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Review

Essentials of Endorheic Basins and Lakes: A Review in the Context of Current and Future Water Resource Management and Mitigation Activities in Central Asia

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Abstract: Endorheic basins (i.e., land-locked drainage networks) and their lakes can be highly sensitive to variations in climate and adverse anthropogenic activities, such as overexploitation of water resources. In this review paper, we provide a brief overview of one major endorheic basin on each continent, plus a number of endorheic basins in Central Asia (CA), a region where a large proportion of the land area is within this type of basin. We summarize the effects of (changing) climate drivers and land surface–atmosphere feedbacks on the water balance. For the CA region, we also discuss key anthropogenic activities, related water management approaches and their complex relationship with political and policy issues. In CA a substantial increase in irrigated agriculture coupled with negative climate change impacts have disrupted the fragile water balance for many endorheic basins and their lakes. Transboundary integrated land and water management approaches must be developed to facilitate adequate climate change adaptation and possible mitigation of the adverse anthropogenic influence on endorheic basins in CA. Suitable climate adaptation, mitigation and efficient natural resource management technologies and methods are available, and are developing fast. A number of these are discussed in the paper, but these technologies alone are not sufficient to address pressing water resource issues in CA. Food–water–energy nexus analyses demonstrate that transboundary endorheic basin management requires transformational changes with involvement of all key stakeholders. Regional programs, supported by local governments and international donors, which incorporate advanced adaptation technologies, water resource research and management capacity development, are essential for successful climate change adaptation efforts in CA. However, there is a need for an accelerated uptake of such programs, with an emphasis on unification of approaches, as the pressures resulting from climate change and aggravated by human mismanagement of natural water resources leave very little time for hesitation.

Keywords: endorheic; lake; Central Asia; Kazakhstan; water resources; climate change; evaporation; drylands; semi-arid

1. An Overview of the World's Main Endorheic Basins and Lakes

1.1. Background

Endorheic basins (i.e., closed or terminal basins) and lakes are land locked drainage networks where water does not drain into large water bodies [1], such as rivers connected to oceans (Figure 1). Considering natural water cycle processes only, endorheic basins and lakes experience water losses through water percolation underground and evapotranspiration [2]. The level of evapotranspiration (ET), which is the sum of evaporation (open water, soil, snow and ice sublimation and canopy interception loss) and plant transpiration, is generally higher than precipitation (P) for basins in arid and semi-arid areas, where most of these basins and lakes are located. In contrast to endorheic systems, exorheic systems are connected to the sea; typically, these basins have relatively abundant precipitation and balanced P–ET terms. The existence of Endorheism-Exorheism is controlled by climate on geological time scales [1].

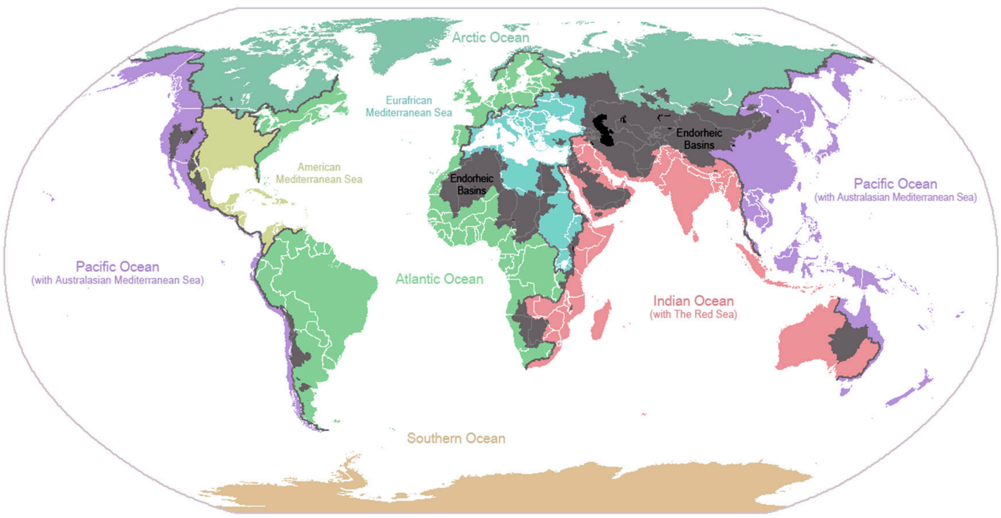

Figure 1. The endorheic basins and related lakes of the world. Dark grey indicates the basins, black are large endorheic lakes. (Source: Smith http://i.imgur.com/Z19wE.png).

Hostetler [3] estimated that terminal drainage basins (including arheic systems—those with no apparent drainage) constitute about 25% of world's continental area (excluding Antarctica and Greenland). These endorheic basins are located mostly in intracontinental arid regions (Figure 1), with basin outlets ending in lakes. Examples include some of the world's biggest lakes, such as the Caspian and Aral Seas in Central Asia (CA), Lake Chad in Africa, Lake Titicaca in South America, Lake Eyre in Australia, and the Great Salt Lake in North America (see Table 1) [3]. The majority of endorheic lakes are saline, as the evaporative concentration process leads to progressive salt accumulation over thousands of years [3]. Varis and Kummu [4] reported that about 6% of the world's population lives in endorheic river basins where discharge constitutes less than 2% of the total land–river discharge.

1.2. Main Aim of this Review Paper

In this review paper, we first provide a brief overview of one large and important endorheic basin on each continent (see also Table 1). Some smaller terminal basins and lakes that are of regional interest will also be highlighted. Next, we consider the CA region, the focus of our paper, its key endorheic basins and how these basins are affected by climate. Finally, we discuss key water resource research and management issues in the context of climate change and anthropogenic activities, together with solutions for adaptation and mitigation, in the CA region, while referring back to issues typical of endorheic basins worldwide.

