods and landslides.

3.2. Geology

The geological evolution of the area has been described by many authors [39–44]. Geodynamically, the ASB lies at the boundary between the Central Asian Orogenic Belt in the north (mainly southern Kazakhstan, northern Uzbekistan and Kyrgyzstan) and the Kara-Kum Craton and the Tethysides in the south (Turkmenistan, southern Uzbekistan, Tajikistan). After the closure of the Paleotethys, the so-called Amu Darya Basin was deposited from the Middle Jurassic to the Tertiary [45]. The main aquifers are within the Cretaceous strata, mainly the Upper Cretaceous in the Aral Sea area and the Lower Cretaceous in the Kara Kum (Shatlyk aquifer), but this permeable unit is better known for its gas reserves than its water supply [33,41,46]. The Aral Sea is situated within a substantial depression that was formed during Cenozoic tectonic events, which took place over three million years ago. The contemporary depression was formed during the Quaternary period by rivers flowing from the mountain belts. The Amu Darya and Syr Darya have fed the Caspian Sea on multiple occasions since at least the middle Pliocene. Over the past three decades, core material has been studied in more detail to identify 'sea level' oscillations as the Aral responded to local climate forcing [47,48]. It has been established that the climate during the last glacial period (approximately 22,000–12,000 BP) was drier than in the present day. During this period, the Aral Depression received limited amounts of water from the Turgay area to the north. The Aral Sea was a diminutive body of water, and Lake Sarykamish was completely desiccated. From 12,000 BP to 9000 BP, the climate underwent a transition from warm/wet to cold/dry conditions [12]. During this interval, the Aral Sea received water solely from the Syr Darya, which flowed eastwards, thereby explaining the location of the deepest part of the Aral Sea depression in the western part of the basin. Conversely, the Amu Darya flowed into the Sarykamish depression. Following the deglaciation (9000 BP), the flow of the Amu Darya increased substantially, reaching approximately 200 km³·yr^{−1}. This increase in flow was accompanied by a substantial sedimentation event, which filled the depression between the Aral Sea and Lake Sarykamish, and potentially extended into the Uzboy Channel, leading to the Caspian Sea. Concurrently, the water discharge decreased to approximately 90 km³·yr^{−1}, resulting in the Aral depression becoming endorheic around 7000 BP [41]. It was during this period that the modern Amu Darya Delta was formed. The period between 5000 and 2000 BP was characterised by elevated water levels, with a notable interruption around 3600 BP, as evidenced by gypsum deposits, suggesting a short regression. Studies of Bronze

Age irrigation systems have revealed that they commenced around 3900 BC along the Amu Darya and the Khorezm delta, reaching a peak between 2400 and 1600 BC. The Aral Sea's retreat is believed to have been primarily caused by medieval diversions, with the last regression event occurring between 1200 and 1300 AD, resulting in water levels lower than those at the beginning of the 21st century [49]. The Aral Sea's ongoing decline since the early 1960s has led to the formation of a distinctive evaporitic sequence, characterised by the accumulation of carbonate deposits in the eastern region, gypsum in the distal south-eastern part of the depression, and terrigenous deposits surrounding the water body. This phenomenon has been the subject of research, particularly by Soviet scientists between 1977 and 1985 [40].

The erosive action of the winds, which transported particles torn from the basin to the south and south-west, led to the deposition of loess, a loose rock that is highly fertile. Sandy or salty soils (e.g., Solonchak) are all poor, with little structure. They are not suitable for agriculture, which partly explains the difficulties and limitations of development. The flooded banks of the Aral basin are the source of saline dust storms, which are traumatic for people, land and water. In this context, the Amu Darya delta is a privileged zone, the most fertile in Uzbekistan, where wind currents blowing from the north (a source of nutrients) meet the fluvial silt of the Amu Darya, the origin of Khorezm's historical prosperity [50].

4. Remote Sensing-Based Results

4.1. Satellites and Sensors

The bibliometrical approach sought to isolate the main satellite data used in remote sensing studies on Central Asia (Figure 4). Table 1 provides a concise overview of the primary satellite data employed in studies of the Aral Sea and its catchment area over the past fifty years. For the sake of simplicity, satellites of the same generation are sometimes grouped together, as precise identification is not always possible in the documentation.

Although MODIS data has only been available for 25 years, it is by far the most widely used in regional remote sensing studies, with more than 300 documents referencing it. This is due to its regional daily coverage, making it the primary tool for large-scale land use mapping. MODIS data are also integrated into numerous databases concerning parameters such as temperature, cloud cover, and aerosols present in the troposphere. Landsat data, which has been available for over 50 years, also features prominently, with just over 200 documents. This advancement is chiefly attributable to the data acquired from the Landsat 4–5 Thematic Mapper (TM), which was operational from 1982 to 2013, and the Landsat 8–9 Optical Land Imager (OLI), which has been in operation since 2013. Digital elevation models (DEMs) have been categorised separately and not included in the table, even though they may have been produced using various satellite data (Shuttle Radar Topography Mission, Spot or Aster stereoscopy, radar interferometry, etc.). These represent around 100 documents. NOAA-AVHRR data are present in around fifty studies. Despite being over 50 years old, they appear to have largely been superseded by MODIS, particularly given that a spatial resolution of 1100 m is inadequate even for synthetic maps of Central Asia. The utilisation of high-spatial-resolution satellites in the study of the Aral Sea Basin is limited. In addition, the exploration of both Alos and first-generation Spot data was limited. The paucity of research in the field of Synthetic Aperture Radar (SAR) is striking. The imminent development of the Sentinel satellites has the potential to offer a wide range of applications in the optical or radar range, and at both small and large scales. It is surprising that no documents have been found with OrbView 3, a very-high-resolution satellite available in the early 20th century, even in relation to Central Asia as a whole or the Aral Sea alone.

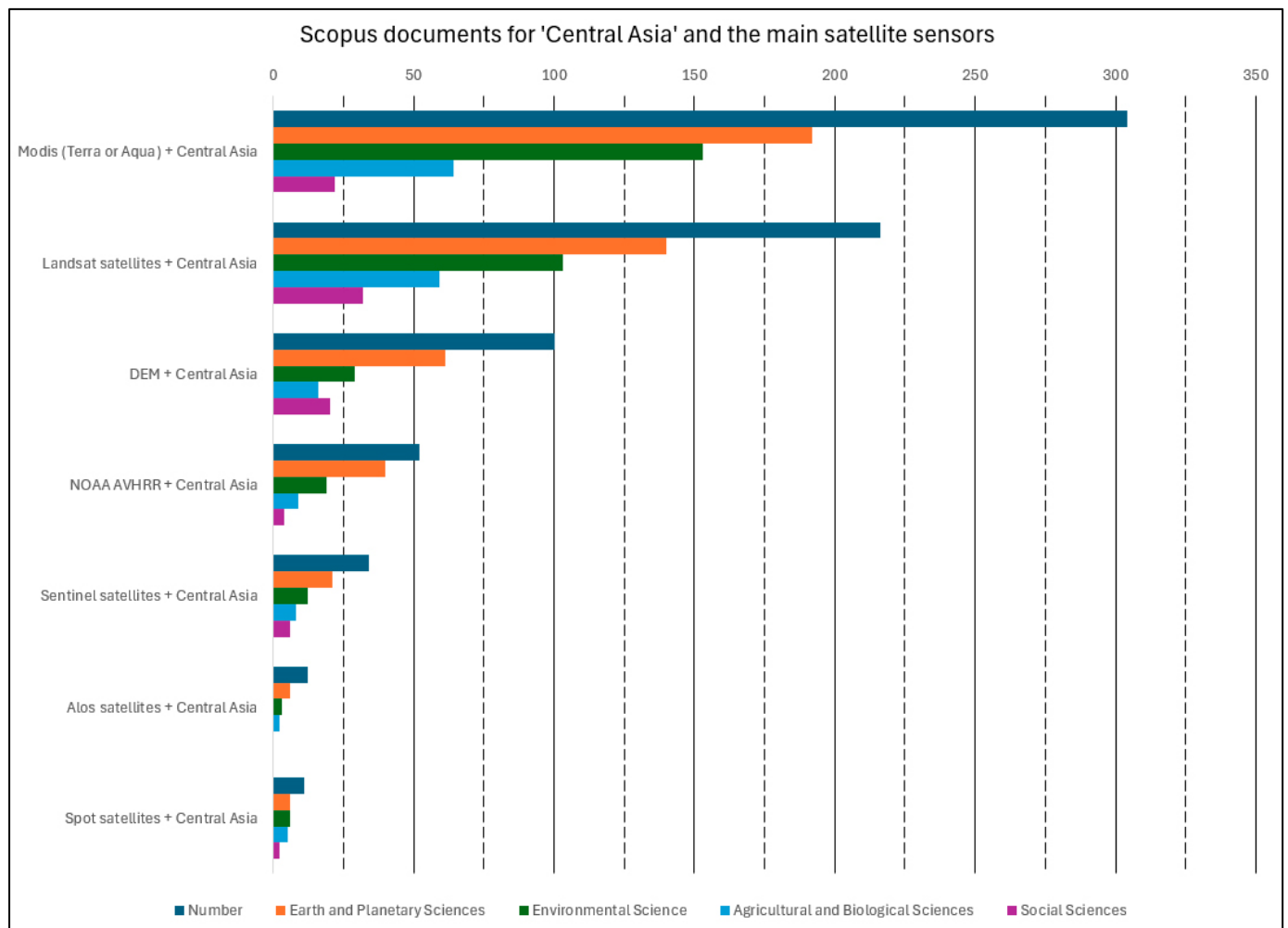


Figure 4. Distribution according to the four main Scopus subject areas of documents corresponding to the main satellites used in remote sensing studies of Central Asia.