1.3. Overview of Key Endorheic Basins and Lakes Worldwide

1.3.1. North America

It is estimated that around 10% of North America is occupied by endorheic and arheic basins [5]; with half of their total area being located in the Great Basin region [5]. The Great Salt Lake and Lake Utah (see Table 1) are the main remnants of the large Pleistocene Lake Bonneville that occupied a significant area of the modern State of Utah in the Great Basin [5,6]. Pyramid Lake and Walker Lake are the remains of another endorheic paleolake system Lake Lahontan which is also in the Great Basin [5].

Great Salt Lake, located in the western part of the continental USA on the territory of Utah, is one of the largest hypersaline endorheic lakes with a current drainage basin of around 55,000 km^2 [7]; its historical watershed area was more than 89,000 km^2 [8]. The lake is very shallow with a mean depth of only 5.5 m and a long-term average water level of 1280 mean sea level (m.s.l.), with the salinity ranging from 50 to 280 g/L [8]. The lake is divided into two parts: its North and South Arms are separated by a causeway that prevents the mixing of the lake water [8]. The water inflow is composed of river discharge (66%) and direct precipitation (31%), with evaporation as the only loss term in water balance [9]. The mean long-term lake precipitation and evaporation are estimated to be around 370 and 1000 mm a year, respectively. The lake's lowest water level, after almost 100 years of decline, was registered in 1963 (a maximum depth of 8 m), and the highest stand was recorded relatively recently in 1987 (a maximum depth of 14 m), followed by a steady decline [9]. The Great Salt Lake is a hypereutrophic ecosystem providing a vital habitat for millions of migratory birds in the western US [8]. It is expected to shrink further due to the impact of climate change; a reduction in precipitation into its basin is predicted, and a concurrent increase in evaporation is expected [8].

1.3.2. South America

Lake Titicaca basin is a high-altitude basin situated on the border of Peru and Bolivia in the central Andes on the South America Altiplano plateau [10,11]. As the largest lake (8100 km^2) in South America by area and volume, it is located at an elevation of 3800 m.s.l. with a maximum depth of 285 m [10]. The lake is divided into two separate basins; the much larger northern Lago Grande (Chucuito; mean depth 135 m) and the smaller southern portion, Lago Huinaimarca also known as Pequeno (mean depth 10 m). These basins are connected by the narrow Tiquina strait [10,11]. Lake Titicaca's outflow occurs via the Desaguadero river that terminates in Lake Poopo [11] which completely dried up in December 2015 [12]. Evaporation, which averages around 1500 mm/year, is the main loss term (90%) of the water balance of Lake Titicaca. The remaining 10% drains into Lake Poopo [13]. The local river discharge provides the major direct inflow [14]. The water cycle of Lake Titicaca basin is controlled by precipitation in upwind Amazonia [10]. The Mid-Holocene levels of Lake Titicaca are estimated to have been about 100 m below its modern levels, and this has been explained by drier conditions in the early to mid-Holocene in the basin, and Amazonia generally [10].

1.3.3. Africa

Lake Chad, located south of the Sahel zone, is the largest African endorheic basin, with its drainage area amounting to around 2,500,000 km^2. In the past, it was reported to be the sixth largest lake in the world [15]. Lake Chad is a relic of a giant freshwater paleolake, called Mega-Chad that existed during the Holocene period. The Chari River is reported to provide about 90% of water inflow into the lake [15]. The annual precipitation decreases from 1000 at the southern to 100 mm at the northern part of the lake [15]. It was reported in 2011 [15,16] that the area of Lake Chad had decreased by 90% during the previous 40 years, due to both persistent drought conditions and water withdrawal from the Chari River for irrigation. The decrease of water levels between 1973 and 1976 caused the lake to split into Big Lake Chad (northern) and Small Lake Chad (southern) [16].

Table 1. Endorheic basins and lakes (Excluding Eurasia and Central Asia, see Figure 1).

Continent	Major Endorheic Basins/Lakes	Lake Type/Origin	Watershed/Lake Area, (km²)	Elevation, m.s.l.	Mean, Max Depth (m)	Salinity, g/L	Inflow/Outflow	Paleolake	Lake Stage	Distinctive Features
North America	Great Salt Lake [1]	hypersaline, hypereutrophic	55,000/2470–5490	1280	5.5, 7.6–13.7	50–280	river discharge, precipitation/evaporation	Bonneville	decline	surface area is divided into several parts
	Utah Lake [2]	eutrophic	9960/380	1368	2.7, 4.2	0.9	river discharge, snowmelt/evaporation, rivers	Bonneville	stable	outflow is regulated
South America	Lake Titicaca [3]	mountain/tectonic	4900/8100	3800	10–135,285	1.2 [4]	river discharge/evaporation, rivers discharge	Mataro [4]	decline	high-altitude
Africa	Lake Chad [5]	shallow/tectonic	2,500,000/1350	278–286	1.5, 11	0.1–03 [6]	river discharge, precipitation/evaporation, groundwater	Mega-Chad	decline	surface area divided into several parts
Australia	Lake Eyre [6]	salt playa/tectonic	11,400,000	−9/−15	1.5, 6	10–50	river discharge, precipitation/evaporation	Lake Dieri	decline	surface area is divided into several parts

Sources of data: [1] Belovsky et al. [8], [2] Fuhriman et al. [17], [3] Cross et al. [10], [4] Dejoux [13], [5] Gao et al. [15], Isiorho and Matisof [18],[6] Habeck-Fardy and Nanson [19].

Despite the continuous desiccation of Lake Chad, the water has remained fresh. This can be explained by high groundwater seepage rates and the low salinity of the Chari River inflow [18]. Like many large terminal lakes, Lake Chad is a transboundary basin shared by Chad, Cameroon, Niger, Nigeria, Central African Republic and Sudan. It is managed by the Lake Chad Basin Commission [16].

1.3.4. Australia

Lake Eyre basin, one of the biggest endorheic basins in the world and the biggest terminal basin in Australia, covers almost one-sixth of Australia (1.14 million km^2) [19,20]. The low river flow, temporally variable precipitation (from 125 to 700 mm/year) and very high potential evaporation rates (PET), (up to 2500 mm/year) have led to desiccation and progressive salt accumulation in the basin. Lake Eyre, the lowest point on the Australian continent, represents a large salt playa consisting of two basins, Lake Eyre North (area of 8030 km^2) and Lake Eyre South (area of 1300 km^2), which are connected by a narrow channel [19]. It has been suggested [19] that Lake Eyre is a remnant of a much larger Pleistocene lake, Lake Dieri, that possibly drained to the ocean through the Spenser Gulf. Harbeck-Fardy and Nanson's recent thorough review [19] provides a comprehensive environmental history of the Lake Eyre Basin.

1.3.5. Central Asia

Eurasia's endorheic area constitutes about half of the world's territory with internal drainage (Figure 1). Moreover, it has the largest number of terminal lakes [3]. The CA endorheic region within the Eurasian continent includes territories of Afghanistan, Kazakhstan, Kyrgyzstan, Pakistan, Tajikistan, Turkmenistan, Uzbekistan, some areas of Southern Siberia, northwest China, and northeast Iran (Figures 1 and 2). While reporting on Central Asian river basins, many authors include the basins around Tien Shan and Pamir mountain systems [21,22] such as the Aral and Balkhash-Alakol Lake basins and the Tarim River basin. Others broaden the scope even further and include the surrounding territories in all directions [23].

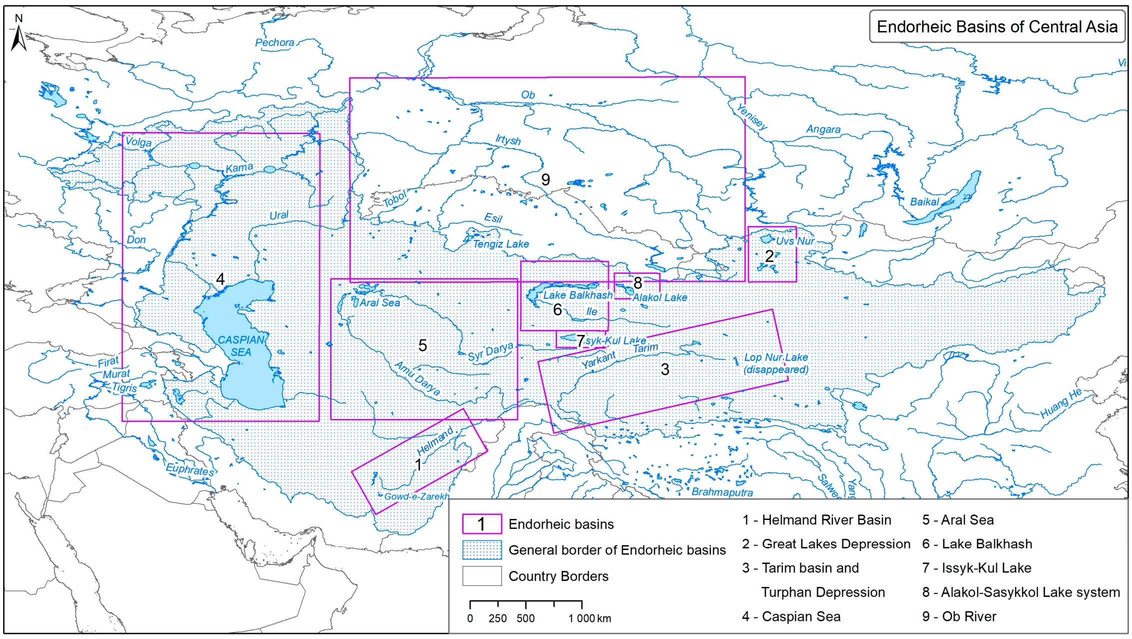

Figure 2. The endorheic basins and lakes of Central Asia.

Among the Central Asian River basins, only the Ob river and its tributaries drain into the Arctic Ocean, whereas all other areas have internal drainage [22]. Even within the Ob River basin, there are isolated basins with internal drainage [24]. This high degree of climate continentality and endorheism make these Central Asian basins particularly susceptible to climate change [21,23].

Precipitation in the CA region is highly variable: the highest precipitation rates (>2400 mm/year) are found in the mountainous areas, whereas on the plains of Kazakhstan the mean annual precipitation is only around 250 mm [25]. Desert regions receive annual rainfalls of 100 mm or less [25]. The inland Eurasian atmospheric moisture supply is dominated by westerlies [23,26–28]. Numaguti, in his seminal study [26], demonstrated that more than 80% of the precipitation in continental Eurasia comes from evaporation recycling, with a relatively small direct moisture contribution from oceans. Thus, most of the summer rainfall in CA is derived from evaporated winter precipitation, particularly in the upwind territories of western Eurasia [26]. Atmospheric moisture in the CA region is mostly derived from the North Atlantic (50–60%) in both summer and winter. Other major sources of water in winter (~30%) originate in the Mediterranean Sea [26]. Evaporation dominates the water balance of the endorheic basins of CA, with PET rates reaching values as high as 3800 mm/year in the Chinese hyper-arid Turpan basin [25,29]. The majority of CA basins can be classified as having semi-arid or arid climates, with meltwater from the cryosphere providing a substantial inflow of water for the dryland rivers [21,30].

The Sistan/Helmand drainage basin (Figure 1, sector 1) is a depression which occupies large sections of the southwest-south of Afghanistan, western parts of Pakistan and a small area in southeast Iran. It receives water from the Helmand River that originates in the Hindu Kush Mountains [31,32]. The basin is sometimes divided into three parts: an upper delta of the Helmand River; a lower delta, which is comprised of wetlands with the lowest part ending in a hypersaline lake named Gowd-e-Zareh (Gaud-i Zirreh) [31]; and finally a number of small endorheic sub-basins such as the Pishin Lora basin, which ends in the hypersaline terminal Hamun-Lora Lake on the border of Afghanistan and Pakistan [33]. The Sistan basin has very low precipitation, and its water supply depends heavily on the discharge of the Helmand River fed by snowmelt from glaciers in southern Hindu Kush [31]. The lower Sistan is one of the driest regions in the world with average annual precipitation rates of only 50 mm/year and potential evapotranspiration as high as 3000 mm/year [31]. The terminal Lake Gowd-e-Zareh is ephemeral and evaporates completely during prolonged dry periods [31].