4.2. Precipitation and Temperature

The study of desertification processes is dependent on two main parameters: precipitation, i.e., the amount of rainfall, and temperature. Remote sensing is an especially important tool when in situ data are diffuse and chronicles are unreliable. In general, MODIS MOD11 surface temperature products are consistent with in situ data and outperform other products as a proxy for air temperature [51]. An interesting synthesis for Central Asia, including China's Xinjiang, covers the period 1980–2015 [52]. The meteorological data come from the National Oceanic and Atmospheric Administration (NOAA) Global Meteorological Station. Multi-source remote sensing data, principally Landsat TM and ETM+, supplemented by high-resolution imagery from Google Earth, were used to study land change, principally with Normalised Difference Vegetation Index (NDVI) maps. Temperature and precipitation in Central Asia have changed a lot, with the biggest temperature increases in the Turgay Plateau, Kazakhstan (Figure 1). Precipitation has also increased, particularly in the upstream countries (Kyrgyzstan and Tajikistan), but has decreased in eastern Kazakhstan and western Xinjiang. Annual precipitation has been highly variable, with the minimum annual average precipitation recorded in 1983 (179.5 mm). Average annual precipitation in Central Asia was higher in 1995–2013 than in 1980–1993. In 1994, abrupt changes in temperature and precipitation were observed across Central Asia.

Table 1. The primary satellites and sensors employed in the study of the Aral Sea Basin and Central Asia. Type: VHR, very high resolution (<2 m); HR, high resolution (2–30 m); MR, medium resolution (30–300 m); LR, low resolution (>300 m). The number in the ‘use’ column corresponds to the number of Scopus articles for Aral + sensor name. The Google Earth Engine (GEE) incorporates a variety of satellite data types. The term ‘End’ is used to denote the conclusion of data acquisition. The term ‘in operation’ is defined as operational in July 2025.

Satellites	Launch	End	Sensors	Type	Use (Aral)
Corona	1959	1972	KH	VHR	2
Cryosat-2	2010	in operation	altimeter	-	1
DMSP	1962	2014	SSM/I	LR	1
ENVISAT	2002	2012	altimeter	-	5
ENVISAT	2002	2012	ASAR	HR	1
EOS	1999	in operation	MODIS	MR	51
EOS	1999	in operation	ASTER	HR	2
ERS 1–2	1991	2011	GOME	-	1
GEOS 3	1975	1979	altimeter	-	2
Geosat	1985	1986	altimeter	-	2
Google Earth	2010	in operation	various	VHR-HR	18
GRACE 1–2	2002	2018	altimeter	-	19
ICESat 1–2	2003	in operation	altimeter	-	1
IKONOS-2	1999	2015	OSA	VHR	0
Jason-1	2001	2013	altimeter	-	5
Jason-2	2008	2019	altimeter	-	2
Jason-3	2016	in operation	altimeter	-	2
LANDSAT 1–3	1972	1983	MSS	HR	3
LANDSAT 4–5	1982	2013	TM	HR	19
LANDSAT 7	1999	2024	ETM+	HR	11
LANDSAT 8–9	2013	in operation	OLI	HR	20
NIMBUS 7	1978	1995	SMMR	LR	1
NOAA 1–21	1970	in operation	AVHRR	LR	16
OrbView-3	2003	2007	OHRIS	VHR	0
RapidEye	2008	2020	JSS 56	HR	3
RESURS-O1	1985	2000	MSU	HR	2
Seasat	1978	1978	SAR	HR	2
Sentinel-1	2014	in operation	SAR	HR	2
Sentinel-2	2015	in operation	MSI	HR	8
Sentinel-3	2016	in operation	OLCI	MR	1
Sentinel-5	2017	in operation	UVNS	-	6
Sentinel-6	2020	in operation	altimeter	-	1
Spot 1–5	1986	2015	HRV, HRG	HR	0
Spot 6–7	2012	in operation	NAOMI	VHR	0
SUOMI	2011	in operation	VIIRS	MR	0
Topex-Poseidon	1992	2005	altimeter	-	10
TRMM	1997	2015	radar	-	3

As demonstrated by Jin et al. [20], the surface temperature of the Aral Sea increased by up to 1 °C during the day and decreased by 0.5 °C during the night. This was due to land surface changes, as observed in MODIS data, resulting in a widening of the diurnal temperature range (period 1960–2015). The same authors used data from the Tropical Rainfall Measuring Mission (TRMM) and Clouds and the Earth’s Radiant Energy System (CERES), later based on Terra, Aqua, Suomi-NPP and NOAA-20. Precipitation and cloud fraction over the Aral are increasing, while surface precipitation is decreasing [13]. The opposite trends may be due to bias in satellite retrievals, caused by neglecting shrinking Aral Sea surface albedo changes. Fixing these instead of using dynamic values in retrieval methods might explain the decreasing cloud fraction effect on rising daytime and

falling nighttime temperatures over the Aral Sea. For the period 1981–2001, Nezlin and Kostianoy [53] highlighted a high correlation between precipitation data from the Global Precipitation Climatology Centre (GPCC) and NDVI from NOAA-AVHRR (Advanced Very-High-Resolution Radiometer) over the northern Aral Sea, in the upper and middle reaches of the Syr Darya, and in the area north of the Syr Darya. At the same time, no correlations were found between precipitation and the vegetation index to the southeast of the Aral Sea, especially along the lower reaches of the Amu Darya. The authors suggest that rain and snow water do not accumulate in the soil and do not support vegetation development.

De Beurs et al. used the MODIS LST (MOD11C2) and ET (MOD16A2) products to analyse changes in land surface temperature and evapotranspiration, respectively [54]. They also used the MCD12C1 product to analyse changes in land cover. Most changes occurred in Kazakhstan and Uzbekistan, while Tajikistan, Kyrgyzstan and Turkmenistan appeared more stable. This phenomenon can be attributed to a combination of anthropogenic and meteorological factors. The transition in crop type south of the Aral Sea, from cotton to wheat, resulted in an increase in vegetation indices, concomitant with a decrease in evapotranspiration.

4.3. Water Surface

The utilisation of remote sensing data has been identified as a particularly effective method for the assessment of the surface area of large lakes, a prime example of this being the Aral Sea. High and medium resolution imagery is required for an accurate assessment. Images from Corona-type satellites (KH series) have been available since the 1960s, but were classified until 1995. As a result, they have been little used in publications and mainly used locally (see below). The Landsat series is the most widely used. Landsat images have been available since 1972 for the MSS sensor on board Landsat 1 to 3 (80 m spatial resolution) and were used in the 1970s to estimate the surface area of the Aral Sea [29]. The successors to MSS are the Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Optical Land Image (OLI) sensors on board Landsat 4 to 9, all with 30 m spatial resolution [55,56]. For example, Tao et al. [57] used Landsat 7 and 8 OLI imagery to estimate the surface area of the four remaining sub-lakes in the Aral region between 2002 and 2018. Other satellites mentioned in the literature were launched in subsequent years, such as the NOAA-AVHRR series since 1978 [58], the Soviet RESURS-01 satellite since 1985 with the Multispectral VNIR radiometer (MSU-SK, this sensor has similar spectral bands to Landsat MSS) combined with data from the Salyut-4 orbital station [59], and Terra-MODIS, operational since February 2000 [20,58]. Zhou et al. have made extensive use of these high spatial resolution data to map water bodies and river widths in several areas of the ASB [60]. Lakes are sometimes defined visually, but generally a ratio is used to highlight water bodies. The most commonly used are the Normalised Difference Water Index (NDWI) and the NDVI. Deliry et al. modelled the temporal and surface temperature changes in the Aral Sea using Landsat-5, 7 or 8 data [56]. The NDWI was used to extract and quantify water surface changes, while the surface temperature values were calculated using thermal bands to investigate land and water surface temperature changes. The results showed a significant decrease in the surface area of the Aral Sea (from 44,164 km² in 1986 to 9772 km² in 2017) (see also Figure 5) and a significant increase in the summer land surface temperature (~12 °C). As mentioned above, NOAA-AVHRR for the period 1981–2000 and Terra or Aqua-MODIS for the period 2000–present are the most commonly used mid-scale data. An original study was carried out using both types of imagery to derive the extent of water bodies over the period 1986 to 2012 [61]. Changes each year were checked using months April, July and September. The Aral Sea has greatly reduced, but also natural lakes

in northern Kazakhstan, far from the ASB. Other mountain lakes there remain stable. The validation was based on high-resolution Landsat imagery.