The Great Lakes Depression in western Mongolia (also called the Valley of Great Lakes) is a large endorheic basin surrounded by the Altai Mountains in the west, Khungai Mountains in the east, Tannu-Ola Mountains in the north and the Gobi Desert to the south (Figure 1, sector 2) [34,35]. The basin area is more than 100,000 km^2 in size. The Khan Khookhii Ridge divides it into two basins: Uvs Nuur (north) and Khyargas Nuur (south) [36]. The modern lakes are remnants of much bigger paleolakes that existed during the Early Quaternary period [35,36]. The Great Lakes Depression is a cold arid zone with the mean annual precipitation ranging from less than 100 mm/year in the lowlands to 300–400 mm/year in the Khungai Mountains [34].

Another example of an endorheic basin in CA is Tarim River basin (Figure 2, sector 3) in Xinjiang Uighur Autonomous Region, China [37]. It is a river basin in the Takla Makan desert, which receives water from several mountain regions: Kunlun, Karakorum, Pamir and Tien Shan. Tarim River basin is the largest endorheic basin in China with an area of 1,100,000 km^2 [37,38]. The basin is located within the Tarim depression in the Takla Makan desert and it historically drained into Lake Lop Nur, but currently it terminates in Taitema Lake [37]. Tarim River has three main tributaries: Aksu, Yarkand and Hotan with the main runoff generated by the Aksu River [38]. Tarim basin is a desert area with precipitation ranging from 50 to 100 mm a year, combined with high potential evaporation, up to 3000 mm a year [38]. Nearby, there is another closed basin—Turpan basin—which is the lowest depression in China with very low precipitation rates of only 7–25 mm/year, whereas the annual PET can reach values larger than 3800 mm [29].

The Caspian Sea is the largest inland water body in the world with a vast drainage basin of about 3 million km^2 , covering almost 2% of the world's territory [39,40]. The Caspian Sea (Figure 2, sector 4) is situated on a virtual border between Europe and Asia, surrounded by the territories of Russia, Azerbaijan, Iran and Turkmenistan [40]. More than 80% of water inflow to the Caspian Sea is provided by the Volga River, with the Kura and Ural Rivers also contributing [40]. The surface area of the Caspian Sea is around 400,000 km^2 and its volume is estimated to make up about 40% of all inland waters [40]. Arpe et al. [39] identified a direct connection between Caspian Sea level variations and the phase and magnitude of El-Nino Southern Oscillation (ENSO). Caspian Sea levels remained stable (<~0.5 m variations) for almost a century (1840–1940) [41]. Between 1940 and 1977, there was a prolonged decline (~1.3 m). A rapid increase of 2.5 m occurred between 1978 and 1995, whereas a decrease of ~1.5 m was recorded between 1996 and 2015 [41]. While the earlier large fluctuations (1940–1995) of Caspian Sea levels are attributed to Volga river discharge fluctuations, the latest decline is attributed to higher evaporation rates that are anticipated to continue in coming decades as a result of a warming climate [41].

The most referenced endorheic lake, which is intensively threatened by anthropogenic disturbances, is Lake Aral, also known as the Aral Sea. Its basin (Figure 2, sector 5) occupies about 2 million km^2, and was previously considered one of the four largest lakes in the world [42]. In 1975, it had a surface area of 59,000 km^2 [42,43]. The Aral Sea was fed by headwaters originating in the Pamir and Tian Shan Mountains through inflow of the Syr Darya and Amu Darya Rivers [3]. Importantly, the glaciers' meltwater helps meet irrigation needs in the Aral basin as most of the summer precipitation is lost through evaporation [30]. From the Roman era until the 17th century the Aral Sea was connected to the Caspian Sea by the Uzboi channel [3,44]. The area of the lake shrank by 75% from its original size from 1975 to 2007 [45]. Panichkin et al. [46] assessed the subsurface drainage to the Aral Sea and concluded that although the reductions of the Syr Darya and Amu Darya Rivers flows are the main contributors to the desiccation of the Aral Sea, intensive groundwater abstractions also contributed to the disaster.

The tragic account of the disappearance of the Aral Sea, which was caused by the mismanagement of water resources in its basin, is well documented [3,42,43,47]. We should note an ecological stabilization of the Small Aral Sea (the northern part), which is separated from the Large Aral Sea by a dike, installed in 2003 by the Kazakhstani government [47–49]. The restoration of the Small Aral Sea has led to a rise in water levels and a lower salinity, which has permitted the return of fisheries [47].

Lake Balkhash is a large terminal lake located in southeastern Kazakhstan (Figure 2, sector 6). It belongs to a basin shared with China and Kyrgyzstan, with a watershed area of more than 400,000 km^2 [50]. The inflow to the lake stems from runoff and streamflow generated in the Tien Shan and Dzungar Alatau Mountains with the Ili River supplying about 80% of all water, while the remaining water comes from the Karatal, Aksu, Lepcy, and Ayaguz Rivers [25,50,51]. The Ili River flow to Balkhash Lake is regulated by the Kapchagay reservoir, which was constructed around 1970, both to generate electricity and to supply water for irrigation in the region [52]. The average depth of Lake Balkhash is about 9 m with maximum depths reaching 26.5 m [50]. The eastern part of the lake is saline 2.5–6 (g/L), whereas the western part is fresh due to the inflow from the Ili River [50]. Bai et al. [43] reported that the surface area of Lake Balkhash was 16,750 km^2 in 2007; its area had decreased by about 3% since 1975. On the contrary, Propastin [50], using satellite altimetry, found an increase in lake levels of more than 1.5 m between 1993 and 2005, indicating that there is uncertainty with regards to the lake's size. The main river in the Balkhash basin is the Ili River that originates in the Chinese Tien Shan, and China has progressively increased the water withdrawals from this river for irrigation [25,51]. Thus far, Kazakhstan and China have been unable to reach an agreement regarding the regulation of the Ili River flow [25].

Issyk-Kul Lake catchment is a mountain basin (altitude 1607 m.s.l.) in northern Tian Shan (Figure 2, sector 7), a part of eastern Kyrgyzstan, with an area of about 40,000 km^2 [53,54]. Issyk-Kul Lake has a tectonic origin and is the second largest mountain lake in the world, superseded only by Lake Titicaca, with a maximum depth of 668 m [54]. Historically, when lake levels were higher, the basin had a surface outlet through Chu River [53,54]. Long-term annual precipitation is around 900 mm [54].

The lake is fed by run-off from numerous local headwater streams and rivers and the main tributaries are the Tiup and Djyrgalan Rivers [54]. The annual water balance of the lake, based on a long-term study [54], is derived from the following inputs: direct precipitation, surface runoff and recharge by groundwater, approximately equally contributing around 300 mm/year each. The outputs comprise lake evaporation of about 800 mm and irrigation withdrawals of less than 100 mm/year.

In the vast Ob River basin in Northern CA (Figure 2, sector 9), there are various isolated watersheds with internal drainage represented by lakes of various sizes. The largest of these is Lake Tengiz (part of the Nura River basin) in north Kazakhstan [55], but there are also a considerable number of small shallow steppe lakes [56] as well as unique ecosystems such as Burabay Lakes located in the mountain ranges along the Kazakh Uplands [24]. The Tengiz-Korgaldzhin Lake system is a large shallow lake and wetland area in northern Kazakhstan, a habitat and migration path for hundreds of waterfowl bird species, including pink flamingoes [55,57]. Lake Tengiz, at the end of the Nura River, is the largest lake in Northern Kazakhstan with an area of 1590 km^2 [21]. Klein et al. [55] reported the decrease of surface water in the Tengiz-Korgaldzhin lakes from 1992–1993 to 2012. Small depressions or "pans" (filled with water or dry, depending on rainfall input) 1–2 km^2 across are widespread in northern CA (covering the plains of west Siberia and northern Kazakhstan). They are formed around relic stream systems or they represent the remnants of larger desiccated lakes [56]. These pans are found to be very similar to the salty playas of the USA High Plains formed in comparable semi-arid climatic conditions and modified by high wind erosion [56].

Bai et al. [43,45] used Landsat images to monitor the area change of nine major inland lakes in CA for the 30-year period from 1975 to 2007 and reported a persistent shrinkage in main endorheic lakes such as Aral, Balkhash, and Ebinur. The decreasing trend seemed to be more significant in the western part of CA on the plains, with a reduced overall decline on the glaciated alpine catchments in the eastern part [43]. Bai et al. [45] concluded that although both anthropogenic activities and climate change led to the lake surface area decrease in CA, the terminal lakes located on the plain areas (Aral Sea, Balkhash and Alakol) downstream of the Pamir, Tien Shan and Dzungar Mountains are more affected by human activities. In contrast, the mountain lakes (Issyk-Kul) and lakes with outlets (Zaysan and Sasykkol) located on higher altitude are more regulated by climate variability.

2. Key Factors Affecting Water Resources in CA Endorheic Basins

The rapid development of satellite based remote sensing technologies have led to the development of global monitoring tools facilitating the assessment of surface water resources worldwide such as the Deltares Aqua Monitor [49] and the Global Surface Water Explorer [58]. These tools utilize more than 30 years of Landsat satellite imagery archives and provide access to data illustrating the extent of change in surface water cover worldwide. Pekel et al. [58] concluded that although the global surface water extent increased during the past 30 years, more than a 70% decrease of terrestrial surface waters occurred on the territories of five countries: Kazakhstan, Uzbekistan, Iran, Afghanistan and Iraq. The majority of these water losses are attributed to both water resources mismanagement and droughts, caused by a number of climatic phenomena.

2.1. Anthropogenic Activities and its Relation to Water Resources Mismanagement in CA

Agricultural productivity in semi-arid and arid areas of CA is relatively low. Nevertheless, agriculture traditionally was and still is the backbone of the economy of all countries in CA, though its contribution to GDP has been decreasing in recent years [21,59]. Agricultural water use through irrigation is a major consumer of water in CA, amounting to 90% of the overall water consumption [21,25]. Crop farming in the Aral Sea basin countries is primarily cotton production, but irrigated grains such as wheat are extensively cultivated in Uzbekistan and Kazakhstan. Apart from extensive crop cultivation, animal husbandry is also an important agricultural sector [21]. Bovine milk and meat are among the top agricultural products in CA, particularly in historically nomadic countries, such as Kazakhstan and Kyrgyzstan [21]. Rainfed crop agriculture is found in the northern semi-arid part of CA (Kazakhstan) which consists mostly of grains (e.g., wheat, rye and barley); crop farming in the southern dry part of CA can only be sustained through irrigation [21]. Irrigation crop production generates most of the output [21]. Poor irrigation practices have essentially led to the destruction of the once second largest endorheic lake of the world—the Aral Sea. Unlike in many other parts of the world, the endorheic basins (Figures 1 and 2), and surface water sources (rivers, lakes and reservoirs) are the primary sources for every type of water need in CA. This results in large direct anthropogenic impacts on the availability of surface water resources. A well-known example in this context is the fate of the Aral Sea and related transboundary water sharing issues of its basin [25,47,60].

2.2. Effects of the Global Circulation, Climate Change and Local Land-Surface-Atmosphere Feedbacks

Due to the sensitivity of lakes, especially closed systems, to climate change, there has been ongoing research on lakes as sentinels or indicators of climate change [9,61–64]. Paleoarchives concealed in lake sediments have been used for decades to assess the state of past climates worldwide [65] and in Eurasia [66–69]. There have been multiple efforts to create world lakes databases [61,62]. Apart from the monitoring of lake volumes and area changes, [62] other metrics, such as lake summer surface water temperature (July–September in Northern Hemisphere, January–March in Southern) are also used as a climate indicator [70,71].