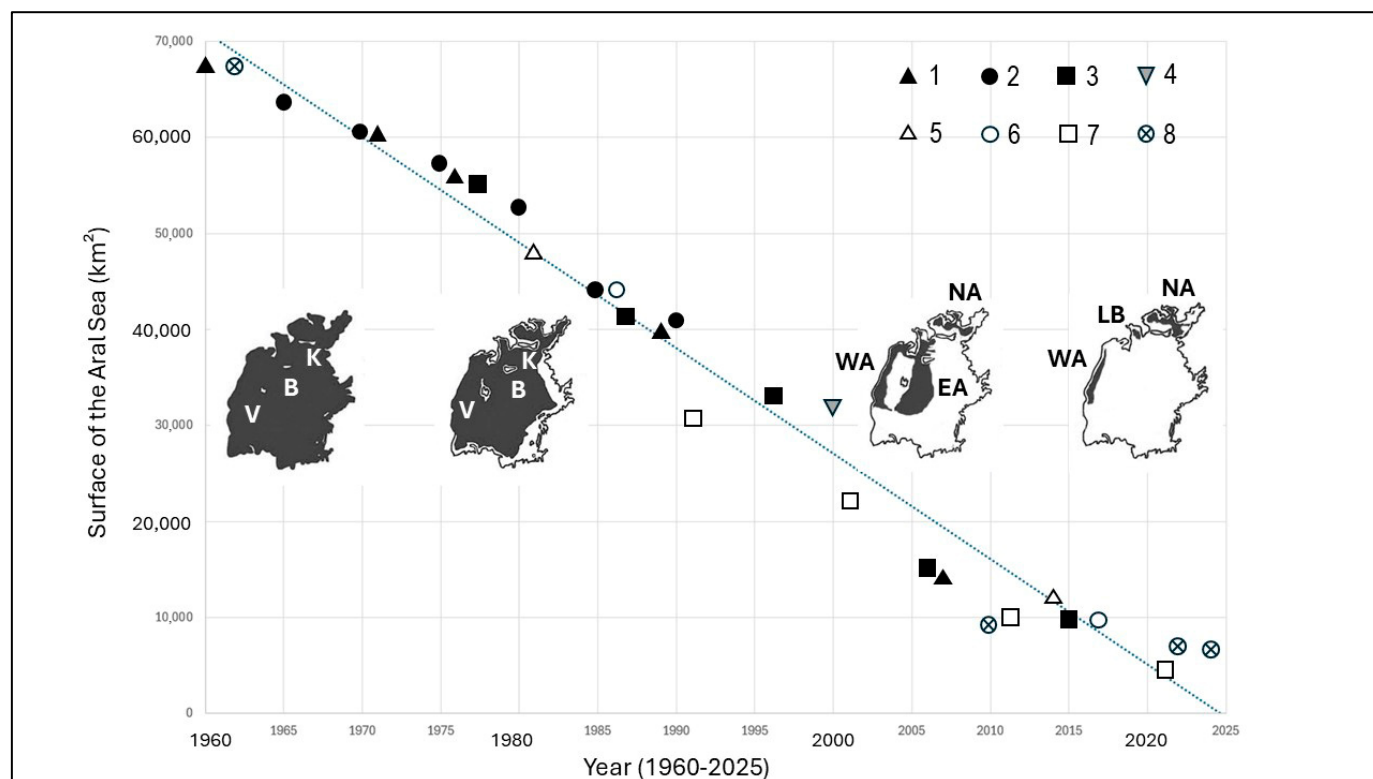


Figure 5. The decline in the water surface in the Aral Sea. 1. [29], KH-5, Landsat-MSS, NOAA-AVHRR, 2. [2], 3. [55], Landsat TM, ETM+, OLI, 4. [20], Terra-Aqua MODIS, 5. [62], 6. [56], Landsat TM, ETM+, OLI, 7. [58], NOAA-AVHRR/VIIRS, Terra-Aqua MODIS, 8. [Deroin, unpublished data, KH-4, Terra-Aqua MODIS]. The different water bodies (shades of grey) correspond to 1962, 1980, 2005, and present. Abbreviations: B, Barsakelmes Is.; EA, Eastern Aral sea; K, Kokaral Is.; LB, Lake Barsakelmes; NA, Northern Aral Sea; V, Vozrozdeniya Is.; WA, Western Aral Sea.

As a synthesis, Figure 5 shows the evolution of water surface area between 1960 and the present from different sources. The decrease is regular, as indicated by the r^2 of the linear trend curve of 0.97. During the first period (1960–1980), only the east coast of the Aral Sea showed a global decrease. At the same time, the islands in the sea grew and merged with the surrounding land (from north to south): Kokaral Island joined the NW coast in the mid-1960s, Barsakelmes Island in the late 1990s, and Vozrozdeniya Island in August 2001. The northern Aral Sea, or Little Aral Sea, was isolated as early as 1987, and the Kokaral dike across the Berg Strait was completed in 2005 to prevent water from the north spilling over to the south. Between May 2014 and February 2015, the Eastern Aral experienced a first episode of drying. This area will dry out completely from June 2019. Three large water bodies remain: the North (or Small) Aral Sea, which has remained relatively stable since 2022 (about 3100 km²), the Western Aral Sea, which continues to lose surface area (about 1900 km²), and Lake Barsakelmes (250 km²), which dried up completely in the summer of 2024. The total surface area of the water bodies is 5250 km², or 8% of the original surface area.

4.4. Water Surface Altimetry

Researchers have studied satellite radar altimetry data as a contributor to surface elevation variability [63–65]. The main radar altimetry satellites used for studies in the Aral Sea basin are, in chronological order: GEOS-3 (1975–1979), Seasat (1978), Geosat

(1985–1986), Topex-Poseidon (1992–2005), Jason-1 (2001–2013), Jason-2 (2008–2019), Cryosat-2 (2010–present), Jason-3 (2016–present), Sentinel-6 (2020–present). The primary altimetry satellites traverse the Aral Sea from a south–western to a north–eastern direction, following a consistent ground track, allowing sea level heights to be calculated. Shi et al. studied a 21-year chronicle (1993–2014) of Topex-Poseidon, Jason-1 and Jason-2 altimetry data [62]. The surface was also monitored with optical data using a NOAA-AVHRR chronicle from 1981 to 2014. The coverage maps since 1981 demonstrate a consistent decline in the Aral Sea. The authors found a rising water level in 2005–2006, when a dam was built between the northern and south–eastern Aral Sea in 2005. In another case, water levels were estimated in combination with shoreline changes from Landsat imagery (TM and ETM+) [66]. ICESat (Ice, Cloud and land Elevation Satellite) was the first satellite lidar to provide water surface independent of radar altimetry and in situ measurements. Unfortunately, it only operated from 2003 to 2010 and only 2–3 times per year over continental lakes, with few applications to Central Asia [67]. ICESat-2, launched in 2018 in combination with Cryosat-2 (radar interferometry), shows that the combination of the two satellites has the potential to facilitate a more precise investigation into the water level of Lake Issyk Kul. The study demonstrates a higher degree of consistency with in situ data [68]. Finally, it should be noted that Lake Issyk Kul serves as a permanent calibration and validation site for altimetry satellites such as Jason 3 and Sentinel-3 [69].

4.5. Water Volume of the Water Bodies and Irrigation Systems

The studies of the surface, altimetry and bathymetry of the Aral Sea have also made it possible to estimate the volume of the Aral Sea at different times, particularly in relation to the flow of the two main rivers and precipitation. All studies show that if the surface area is divided by 10 between 1960 and 2020, the volume will be divided by 100. The volume of runoff decreased from 20.6 km³ in 2003 to 4.5 km³ in 2010, while precipitation decreased from 9.4 km³ in 1960 to 3 km³ in 2010. Subsequently, the estimated range of water salinity was from 10.6 g/L in 1960 to 122.5 g/L in 2009, close to the observed values (10 and 120, respectively) [13]. The increased precipitation and glacial meltwater in the upstream part of the basin was unable to compensate for the water loss experienced by the Aral Sea. [70]. This later study is based on NDVI from a long-term satellite data chronicle from MODIS (2000–2018) and, in particular, MOD02QKM products. The utilisation of Landsat ETM+ images from 2002, 2007 and 2012, in conjunction with OLI images captured in 2017, served as the basis for the validation data. The authors used MODIS products (MOD13Q1, MOD13C2, MOD11C3) and focused on a short period from 2000 to 2015, during which the lake surface decreased (from 32,000 to 10,000 km², see also Figure 5) due to a decrease in water storage in the ASB. Environmental changes, including drier soils, reduced vegetation, decreasing cloud cover and precipitation, and more frequent and severe dust storms are also highlighted. As mentioned above, there is a widening of the diurnal temperature range [20].

Between 1993 and 2017, the Southern Aral Sea lost about 195 km³ of water, accompanied by a decrease in lake size, an acceleration in actual evapotranspiration (AET), and an increase in sea surface temperature (SST) [71]. The authors proposed that the Western Aral Sea could disappear by almost 2032 on the current trend (almost −2.7 km³/yr^{−1}). The aforementioned authors identified a decline in terrestrial water storage (TWS) within the Amu Darya delta region, primarily attributable to an augmentation in water mass within the central segment of the Amu Darya basin, a phenomenon that is presumably precipitated by enhanced infiltration in conjunction with the deterioration of the canal infrastructure. This supposition remains unvalidated due to an absence of field data, yet it is corroborated by the concurrent decline in ET and NDVI within the region, concomitant

with the escalation in TWS. A local study in the Amu Darya Delta was conducted by Liu et al. using the Surface Energy Balance Algorithm for Land (SEBAL) model [72]. Landsat TM, ETM+ and OLI images were used to extract some parameters (e.g., NDVI). It was determined that in years with high precipitation, irrigation water can replenish groundwater, thereby indirectly contributing to the feeding of the southern Aral Sea. Conversely, in years with low precipitation, groundwater meets the evaporation needs of crops, yet even upstream groundwater requires recharging. In the absence of field monitoring, remote sensing studies based on NOAA-AVHRR allow the identification of leakage in natural and human systems. Significant groundwater leakage has been identified along the entire coastline [73]. The same authors, utilising hydrogen and oxygen isotope snapshots, ascertained that groundwater discharge constitutes a significant contributor to the lake during the spring and autumn months. In the Lebap province of Turkmenistan, water losses along irrigation canals were detected by a gap between cotton ET calculated from satellite imagery and crop water demand [74]. Field validation was supported by very-high-resolution Quickbird imagery.

The Gravity Recovery and Climate Experiment (GRACE) mission consisted of two satellites (GRACE-1 and 2) that made detailed measurements of the Earth's gravity field. It ran from 2002 to 2018 and allowed the vertical change in water mass over large river basins to be estimated. The measurement is not based on electromagnetic waves, but on a microwave ranging system. A reference already cited shows a successful comparison of the changes. The latter are determined from satellite altimetry combined with the use of Landsat imagery, which provides images of temporal coastline variations and gravity data with GRACE [66]. The authors highlight a progressive drying up until early 2009, followed by an abrupt increase in water in 2009–2010 due to an exceptional discharge of the Amu Darya. Several publications illustrate the contribution of GRACE gravity data in the Aral Sea region [20,65,71,75]. Estimates from 2003 to 2012 show that up to 14 km³ of equivalent water mass was lost from the basin annually from 2002 to 2013 [65]. Changes in GRACE liquid water equivalent thickness (LWET) have been used as a metric to indicate alterations in surface and groundwater resulting from irrigation activities [20]. Changes in terrestrial water storage (TWS) as observed by the GRACE mission in the Aral Sea region have been shown to be indicative of water levels in the eastern Aral Sea with a high degree of accuracy, as determined by altimetry observations [71]. Shi et al. [75] used the GRACE dataset to extract the equivalent water height (EWH). They also discuss purely methodological aspects, highlighting the difficulties associated with data pre-processing. No published results were found using the Gravity Field and Steady-state Ocean Circulation Explorer (GOCE), which operated between 2009 and 2013.