Using a regional climate model study and verified by satellite observations, Elguindi et al. [72] identified that dust and aerosols from Central Asian deserts reduced shortwave radiation in the Caspian see area which led to a reduction in open water evaporation of 8%. Syed et al. [73] utilized the ReGCM3 regional climate model, driven by ERA40 reanalysis meteorological data, to analyze the influence of North Atlantic Oscillation (NAO) and ENSO on Central-Southwest Asia and established a connection between a positive NAO phase combined with a warm ENSO phase and an increase in winter precipitation in Northern Pakistan, Afghanistan and Tajikistan. These studies demonstrate that endorheic basins in CA are influenced by large climatic oscillations via teleconnections. However, their interactions with and feedback to global climate systems are still poorly understood.

With regards to climate change, the CA region has a rising air temperature trend with the biggest increase in the winter in the northern and mountain areas (this increase is characteristic of what is occurring over most of the Northern Hemisphere) and stronger summer warming in the southern part [22,23,74]. In a recent review of climate studies on CA's headwater catchments, Unger-Shayesteh et al. [74] reported a range of -0.1 to $+0.6$ °C trend per decade of annual air temperature change. Higher air temperatures will increase saturation vapor pressure amplifying atmospheric demand for water and thus potential evaporation, which in turn will affect the levels of endorheic lakes. Recent data show a persistent increased trend in lake surface water temperatures globally (which in theory would increase lake surface saturated water vapor pressure, and hence increase evaporation) and a lengthening of the open water period for seasonally ice-covered lakes [70,71]. Global stilling and global dimming reported in many parts of the world during past decades have led to observed decreases in pan evaporation, than can be used as a proxy for lake evaporation [75–77]. Although these two effects may compensate the increase in air temperatures, the latest publications indicate an increase in both terrestrial ET and pan evaporation [78,79]. Declines in surface water extent of endorheic lakes in CA, together with such climate indicators as rising surface water temperatures and air temperatures, signal an increase in open water (lake) evaporation in CA.

The majority of studies on precipitation changes in CA, using both modeling and observations, report no significant trends [22–24,74,80]. The recent framework developed by Roderick et al. [81] for local climate change impact on the hydrological cycle, based on an analysis of Budyko'a curve applied to the surface energy balance, suggests that a greater warming in summer in south CA indicates a decrease in actual terrestrial evaporation, despite increased PET, due to a limited moisture supply. Although changes in precipitation due to climate change are predicted to be small [21–23], variability and changes in climate affect other terrestrial water inputs into endorheic systems; the latest research by Shahgedanova et al. [80] reported that the peak of run-off generation from increased glaciers melt in northern Tien Shan has already been reached, and a decline in streamflow is expected to be observed after 2020.

Huang et al. [82] showed that the current 2 °C surface air temperature target to limit global warming which was set by the Paris Agreement, is not enough to prevent catastrophic effects in water-limited regions (P/PET < 0.65). Those areas would benefit from adopting the lower limit of 1.5 °C. Higher warming in the drylands is forecasted to continue in the future [82].

Much of the hydrological, water resource and climate research in CA is concentrated on the understanding of precipitation, rainfall–runoff relationships, and tendencies of surface air temperature, whereas terrestrial evaporation mechanisms and trends have received less attention. There is an urgent need to improve our understanding of the role of terrestrial evaporation in CA because it dominates the hydrological cycle. The vital link between soil moisture, meteorological (precipitation, PET), and agricultural (primary productivity) activities and drought conditions also seem to be overlooked by ongoing research efforts in CA. The European and International Earth observation missions such as Soil Moisture and Ocean Salinity (SMOS) [83] and Soil Moisture Active Passive (SMAP) [84] which aimed to provide soil moisture data globally, have not been utilized in research nor for forecasting in CA.

The importance of understanding evaporative losses can be illustrated by the recent disappearance of high Arctic ponds in Canada due to increased ET/P ratios [85]. These shallow ponds had been permanent water bodies in the Artic for millennia [63,85]. Moreover, a recent study of Miralles et al. [27] corroborated the leading role of precipitation having a continental origin by evaporation recycling in CA. Reduced terrestrial evapotranspiration may cause a reduction in atmospheric relative humidity, although the increased lake evaporation may make up for this. CA is a hotspot of climate change [23,86], but the influence of its vast domain on local climate variability and climate change remains poorly studied due to limited regional research capacity and data sharing issues.

Apart from direct water withdrawals for irrigation and drinking water, land use and/or surface cover changes and management strategies can influence the local and regional precipitation [27] and water drainage regimes [24] via land and atmosphere feedback mechanisms [81].

In the context of surface cover changes and related feedbacks to the atmosphere, a "*global greening*", induced by elevated CO_2 (fertilization) and causing increased plants water-use efficiency, is widely documented to cause increase in primary productivity of drylands worldwide [87–89]. Due to the CO_2 fertilization, semi-arid areas in particular will be playing a more significant role in global carbon sequestration, especially in wet years [89–91]. Lioubimtseva [92] reported an observed "*greening*" trend in the drylands in CA based on remote sensing studies between 1982 and 1994, followed by a decline from 1996 to 2001. These variable trends were attributed mainly to land use changes and partly to vegetation response to changing temperature, precipitation and CO_2 levels. The latest research on Net Primary Productivity (NPP) trends in CA has shown that it has declined by around 10% since the 1980s [93]. Zhang et al. [93] attribute most of this decline to a continuous increase in dryness in the region, thus off-setting the CO_2 fertilization effect and causing a reduction in leaf area. They argue that NPP for most of the CA territory is controlled predominately by precipitation, and not by temperature or CO_2 changes. [93]. Zhang et al. [93] reported that the largest decline in NPP in CA during the past thirty years took place in the areas of evergreen needle-leaf and broadleaf forests, with crop areas less affected by droughts.

These findings underline the importance of land–atmosphere feedbacks driven by land use changes and climate variability, as well as a significant need for reliable environmental monitoring to deepen our understanding of the hydrological cycle, in the context of evidence based decision-making on water resources in CA.

3. The Human Dimension

One of the largest problems in relation to management of water resources in CA's endorheic basins is the lack of proper integrated surface water, including evaporation, and groundwater studies [94,95]. In addition, both the agriculture sector and governmental agencies tasked with monitoring of water resources rely heavily on rudimentary traditional technologies and methodologies. Progress with regards to improved water resource management, to ensure long-term sustainability of the basins and lakes, will be hampered without the implementation of suitable modern technologies such as precision agriculture, and modern automated in-situ sensors or remote sensing technologies and modeling tools for monitoring activities. Ideally, various advanced approaches, including those that explicitly and carefully consider the water–energy–food nexus, Managed Aquifer Recharge (MAR), evaporation shields such as floating solar covers, and local landuse and landcover management practices, are implemented and expanded in CA.

3.1. Water–Energy–Food Security Nexus Issues in CA

A new concept—the water–energy–food nexus, often used in combination with an analysis on the challenges posed by climate change—has emerged in the last decade. The water, energy and food security nexus indicates that water security, energy security and food security are inextricably linked and that actions in any one area generally impact one or both of the other sectors. The nexus philosophy is strongly related to the more established approach of Integrated water resources management (IWRM) that has been defined by the Global Water Partnership (GWP) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" [96].

Only while taking into account this key nexus, and while practicing IWRM where feasible, are we able to seek holistic solutions for complex problems relating to the increasing pressure on our planet's resources [97,98]. According to recent data, the population of CA is expected to increase by almost 40% by the end of the 21st century [99]. Population growth inevitably leads to increases of food, water and energy requirements. Hence, policy makers in CA should develop strategies that take full account of the water–energy–food security nexus, but this will be particularly challenging in transboundary river basins [99].

The role of water in the water–energy–food nexus is crucial as it is acting as an enabler, whereas in areas dominated by water scarcity it limits food and energy production [100]. This is precisely the case for CA, as water has always been a limited but vital resource and a source of tension and conflict in the area [101]. Probably nowhere else on the planet has the strong link between agriculture and water requirements led to a tragedy of such great proportions as in the Aral Sea [102]. However, in a recent advanced review devoted to water and food stocks in the 21st century, Marsily and Abarca-del-Rio [103] argue that the availability of arable land, not water resources, will limit food production. They predicted that Asia will not be able to feed its own population by 2050.

The basins of Amu Darya and Syr Darya are considered by researchers and geopolitical analysts to be at very high risk of potential hydropolitical tension. They are also conflict-prone and attempts to solve the water sharing problems in the past have failed [104,105]. The situation surrounding the Syr Darya River underlines the fragility of the water–energy–food nexus, and the high interdependence of the three sections, in CA. Uzbekistan's territory in the Fergana Valley is almost entirely dependent on the Syr Darya's water entering the country from Kyrgyzstan where the energy-producing hydraulic infrastructure controls its flow to a large extent. Climate change-induced shifts in the Syr Darya discharge rates may contribute to a further deterioration of the strained relationship between Kyrgyzstan and Uzbekistan. Kazakhstan is also concerned about the river's water quality and availability of irrigation water, since a large fraction of the population in Kazakhstan uses the river water for household purposes. The quality of the water is compromised by high amounts of total dissolved solids, heavy metals, pesticides and herbicides coming from irrigation drainage return flows from Uzbekistan [104,106]. However, only 6% of Kazakhstan's GDP is generated in the agricultural sector as compared to 22% in Uzbekistan. In addition, unlike Uzbekistan, Kazakhstan faces no population pressure in the rural regions. Nevertheless, Kazakhstan is creating a water storage system within its territory to reduce its dependency on the reservoir operations located upstream in Kyrgyzstan and Tajikistan [107,108]. Uzbekistan has followed the same strategy but it is much more vulnerable to potential water shortages than Kazakhstan. The most serious disputes in the Syr Darya basin remain between Kyrgyzstan and Uzbekistan [104]. Bernauer and Siegfried [104] argue that because of this a serious international conflict could occur in this region.

The Amu Darya River Basin offers another food–water–energy nexus dilemma [109]: the upstream countries (Kyrgyzstan and Tajikistan) have abundant water resources and they rely mainly on hydropower for energy, while the downstream countries (Uzbekistan and Turkmenistan) are major producers of fossil fuel energy and agricultural crops. The planned Rogun dam on the Vakhsh River, a tributary of the Amu Darya River, is a water resources conflict hot spot in the region. The dam will provide upstream Tajikistan with hydropower, while the downstream countries fear that it could negatively impact their irrigated agriculture [99,110]. In addition, tensions between Uzbekistan and Turkmenistan are not uncommon as the water storage infrastructure providing water to Uzbekistan is located in Turkmenistan [100,111]. These countries have considered switching from cotton to wheat production for food self-sufficiency, which could lead to water savings if the irrigation systems were efficient [111]. Wegerich [111] demonstrated that, given the current situation, the riparian states of Turkmenistan, Tajikistan, and Uzbekistan will follow the strategy of resource capture, without consideration of the water requirements of neighboring countries.

3.2. Solutions for Improved Water Conservation and Management in CA

3.2.1. Managed Aquifer Recharge

Open reservoirs, including endorheic lakes, have substantial water losses through evaporation, which is undesirable from a water conservation point of view and could also lead to progressive salinization. One water saving strategy is to keep water in aquifers and to further recharge the aquifers [103]. Technologies based on Managed Aquifer Recharge (MAR) [112] could be applied in the CA region. However, implementation of such projects is hindered by the lack of groundwater data availability in the public domain, and limited local capacity in funding and engineering skills. This is illustrated by the absence of CA on the International Groundwater Resources Assessment Center (IGRAC) MAR portal for example [113]. One of the main reasons for the absence of data is related to the restriction by some CA government policies on the sharing of such data, and the related challenges around development of groundwater water research projects.