4.6. Snow and Ice

The Tien Shan and Pamir regions are the main source of water for ASB, potentially stored in the form of glaciers. Using ICESat and GRACE data, Gardelle et al. found that Pamir glaciers had a slightly positive mass budget between 1999 and 2011 [76]. They proposed to extend the famous Karakoram anomaly to a Pamir-Karakoram anomaly. However, recent studies using archived KH-4 and KH-9 data have revealed negative mass budgets in the central and northern Tien Shan and eastern Pamir, even in regions where glaciers were previously in equilibrium with the climate. The observed increase in summer temperature has been identified as a primary factor contributing to the long-term trend of mass loss [38].

For snow cover, specific studies have been carried out using the medium resolution VIIRS instruments on board Suomi NPP combined with the higher resolution of Landsat 8 OLI [77]. The authors found that Landsat 8 OLI avoids the saturation problems common to

Landsat 1–7 in the visible wavelengths and re-evaluated previous assessments using data from earlier Landsat sensors. It was also confirmed that the VIIRS instruments can be a suitable replacement when the MODIS sensors reach the end of their life. In order to link the TOPEX/Poseidon results to historical observations ending in the mid-1980s, a study was conducted in which long time series of passive microwave data from SMMR onboard NIMBUS-7 and SSM/I onboard DMSP (Defence Meteorological Satellite Programme) sensors starting in 1978 were analysed [78]. The analysis revealed a strong correlation between the satellite data and the historical records, highlighting significant variations in ice conditions across different spatial and temporal domains. A notable decline in the duration and extent of the ice season was observed during the winters of 1998/1999 to 2001/2002. In the upper Syr Darya catchment (Tien Shan), a time series analysis of daily MODIS snow cover products and in situ data demonstrates a decrease in spring snow cover duration of -0.53 to -0.73 days per year over the 22-year period (2000–2022) [79].

Glacial lakes represent a highly significant category of water bodies in mountainous regions. A multi-temporal lake inventory has been produced based on archival data of 1968 Corona imagery, which has been compared with more recent ASTER and Landsat 7 imagery [80]. A total of 1642 lakes were mapped in the headwaters of the Amu Darya in the Pamir and Hindu Kush mountains, of which 652 are classified as glacial lakes. Between 1968 and 2009, a highly significant increase in glacial lakes was observed, while the average size of other lake types (erosion or debris dam lakes) remained constant [80].

4.7. Geology and Seismicity

Some pioneering work was performed by Soviet scientists using Soviet satellite imagery. There was even a special study between 1974 and 1980 [81]. One paper describes the implausible water diversion project to transfer water from Siberian rivers to the Aral [82], a project abandoned in 1986. Unfortunately, thematic or methodological elements related to remote sensing are almost non-existent in most of the articles, for example, in the interesting studies of Lake Sarykamish [83–85], a lake that grew in size as irrigation became more important in the Khorezm region. Water discharge in the Aral Sea has been studied using thermal infrared data [86]. Large-scale geological mapping supported by modern remote sensing is rare, particularly in Central Asia. However, there are some interesting approaches in the field of very-high-resolution digital elevation models (DEMs), such as those obtained at 2 m resolution from Pleiades data in the Alatau range (Kazakh Tien Shan) [87]. The applications are mainly in the area of active faults, which are of great regional importance due to the highly seismic nature of the Tien Shan and the surrounding areas. Another paper in the same region refers to the use of a 3 m resolution digital elevation model (DEM) from Spot 6 data [88]. This later study uses much more satellite data, including a 1969 Corona image showing that the Big Almaty canal was built on an active fault and its associated scarp. The ASTER sensor on board Terra provided interesting DEM, but it is also known for mineral exploration using the shortwave infrared (SWIR) part of the spectrum (no longer available as of April 2008). No published application in Central Asia could be found, although these data have been used successfully on the Chinese side of the Tien Shan [89]. While remote sensing data are currently little used for geological and mining prospecting, they are widely used to manage the associated risks. In Kyrgyzstan, the two largest gold mines have been monitored using satellite data, in particular the Kumtor mine [90], which has been known to suffer from various hazards since its discovery in 1978 (accidental spillage from a cyanide truck, partial destruction by a melting glacier). At Taldybulak Levoberezhny, the second largest gold mine in Kyrgyzstan, Landsat TM/OLI imagery and nighttime light (DMPS) data have been processed for remote monitoring at various stages of development to enhance the rational development of mineral resources [91]. In the

petroleum industry, He et al. [92] identified two methane (CH_4) plumes near a gas compressor station in Turkmenistan. The Tropospheric Monitoring Instrument (TROPOMI), which is installed on board the Sentinel-5 satellite, was used in conjunction with the Shortwave Infrared (SWIR) band of the Sentinel-2 satellite. Results from Sanchez-Garcia et al. [93] have shown the good performance of WorldView-3 for CH_4 mapping, also using the SWIR band (WV3 band 7).

Utilising an automated lineament detection method performed on Landsat 8 data, Sichugova and Fazilova [94] identified a rapid augmentation in lineament density 20 days prior to an earthquake, attaining a zenith approximately 4 days before the seismic occurrence, and subsequently diminishing 16 days following the earthquake. In the very important area of seismic precursors, it is worth mentioning a recent paper analysing potential anomalous signals associated with earthquake activity using the large-scale Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument, on board the Japanese Space Exploration Agency's Global Change Observation Mission 1st-Water (GCOM-W1) satellite. Increased microwave radiation was observed within a week of two earthquakes in the Tien Shan (2024) and Pamir (2023) [95]. The idea that some strong earthquakes may be accompanied by IR radiation flux anomalies originated in the USSR in the 1980s. The most prominent example is the Ghazli earthquake of 19 March 1984 (magnitude 7.2), in Uzbekistan [96]. A positive anomaly of exceptional intensity was detected 8 days before the main shock using NOAA-AVHRR data. Although various explanations have been proposed, such as interactions between gas emissions, relative humidity, and water vapour, no recent application to Central Asian countries has been identified.

4.8. Salinisation (Minerals and Soils)

As it dried up, the Aral Sea gave way to extensive evaporite formations consisting of halite, gypsum and other minerals. Geochemical studies are common (e.g., [97–100]), but no specific remote sensing study of the evaporite surfaces was found. Nevertheless, the direction of water flow through the Kulandy Strait, which connects the East Aral Sea to the West Aral Sea, has been determined by the use of a combination of radar and laser altimetry with MODIS imagery [67]. This was a key area for understanding the distribution of mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), epsomite (MgSO_4) and halite (NaCl) deposits. It is worth mentioning an interesting study based on the extraction of mineral surface backscattering from Sentinel-1 radar data [101]. The results of the desertification classification demonstrated that more than 68% of the arid area of the Aral Sea is subject to varying degrees of desertification.

Akramkhanov et al. correlated salinity data from two farms in Urgench (Khorezm) with NDVI, Transformed Normalised Difference Vegetation Indices (TNDVI) and additional indices such as Soil Adjusted Vegetation Index (SAVI) and Ratio Vegetation Index (RVI). The indices were calculated from a single Landsat 7 image and show a correct correlation with the salinity field measurement. As the indices are mainly an indication of vegetation, the correlation suggests that salinity has a significant effect on plant growth [102]. The Markov cellular automata technique applied to Landsat imagery revealed further desertification of the landscape, with potential expansion of saline soils and bare areas in the former Aral Sea region. At the same time, the vegetation cover of the region showed an increase, which was interpreted as a good signal of ecological recovery [55]. The utilisation of various soil salinity indices facilitated the identification of areas exhibiting high and extreme levels of salinity, with these regions being located in the northeastern region of the Eastern Aral Sea and the western part of Vozrozhdeniya Island, respectively. These areas were identified as the primary origin of salt-dust storms [103].

4.9. Dust

The Aral Sea disaster has had far-reaching consequences, not least in the form of large mineral surfaces, which have been identified as a significant source of dust storms. The role of mineral dust in climate forcing has been well documented, with the phenomenon of high aerosol concentrations in the atmosphere being attributed to alterations in radiation balance. The first documented instance of a dust storm was recorded by the Meteor and NOAA satellites in the spring of 1975 [104]. In 1982, the second significant dust source area was observed around the dry seabed of the island of Vozrozhdeniya, covering an area of 2000 km². This was also observed using satellite imagery. In 1989, satellite imagery revealed a third, smaller (200 km²) dust source on the northwestern side of the sea [105].

Persistent dust activity has been detected at the southern and south-eastern ends of the Aral Sea in the Turan lowlands [106]. The most intense regional activity was centred over the Kara-Bogaz Salt Lake, a lagoon-like embayment that was formerly a gulf of the Caspian Sea and is now isolated from the sea by an artificial dam during 1980–1992. The authors utilised the NIMBUS 7 TOMS instrument, which was engineered to furnish global estimates of total column ozone through the measurement of backscattered UV radiance. Using the 8-day MOD09A1 surface reflectance product from the MODIS sensor, complemented by Landsat 5 and 7 data, Löw et al. found that the drying of the Aral Sea accelerated between 2004 and 2008 [107]. The area of sandy surfaces and saline soils, which have the greatest potential to generate dust and salt storms, increased by more than 36%. In the Aral Kum, soil desalinisation was found to occur within 4–8 years. Dust originating from the area south of the Aral Sea, combined with dust transported from the Euphrates and Tigris region in Iraq, resulted in high dust concentrations in the southern Caspian Sea region affected by a major cyclone in 2009 [108].

In recent decades, the Aral Kum, which once constituted the Aral Sea, has emerged as a prominent geographical phenomenon in the region [109,110]. The study of dust storms and their source areas has been facilitated by the utilisation of NOAA AVHRR, TOMS and OMI data. The northeastern region of the Aral Kum Desert has been identified as a primary contributor to the region's dust emissions. Recent research endeavours have focused on the interplay between wind and erosion. The Soil Wind Erosion Potential (SWEP) has been estimated from remote sensing data (primarily MODIS), climate assimilation data and other geospatial data. SWEP has been calculated on a monthly basis for the period 2000–2019, encompassing Central Asia with a spatial resolution of 500 m [111]. The findings indicate that the mean SWEP exhibited strong concordance with the ground-based Dust Storm Index (DSI), the satellite-based Aerosol Optical Depth (AOD), and the Absorbing Aerosol Index (AAI). The erosion of the Aral Kum was estimated to be about 47 kg.m⁻².yr⁻¹.

4.10. Landslides

Landslides are a very important hazard in the mountainous areas of the ASB. Kyrgyzstan, Tajikistan and, to a lesser extent, Uzbekistan are the main countries affected. In Tajikistan alone, more than 1000 people were killed in 3460 emergencies between 1996 and 2018 [112]. Landslides can be divided into two main categories: earthquake-induced landslides and rainfall-induced landslides. Remote sensing is particularly well suited for local studies of landslides, especially when it is combined with field observations [113]. Very-high-resolution (<2 m) satellite data and accurate digital terrain models are required. Radar and optical data can be used successfully, as recently demonstrated [114] in the emblematic case of Lake Sarez in eastern Tajikistan, which was affected by a major landslide in 1911. The area remains under observation because of two zones of instability near the Usoy dam. Images from Spot-6 and Spot-7 were used for the optical data and Sentinel-1 for the InSAR approach. Sentinel-2 (pixel size 10 m) and an ALOS-PALSAR DEM (pixel size

12.5 m) have been combined to produce a landslide inventory in the Hissar-Allay region of western Tajikistan [112]. The utilisation of DEM analysis is precluded in the case of small landslides; instead, very high-resolution images from Google Earth were employed for the labelling of rockfalls and shallow landslides.

In Kyrgyzstan, many studies have focused on the eastern margin of the Fergana basin (e.g., [115]). As early as 2005, methodological studies in the area of the Upper Maili Suu River Basin were already focusing on the potential of satellite remote sensing data from various optical (Landsat-TM, Landsat-ETM+, ASTER, MOMS-2P) and radar (ERS-1/2) systems to provide an improved knowledge base for hazard assessment [116]. In a recent study, Ozturk et al. [117] compared a landslide inventory in the form of a historical inventory originally covering the entire Tien Shan with their own inventory. The latter consisted of landslide objects in the form of polygons semi-automatically derived from time series of optical satellite remote sensing data (RapidEye), covering the period between 2009 and 2017. By analysing temporal changes in NDVI, Iron Index and relief-oriented parameters (slope inclination, relief position) in a rule-based approach combining pixel- and object-based analyses, they conclude that the use of landslide toe areas may be sufficient for this particular model and may be useful where landslide scars are vague or hidden. In 2015, Teshebaeva et al. [118] conducted an interferometric analysis using Differential Synthetic Aperture Radar (D-SAR) to detect slow-moving, deep-seated landslides in close association with lithology near the town of Uzgen. A strong correlation was identified between deformation peaks and precipitation, thus indicating continuous activity affecting the slope of the landslides. The Advanced Land Observing Satellite Phased Array type L-band SAR (ALOS PALSAR) dataset was used for this purpose. While L-band radar sensors possess a longer wavelength that allows for partial penetration of surface vegetation, their temporal resolution of 46 days is not optimal. Other authors [119] processed the C-band Sentinel-1 satellite images and combined them with optical data. In spring 2017, Kyrgyzstan suffered significant losses due to a substantial landslide activation event, which also reactivated two of the largest deep-seated mass movements of the former Mailuu-Suu mining area—the Koytash and Tektonik landslides. The study used optical and radar satellite data to delineate deformation zones and identify displacements prior to the collapse of the Koytash landslide and the more superficial deformation of the Tektonik landslide. A comparison of the digital elevation models from 2011 and 2017 was undertaken, with the former being based on satellite imagery and the latter on unmanned aerial vehicle (UAV) imagery. This comparison revealed areas of depletion and accumulation in the scarp and near the toe, respectively. D-SAR interferometric analysis identified slow displacements in the months prior to reactivation in April 2017, indicating long-term slip activity of the Koytash landslide and the Tektonik landslide. Optical data were used for NDVI, specifically two Pleiades-1A images (pre- and post-landslide) with a spatial resolution of 0.5 m. In recent research, Wang et al. [120] utilised Sentinel-1 data and developed an unsupervised multi-variate transform-based deep learning model to automatically and efficiently estimate landslide occurrence times. This was achieved using multivariate SAR-derived parameter time series analysis. The focus was on the Kugart landslide and the Jalgyz-Jangak landslide, both of which were active in 2018. The results suggest the potential of SAR data when used in conjunction with optical data.

Landslides along the Chirchik River in Uzbekistan were studied using very-high-resolution GeoEye 1 data in combination with DEMs extracted from stereoscopic WorldView data and ASTER GDTEM [121]. Along the western coast of the Aral Sea in Uzbekistan, Aslan et al. identified a slow-moving landslide, as revealed by Sentinel-1 interferometry. The occurrence of this landslide is attributable to the lithological sequence and local faulting, with the potential for long-term sea-level decline acting as a contributing factor [122].

4.11. Flooding

The critical period for floods in Central Asia is spring and summer, as the rivers have a clear fluvial-nival regime. It is anticipated that temperatures in mountain ranges will continue to increase. This will result in a further advance of the spring flood and a reduction in runoff. This will require the coordinated management of water resources, particularly in the Syr Darya basin [79]. In this particular instance, the MODIS daily snow cover product M*D10A1 is used in order to ascertain the duration of snow cover, in addition to the precise dates of snow onset and snow melt. Flood damage assessment in Central Asia using remotely sensed data is poorly illustrated. The catastrophic dam failure of the Sardoba reservoir (Uzbekistan) in May 2020 was investigated using Sentinel-1 and Sentinel-2 [123]. The Soil and Water Assessment Tool (SWAT) is a computerised model that is used to simulate the quality and quantity of surface and groundwater at various scales, from small watersheds to large river basins. It was employed to simulate the Aktash River basin in Uzbekistan in order to predict the environmental impacts of various activities. The MODIS evapotranspiration/latent heat flux product (MOD16A2) was used as a proxy for field measurements [124].

4.12. Glacial Lake Outburst Floods (GLOFs)

A special case of high mountain landslides are glacial lake outburst floods (GLOFs) and associated debris flows. GLOFs peaked in the 1970s, when strong positive temperature anomalies and glacier melt were observed [125]. One of the first attempts to apply lake outburst potential and hazard assessment of mountain lakes was carried out in Uzbekistan using WorldView 2, IKONOS and SPOT 5 satellite imagery [126]. In the Tajik Pamir, Mergili and Schneider [127] conducted a study on the village of Dasht (Shakhdara Valley), which was impacted by a GLOF in August 2002. The incident involved the sudden release of an estimated volume of 320,000 m³ of water from a lake with a surface area of 37,000 m². Multi-temporal analysis of Landsat imagery revealed that the lake had been in existence for less than two years prior to its drainage. A comprehensive mapping of all lakes in the area was conducted across three time windows: 1968 (Corona imagery), 2001/2002 (ASTER and pan-sharpened Landsat ETM+ imagery) and 2007/2008 (ASTER imagery). The authors of the study identified two major limiting factors for regional-scale lake outburst hazard analyses: the lack of detailed geological information and information on seepage through the dam, particularly sediment consolidation. Satellite imagery and digital elevation models only provide information on surface features and patterns and do not provide insight into the subsurface. The deadliest GLOF in Central Asia for at least a century occurred on 8 July 1998 in the Shakhimardan area of Kyrgyzstan, but the majority of the 100 victims were killed in the local Uzbek enclave. The utilisation of remote sensing techniques, predominantly Sentinel-2 imagery, has led to the revelation that the lake in question, which is the point of origin for the phenomenon under investigation, first appeared in the 1960s and has been subject to periodic drainage [128]. The authors of the study have highlighted certain limitations of the very high-resolution imagery, including Ikonos, due to the absence of nadir views. Erokhin et al. [129] conducted a study of the Teztor lake complex in northern Kyrgyzstan, which experienced a GLOF in 1953. A comprehensive analysis was conducted on five high-resolution aerial and satellite images, which were obtained from Google Earth and aerial archives, spanning the period from 1962 to 2014. This analysis was supplemented by topographic maps, helicopter photographs captured in the months preceding and following the 2012 event, and historical data, including oblique views and prior field surveys. The authors also analysed meteorological parameters and found that the 2012 GLOF was caused by a combination of intense precipitation in the days preceding the event and a rapid rise in air temperature. Shangguan et al. studied Lake Merzbacher

in eastern Kyrgyzstan, a glacial lake located in the upper reaches of the Aksu River [130]. The extent and storage capacity of the lake were determined by the utilisation of DEM data. The approach adopted was distinguished by the incorporation of multi-source DEMs, acquired from KH-9 (1974), SRTM (2000), ALOS (2006) and Spot (2008). The study posits that the GLOFs of Lake Merzbacher were precipitated by a gradual increase in summer air temperature and by variability in water supply due to variability in precipitation. A multi-source remote sensing study, primarily using Corona 4H-4B, Landsat MSS or ETM+ and Aster [131], has revealed an escalating number and area of glacial lakes within the northern Tien Shan region, encompassing Kazakhstan and Kyrgyzstan. A subset of these lakes exhibits medium to high outburst potential. The NDWI has been employed as a means to detect water bodies. Daiyrov et al. [132] focused on the Toguz-Bulak glacial lake in the Teskey mountain range, Kyrgyzstan, with a large dataset including Corona 4H-4A, Landsat-5 TM, Landsat-7 ETM+, Landsat-8 OLI, Sentinel-2, ALOS-PRISM, ALOS-2, and others. The analysis of satellite images for the period 2010–2019 revealed that the lake's presence was observed in June and its subsequent disappearance in September on an annual basis. Subsequently, Daiyrov et al. [133] expanded the study to encompass the entire Kyrgyz and Teskey Ranges, where the majority of glacial lakes capable of triggering outburst floods are of a diminutive nature. Using Sentinel-2 (10 m) and PlanetScope (3 m), a total of 800 glacial lakes were identified, of which 242 exhibited significant variations in area, and 46 were classified as new glacial lakes, five of which demonstrated rapid expansion. In the Ala-Archa and Alamedin valleys of the Kyrgyz Range, a 10 m spatial resolution DEM was generated from Sentinel-1 imagery to define catchment areas [134]. The study's novel approach entailed the integration of available aerial and satellite imagery, extending from 1960, with growth ring records of trees subjected to extreme events. This facilitated the reconstruction of a chronology of GLOFs, extending back to the second half of the 19th century. In a similar region, Meyrat et al. have recently proposed a simulation of GLOFs, employing WorldView data to derive high-resolution DEMs [135].

5. Discussion

5.1. Numerical Overview

The list of selected publications shows different scales of application. These range from the global to the local. (1) The regional scale, i.e., the ASB or the five countries of Central Asia, sometimes supplemented by the Chinese Xinjiang or the Ili River Basin, and rarely northern Afghanistan; these studies cover about 1 to 2 million km². It can be estimated that only 10% of the selected articles have a regional scope, covering the entire study area (ASB). These articles generally consider climatic parameters (temperature, precipitation) or the hydrographic network as a whole. (2) The national level, represented by national inventories (100,000 to 1 million km²); this level is mainly used for risk assessment and is used in only 5% of the publications. (3) The provincial level, covering a region (e.g., Khorezm in Uzbekistan or Lebap province in Turkmenistan); this level usually covers 5000 to 100,000 km² and includes the Aral Sea and its relict water areas; it is very common and accounts for 65% of the studies; the Fergana Valley, shared by Uzbekistan and Kyrgyzstan, has been particularly studied. (4) The local level is that of isolated landslides or GLOFs, which account for about 20% of publications. In terms of countries, Uzbekistan and Kyrgyzstan are the most studied, followed by Tajikistan and, to a lesser extent, Kazakhstan and Turkmenistan. Afghanistan is virtually absent from the review.

The differences in the spatial scope of studies on the Aral Sea basin undoubtedly account for some of the challenges associated with comprehensive management of the evolving phenomena in the region. There often appears to be a lack of follow-up in the

measurement records. This issue first arose at the time of the dissolution of the Soviet Union, when many regional observatories were abandoned.

Studies on the physical environment, such as topography or fault network, are rare. Most of the studies focus on privileged sectors. Among these sectors, the Aral Sea and its residual lakes are often studied to estimate the surface area, volume and sometimes salinity of the water, but the associated field data are very rare, especially in the case of mineral surfaces. If the Amu Darya and its delta (Khorezm) are the subject of numerous publications, this is much less the case for the Syr Darya and the irrigated areas of Kyzylorda. This geographical specialisation is also found in the area of geological risks, which mainly affect the countries upstream of the ASB. The glaciers and landslides studied are mainly concentrated in a few areas. It should be noted that this point is accentuated by the geopolitical difficulties of the sector, which is characterised by a very complex layout of borders. For example, there are far fewer publications on the glaciers in the Tajik Pamir than in the Kyrgyz Tien Shan, even though the number and volume of ice in the Pamir is greater than in the Tien Shan. The UN Charter on Natural Hazards (<https://disasterscharter.org> (accessed on 1 June 2025)) shows that there are few examples covered in the ASB, with the three largest countries (Kazakhstan, Uzbekistan, Turkmenistan) completely missing. Tajikistan has been the subject of three relatively recent investigations (landslide and mudflow in May 2009 and April 2014 and earthquake in December 2015), while Kyrgyzstan has invoked the Charter three times but only in 2024, including twice in the west of the country (landslide in June 2024 and flood in July 2024) and once in the Lake Issyk Kul region (mudflow in August 2024). Two floods were recorded in northern Afghanistan (April 2014 and May 2024). It is worth noting that the main nationality of the first author is China (about 30%), followed by Germany (15%), USA and Uzbekistan (8% each), Russia (7%), France (6%) and Japan (4%).

It should be noted that only studies using a remote sensing approach were considered. Quantitatively, we found 934 Scopus documents containing the keyword ‘Aral Sea’, including 773 articles. However, only 93 documents and 75 articles, i.e., approximately 10%, also contained the keyword ‘remote sensing’. The potential of remote sensing in the case of the Aral Sea, one of the world’s major disasters, is clearly underexploited.

5.2. Some Remote-Sensing Data Limitations

Prior to the discussion of the primary results of the analysis of satellite data for the Aral Sea Basin, it is imperative to emphasise the limitations of the present approach. As illustrated in Table 2, cloud cover is one of the primary challenges associated with the application of remote sensing to land surfaces. The MODIS Terra chronicle has been analysed over the Aral Sea region for the last twelve months from WorldView snapshots in the Earth data from NASA (<https://wvs.earthdata.nasa.gov> (accessed on 24 July 2025)). In this case, the 7-2-1 colour composite is particularly effective at distinguishing between bare soils, vegetation, snow, ice, and clouds. From October to mid-May, cloudy or partly cloudy conditions predominate. From December to March, snow covers at least some of the surfaces. The best time to study the Aral Sea’s surfaces is from mid-June to September. Cloudy or partly cloudy conditions are experienced on 67.1% of days.

Another issue in remote sensing is achieving a balance between spatial and temporal resolution. The better the temporal resolution, the poorer the spatial resolution. MODIS, for example, has a spatial resolution of 250 m and a swath width of 2330 km and is acquired daily, whereas Landsat-9 OLI has a spatial resolution of 30 m and a swath width of 185 km and is acquired every 16 days. Therefore, it remains difficult to survey dynamic, short-lived phenomena such as dust storms using high-resolution data. The same applies to studying the effects of drying up after heavy rainfall. Synthetic aperture radar can help

solve the problem of cloud cover, but interpreting the data remains difficult in terms of soil moisture, slope, and surface roughness—the three parameters affecting SAR backscattering. The bibliometric analysis indicates that SAR studies are predominantly characterised by confidentiality, with a limited number of exceptions, including select applications in differential interferometry. These applications facilitate the detection of movement at the surface.

Table 2. Number of days per month with cloud-free, partly cloudy or cloudy conditions over the Aral Sea, as observed in MODIS Terra images.

Month/Year	Cloud-Free and Snow-Free Surface	Cloud-Free and Snow-Covered Surface	Partly Cloudy	Cloudy
August 2024	15	0	16	0
September 2024	17	0	11	2
October 2024	2	0	16	13
November 2024	7	0	12	11
December 2024	2	5	6	18
January 2025	0	9	4	18
February 2025	0	5	7	16
March 2025	5	3	14	9
April 2025	9	0	15	6
May 2025	14	0	13	4
June 2025	10	0	17	3
July 2025	17	0	12	2
Total	98	22	143	102
In percent	26.9	6.0	39.2	27.9

The remote sensing methods used in the studies are also worth mentioning. By far the most popular of these is the Normalised Difference Vegetation Index (NDVI). In Scopus, the term ‘NDVI’ appears in 56 documents, including 40 articles, when combined with the term ‘Aral’. Combining it with “Central Asia” yields 280 documents, including 228 articles. This simple method uses reflectance in the visible and near-infrared spectrum to classify vegetation types and vigour (e.g., according to the season). While the method is highly effective for studying crops, it is more challenging to apply to complex vegetation that has undergone significant changes in the last fifty years. The discrepancy between the studies of vegetation and the studies of the soil surface is evidently demonstrated by the fact that a mere six Scopus documents, including five articles, respond to the combination of Aral and Normalised Difference Water Index (NDWI) in the bibliometric analysis. This also highlights the scientific community’s relatively low interest in studies of mid- and short-wave infrared radiation, despite these being essential for studying predominantly mineral environments such as soils and rocks.

5.3. Remote Sensing Data Used

The previous summary is limited to remote sensing contributions in the Aral Sea Basin to earth science themes, i.e., information on the geological subsurface, soils, deep and surface water and their interaction with the atmosphere, including geological hazards (landslides, floods, dust). Land cover, crop type mapping or urbanism are excluded from this review. The main data used are MODIS data products, which generally correspond to dynamic data such as evapotranspiration, precipitation, temperature or NDVI. In this case, the scale is regional, with a typical spatial resolution of 500 m. The focus of the studies is on monitoring changes that lead to increased desertification. Most studies of medium resolution multispectral data are based on the use of NDVI. This very simple ratio has been heavily criticised because it takes little account of inter-annual variations in climate and vegetation characteristics, which are sometimes difficult to detect, particularly in sub-desert regions. In situ observations are rare or very specific, making it difficult to generalise. For the 1980s and 1990s, NOAA-AVHRR records are used, but their resolution of 1100 m is

difficult to compare with the 250 or 500 m resolution of MODIS. The models capture all the major changes in the landscape, but the respective roles of water abstraction, interannual variations in meteorology and the drying of the Aral Sea are rarely more than sketched. Data with better spatial resolution (about 30 m), such as the Landsat series, in particular Landsat-TM, ETM+ and OLI, are used for studies at a more local scale. Recently, there has been a renewed interest in data with better resolution, such as Sentinel-2, which has been available for almost ten years and offers a better spatial resolution (10 m) and a higher repeatability (5 days instead of 16 days for Landsat). The two satellites Landsat 8 and Landsat 9 now reduce the latter parameter because their orbits are 8 days out of phase. On the other hand, Spot 1–5, Terra-Aster and ALOS 1–2 data are not widely used in the literature, while Spot 6 or Spot 7 are used for some detailed studies. The first paper with a significant contribution of Google Earth Engine applied to the Aral Sea Basin dates back to 2019 [136]. The aim was to reconstruct long-term and high-frequency time series of the inundation areas of the world's major lakes, including the North Aral Sea and Lake Yssyk Kul. The results are consistent with those obtained using altimetry. The observed increase for Lake Yssyk Kul may be related to accelerated glacier melt due to regional warming. Google Maps provides very interesting data. However, it is unfortunate that in the literature the sensors used are too often not specified (Worldview-3, Landsat 8, Pleiades, Spot 6–7, etc.) (e.g., [129]). Each sensor has its own characteristics in terms of spatial, spectral and temporal resolution, which should be specified and exploited. GoogleEarth is limited to data in the visible range, which is not the most relevant for most natural objects, even if it is the only one capable of providing very high spatial resolution. Another case is the so-called Landsat images, because in some studies it is difficult to know exactly which sensors are being studied: MSS, TM, ETM+, OLI. . .

In addition to imaging sensors, many studies use digital elevation models. All types of models have been used, from DEMs based on aerial photography or the first Corona data, to the most accurate DEMs based on radar interferometry or very-high-resolution Pleiades Neo data. There is a lack of studies using radar images. This is reflected in the low number of remote sensing publications (31 out of 172, or 18%). Radar is rarely used as amplitude data, with the notable exception of a paper using ENVISAT-ASAR imagery to monitor the extent of flooding in the Aral Sea in 2010–2011 [137].

It should be stressed that satellite data can be used in raw form, based on the original imagery, but there are also many databases of data that have already been formatted. This is the case, for example, with the DAHITI altimetry data (University of Munich), which is a remarkable tool for regular monitoring of different sectors of the ASB. For the northern Aral Sea, for example, the highest level was recorded in April 1999 (43.63 m), followed by a decrease in August 2002 (40.02 m) and an increase until July 2006 (43.14 m), but since then there has been a clear downward trend (41.23 m in December 2024). Many papers rely on the use of websites, but some of these no longer exist.

This review has highlighted some of the limitations of remote sensing sensors. Old sensors have limited capabilities, as evidenced by NOAA-AVHRR sensors, which have only two broad bands in the visible (580–680 nm) and NIR (725–1000 nm). This results in a limited number of indices that can be calculated, and the band placement and width are not optimised for vegetation detection. Additionally, there are sometimes gaps in the dataset. For instance, data from NOAA afternoon satellites (NOAA-7, -9, -11 and -14) covers the period from July 1981 to September 2001, with a data gap in September–December 1994 due to satellite failure. An interesting methodological aspect regarding MODIS, which is generally considered to be the successor to the first generation of NOAA imagery, was raised by Jin et al. [20]. They highlighted the fact that MODIS-Aqua (launched in May 2002) performs better than MODIS-Terra (launched in December 1999) in retrieving aerosol

optical depth (AOD) over land, because MODIS-Terra is older and more degraded than MODIS-Aqua. However, the MODIS instrument on board Aqua suffered the loss of 75% of its Band 6 detectors shortly after launch [138]. MODIS band 6 observes radiances in the spectral range 1.628–1.652 μm (i.e., mid-infrared or MIR), which is a key bandwidth for common snow retrieval algorithms and more generally for ratios dealing with moisture. Other common problems include the failure of the Landsat-7 Scan Line Corrector (SLC) since May 2003 and the failure of the ASTER SWIR detectors since April 2008.

5.4. The Question of the Origin of the Aral Sea Disaster

A number of studies have attempted to link the Aral Sea disaster to climate change. Moreover, the combination of ‘Aral’ and ‘climate change’ yields no fewer than 413 Scopus documents, including 295 articles. Given that the disaster was predicted in the 19th century and occurred mainly between 1960 and 2000, it seems difficult to deny that water abstraction from major rivers was a major cause of the drying up. On the other hand, it is clear that the drying up of an inland sea of almost 70,000 km^2 has had a major impact on the local climate, changing rainfall and temperature regimes and generating dust storms since the 1970s. In particular, it has caused changes in the start and end dates of the ice season. Due to the remoteness of the Aral Sea, remote sensing has proven to be the best method to map the evolution of this vast body of water.

In order to identify further causes for the Aral disaster, it is necessary to consider the two primary causes—water diversion and climate change—in conjunction with one another. One such potential cause is regional tectonic activity, encompassing orogenic movement and associated seismicity. Geologists agree that the Syr Darya was the first tributary of the Aral Sea during the formation of the Aral tectonic basin. Meanwhile, the Amu Darya flowed into the Aral Depression as it was being shaped, as well as into the Caspian Sea via fossil channels such as the Ouzboy. This demonstrates the close relationship between the evolution of the Aral Sea and the Caspian Sea [3,12].

5.5. Comparison with Similar Case Studies Worldwide

While the Aral Sea is the most spectacular example of man-made disaster, unfortunately it is not unique (Table 3). There are many examples demonstrating the impact of water diversion. As early as 1913, for example, the Owens River in California was diverted into the Los Angeles Aqueduct, causing Owens Lake to dry up by the mid-1920s. This is probably the largest single source of very fine aerosol particles in the United States. Several studies have compared the situation of the Aral Sea with that of other inland seas and saline lakes. The main ones deal with Lake Urmia, the Dead Sea, Lake Chad, and the Caspian Sea.

Lake Urmia, situated within the borders of Iran, was formerly among the most voluminous hypersaline lakes in the Middle East. However, there has been a marked decline in the environmental integrity of the region over the past few decades, with only 10% of the initial surface area remaining intact. Studies have employed satellite remote sensing, hydrological modelling and machine learning to analyse changes and support sustainable water management [139]. The elevation of the Dead Sea has fallen by over 26 m since the 1930s. This relatively small fractional decline in volume can be explained by the Dead Sea’s great depth [140]. Unlike the other water bodies described, Lake Chad, located in the arid and semi-arid regions of Central Africa, is an endorheic freshwater lake. Its shrinking of the water surface area is comparable to that of the Aral Sea [141]. The Caspian Sea is affected in its northern part where the water depth is less than 10 m [142]. Duan et al., who have worked on a Landsat chronicle from 1985 to 2023, predict that the disappearance of the eastern basin of the South Aral Sea could be replicated in the northern part of the Caspian Sea by the year 2100 [143].

Comparisons with Lake Balkhash and the Great Salt Lake in Utah are less common. However, both of these are also shrinking due to the diversion and extraction of water from their tributaries, particularly from 1970 to 1987 in the case of Lake Balkhash [144] and from 1985 onwards in the case of the Great Salt Lake [145]. Other lakes, such as Qinghai Lake in China and Lake Issyk Kul in Kyrgyzstan, experience seasonal variations, but no major changes have been observed.

The Aral Sea disaster is one of a kind. However, the dramatic decline in Lake Chad and Lake Urmia is of a similar scale. In both cases, while human influence is fundamental due to the extraction of water from the main rivers feeding the depression, the amplification of climate change seems to be reinforcing the effects of drying.

Table 3. The Aral Sea. Similar case studies worldwide. The areas are given in km². Countries: AZ, Azerbaijan; CM, Cameroon; IL, Israel; IR, Iran; JO, Jordania; KZ, Kazakhstan; NE, Niger; NG, Nigeria; PS, Palestine; RU, Russian Federation; TD, Chad; TK, Turkmenistan; US, United States; UZ, Uzbekistan.

Lake/Sea	Maximum Area	Year of the Maximum Area	Current Area	Trend	Countries
Aral Sea	68,700	1960	5250	−92%	KZ, UZ
Caspian Sea	420,000	1960	371,000	−12%	AZ, IR, KZ, RU, TK
Lake Balkash	20,000	1970	16,600	−17%	KZ
Lake Chad	21,000	1960	1350	−94%	CM, NE, NG, TD
Great Salt Lake	8500	1985	2500	−71%	US
Lake Urmia	5250	1990	<500	−90%	IR
Dead Sea	1050	1930	605	−42%	IL, JO, PS

5.6. Paths of Research

The utilisation of in situ data constitutes an integral component of RS-based studies, owing to its pivotal role in the calibration and validation of results. It is estimated that approximately 20% of the studies conducted in the Aral Sea Basin incorporated in situ data obtained during field campaigns. In contrast, the remaining studies did not employ in situ or secondary data for validation purposes. There is an evident necessity for more pertinent field data. For instance, while declines in the flow of the Amu Darya and Syr Darya are now well documented, changes in the flow of their tributaries, particularly in the headwaters, have received less attention [146]. Moreover, it is imperative to consider a more extensive area surrounding the ASB, encompassing the Asian Water Tower. While knowledge of snow and glaciers is relatively advanced, knowledge of permafrost is more limited [147].

A number of studies have incorporated geospatial data from other external sources; however, the primary issue lies in the fact that statistics and data for the ASB are frequently outdated or of questionable quality. Meteorological data are imperative for the evaluation of irrigation water usage, particularly in the context of modelling evapotranspiration in relation to biomass and crop yields. Secondary data are a fundamental component of driver analysis, particularly in the context of spatial patterns of land degradation (e.g., soil salinisation) or cropping pattern analysis. RS-based methods have received less attention in this review, as the majority of the methods and algorithms employed in the studies were developed elsewhere. However, it should be noted that radar data should be more effectively used, particularly in the flat central region of the Aral Depression. Technically, the integration of SAR data into RS-based applications remains unexplored in the ASB. Radar, e.g., with Sentinel-1, can help to detect changes in surface and soil moisture, which could be positively combined with the observation of land cover changes. Archival images from the 1960s, either from US spy satellites (Corona programme) or from the former Soviet satellites (Resurs, Meteor, etc.), which are still poorly represented

in the literature, are also poorly used, although they could be of great interest for better understanding the first phase of the Aral Sea's drying in the 1960s and early 1970s. In general, there is a lack of applications of very-high-resolution data (<2 m). For instance, no studies were identified utilising the very-high-resolution (1 m) OrbView-3 data, despite these data being freely accessible for a pivotal period of the Aral Sea disaster (2003–2007) (<https://earthexplorer.usgs.gov/> (accessed on 24 July 2025)).

In light of the substantial increase in the number of publications in recent years, there is a growing imperative to undertake a greater number of bibliometric analyses. A search for the two terms 'bibliometry' and 'geosciences' yields only two Scopus documents [148,149], one of which directly concerns remote sensing and more precisely the GRACE satellites [149]. There are also a few bibliometric summaries in the field of agronomy (e.g., [150]), but they remain rare and are exceptionally related to remote sensing. Conversely, studies incorporating multi-source data (field, remote sensing, GIS) may inform future research [151]. The field of remote sensing is undergoing rapid evolution, with a wide variety of satellites and sensors now available. Nevertheless, as demonstrated by the case of ASB, the full potential of this technology has yet to be realised. The presentation of its potential could suggest further studies. It is evident that the Google Earth Engine is a sophisticated instrument of considerable potency. However, it is important to acknowledge that its full potential has not yet been realised, particularly in the domains of spectral resolution and large-scale studies. Nevertheless, there has been an increase in the number of scientific articles relating to geoscience and machine learning methods in recent years, indicating the potential for future research in the area of artificial intelligence. A recent study in the field of worldwide drought offers an illuminating perspective on this phenomenon [152], and the extension to the ASB is a conceivable outcome.

5.7. An Example of Future Challenge: The Qosh Tepa Canal

As a preliminary conclusion, it is worth noting that an emblematic case in the region is the Qosh Tepa Canal (QTC), launched in 2018 by the Taliban regime in Afghanistan (see also location in Figure 1). This canal is expected to help irrigate up to 550,000 hectares of land in the northwestern provinces of Balkh (Mazar-e Sharif), Jowzjan and Faryab (Andkhoy). Traditionally, Central Asian countries have managed shared water resources through agreed quotas, but this canal was designed to divert significant amounts of water from the Amu Darya (15–20% of the total flow) without consultation with neighbouring countries. The canal was built in two phases, the first being 108 km long and the second being 177 km long. The initial phase was initiated in 2022 and concluded in the autumn of 2023, as substantiated by the analysis of Sentinel-2 imagery (Figure 6A–C). As of July 2025, construction of the second phase was still ongoing in the area of Andkhoy.

As illustrated in Figure 6, a pivotal moment in the construction of the QTC is shown. In early November 2023, space-based monitoring revealed the presence of water leakage from a section of the right bank, located 75 km from the Amu Darya in the Balkh region. Sentinel-2 imagery shows that, within the first month of filling the canal with water, the hydraulic structure's walls appeared unable to withstand the pressure of the water flow. This resulted in a substantial volume of water escaping from the canal and spreading into the surrounding area. By November 2023 (Figure 6D), the canal had overflowed an area of 450 hectares, with this phenomenon continuing to increase to 1250 hectares in February 2024 (Figure 6E), 1700 hectares in February 2025 (Figure 6F), and 2400 hectares in April and July 2025 (Figure 6G,H). This event has caused a great deal of controversy between the different Central Asian countries.

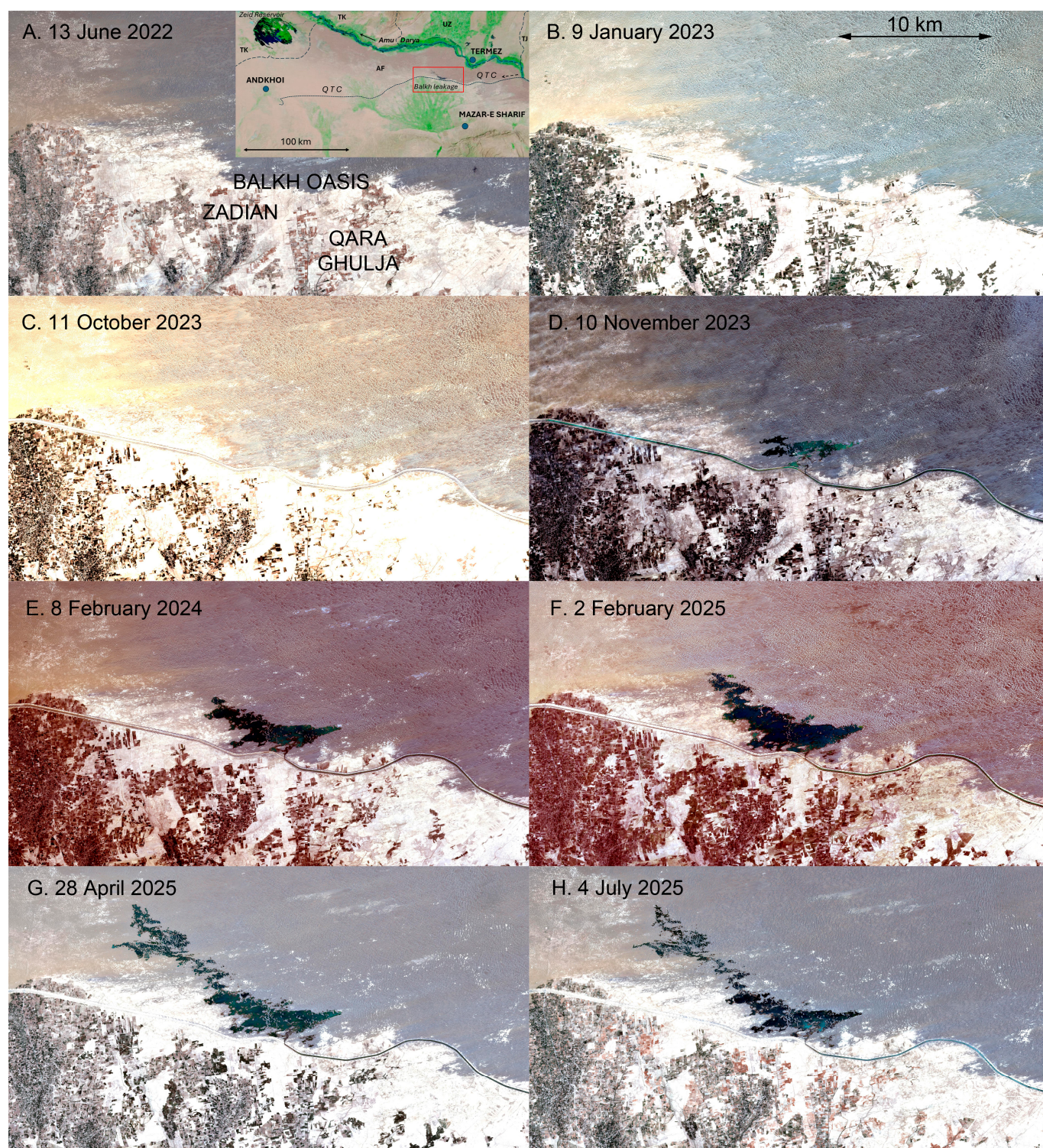


Figure 6. The Qosh Tepa Canal (QTC) in the Balkh region of northern Afghanistan. True colour composites: (A,B,G): Sentinel-2B; (C–E,H): Sentinel-2A; (F): Sentinel-2C. The inset in Figure 6A shows the location of the region: AF: Afghanistan; TJ: Tajikistan; TK: Turkmenistan; UZ: Uzbekistan. The background image is a MODIS false colour composite (11 July 2025). The leakage is characterised by a dark tone corresponding to the extent of the water in the sand dunes of the desert area.

6. Conclusions

The bibliometric analysis of the Scopus database discloses the primary contributions of remote sensing to thematic studies of the Aral Sea basin, concerning land, water and atmosphere, as outlined below:

- The survey of the Aral Sea's drying, particularly from the 1980s onwards, utilised a range of high- to mid-resolution satellites (Landsat TM, MODIS, NOAA-AVHRR, altimetric data, etc.) for estimating the surface and volume of water bodies.
- The analysis of the temperature evolution of the Aral Sea, and more generally all the ASB, is conducted using MODIS data.
- The estimation of the water stored in the glaciers of the Pamir and Tien Shan mountains, which are the primary sources for the ASB, is to be conducted using multisource data, and includes lake inventories.
- The analyses of landslides and GLOFs—two geological risks that are becoming more common as the climate changes—in the upstream area of the ASB by employing very high-resolution satellite data and digital elevation models (DEMs).
- The investigation of the impact of dust and aerosols, generated by the new mineral surface that has formed in the area that was previously occupied by the Aral Sea. This investigation will be primarily conducted using specialised sensors at a large scale, such as the NOAA AVHRR.

The following research directions have been identified as potentially fruitful for future study.

The monitoring of water management projects, with a particular focus on the Qosh Tepa Canal in Afghanistan, can be facilitated through the utilisation of remote sensing data. This undertaking is of significant concern, given the canal's profound implications for both water resources and geopolitics. The acquisition of high- to very-high-resolution imagery is imperative for the successful execution of this endeavour. The utilisation of sensors such as Sentinel-2 is essential for achieving the requisite spatial and spectral resolutions necessary for this project.

The mineral surfaces that were formed when the Aral Sea dried up could be studied in greater detail. This could be achieved by using multispectral data to analyse the minerals' composition or radar data to analyse the surfaces' composition, humidity and changes over time.

It is imperative to persist in the undertaking of comparative studies, with a particular focus on analogous cases, such as the Caspian Sea. The repercussions of its drying up have the potential to surpass those witnessed in the Aral Sea. In order to achieve this objective, it will be necessary to employ multisource remote sensing and exogenous data, including but not limited to hydrogeology and geochemistry.

As evidenced by the historical record, major seismic events have occurred in Almaty (1887), Ashgabat (1948), and Tashkent (1966), causing widespread destruction. The identification of seismic precursors along the primary active faults of Central Asia through the utilisation of remote sensing data constitutes a significant research challenge, irrespective of its indirect association with the Aral disaster.

As early as 1991, Orlov and Sokolova [153] asserted that 'without these data [aerial and space photography data], the Aral Sea conservation projects are unlikely to be implemented'. A total of 34 years later, a paradox remains between the potential contribution of remote sensing data and the actual use of all datasets available on the ASB. In addition, some areas remain difficult to access for a variety of reasons. Consequently, the employment of studies integrating long-term field observations with satellite imagery is imperative to achieve a more profound comprehension of the region's phenomena. Notwithstanding the inevitable

decline in the Aral Sea, the implementation of regional water policy remains paramount, irrespective of the number of future satellites in orbit.

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