Recently, Sagin et al. [114] made a conceptual assessment of the ground water resources in Kazakhstan based on a water budget approach with consideration of the underground lateral flow, hydrogeoecological regions, and river basins. The flow of water in all of the rivers of Kazakhstan is estimated at 102.3 km^3/year. With a potential increase of the underground water usage up to 15.5 km^3/year, the surface water volume use could be decreased to 5 km^3/year. Water reinjection into the aquifers, similar to MAR, is recommended in combination with the expansion of water recycling and more efficient water use strategies.

3.2.2. Evaporation-Reducing Covers, including Floating Solar Covers

Another water saving strategy is to decrease evaporation by covering the water bodies, using floating objects such as “shade balls” [115], shade and sheltering structures, and chemical evaporation retardants [116]. The choice and application of these methods and technologies must be carefully evaluated in the light of the local conditions and possible environmental impacts. To our knowledge none of these specific technologies have been applied in the CA region yet.

An innovative solution among the cover strategies, that addresses two sections of the nexus, is a technology involving floating solar covers [117]. The floating photovoltaic system is a new concept in energy technology that can help meet current energy needs and allow for successful adaptations to the changes in climate. The use of floating solar technologies is expanding in many countries, including Australia, Brazil, China, Germany, Japan, the UK, and the USA [117,118].

The system integrates existing land-based photovoltaic (PV) technology with a newly developed floating PV technology. The energy generation efficiency of the floating PV systems is greater (11%) than that of overland PV systems, because of the reduced module temperature [119]. Moreover, it decreases the evaporation rate. During CA summers, water sources face the threat of desiccation that can lead to irrigation problems. With floating solar panels, around 70% of the evaporation could be prevented, which in turn would help in retaining a sufficient amount of water for irrigation in the canals and small river bodies [120]. In addition, because of the abundance of sunlight, most of CA has a significant capacity to collect the solar radiation [121]. Despite this, the uptake rate of renewables for energy provision in CA is low [122]. Nevertheless, the example of China as an emerging world leader in the application and development of renewables is certainly encouraging.

3.2.3. Climate Change Adaptation and Mitigation Activities

Some climate change adaptation projects are already under way in CA: in 2015 the United Nations Development Programme (UNDP) and Global Environmental Facility (GEF) partnered with Kazakhstan and Uzbekistan to plant salt and drought resistant saxaul trees around the Aral Sea [123,124]. Various projects of different scales have been piloted in the drought stricken areas of south Kazakhstan. Examples include local ecotourism initiatives, small-scale renewable energy generation facilities, drip-irrigated and drought resistant agriculture, sustainable livestock farming and the introduction of water saving technologies [125].

Irrigation is the biggest consumer of water resources in CA, where agriculture is still an important component of the local economies. To ensure successful climate change adaptation, and possibly mitigation via land–surface atmosphere feedbacks, changes in the agricultural sector are critical, such as the implementation of no-till farming, and switching from cotton and rice crops to drought resistant crops.

Local landuse and landcover changes can modify regional climates by affecting the surface albedo and the latent (evapotranspiration) and sensible heat fluxes via land-atmosphere feedbacks [81,126,127]. Afforestation can help to conserve water in snow-covered regions, decrease air temperatures in summer by evaporative cooling, and decrease the frequency of extreme rainfall events [128]. Increasing vegetation, both in urban and agricultural areas, has been demonstrated to have multiple benefits such as the reduction of "heat island" effects in cities and improved sustainability of food production [126,128]. Davin et al. [129] demonstrated that no-till farming has the potential to off-set summer heat waves by local preferential cooling effects from a cropland albedo increase. Conservative agriculture projects with minimal tillage and crop rotation, already implemented in some parts of CA, have also been proven to foster carbon sequestration (thereby off-setting CO_2 emissions) and reduce soil erosion, as well as increasing crop yields [130].

4. Synthesis and Outlook

4.1. Past and Present State of CA Endorheic Basins

The overview of main endorheic basins and lakes on four continents and Central Asia presented at the start of this paper allows us to synthesize a number of key points: (1) all of the large endorheic lakes are descendants of much larger paleolakes which existed in pluvial epochs (e.g., during the Pleistocene with regards to Lake Bonneville in North America and Lake Mega-Chad in Africa); (2) there is a natural long-term water budget deficit in closed basins, with evaporation, together with other loss terms, exceeding water inputs; (3) during most of the 20th and 21st century lake levels have declined, sometimes very dramatically (e.g., Lake Chad and the Aral Sea); (4) receding water levels often lead to separation of one large water body into two or several water pools/basins with their own ecological and hydrological regimes; (5) endorheic lakes with outlets such as rivers or groundwater discharge, remain fresh or less saline; (6) both climate change and direct anthropogenic impacts, such as water withdrawals for irrigation, have caused environmental deterioration in endorheic basins; (7) apart from problems with water quality and quantity, declining lakes have left dry salty beds leading to dust storms that could most likely worsen in the coming future; (8) high-altitude lakes (e.g., Lake Titicaca and Issyk-Kul) are less affected especially by anthropogenic activities; and (9) many endorheic basins are transboundary especially in CA, often leading to problems related to shared responsibilities for water management.

4.2. Future Pressures on Endorheic Basins in CA

Large parts of endorheic CA are characterized by a semiarid to arid climate, and data indicate that Central Asia is warming faster than the global average [131]. Rising temperatures are particularly relevant for CA as the discharge of some major rivers has increased due to glacier mass losses (caused by increased melt) and led to a considerable increase of water flow to the Aral Sea basin over recent decades [102,106]. According to Bernauer and Siegfried [104] climate change will impact the CA region mainly through temperature effects on the snow and ice cover in the Tien Shan Mountains and while aridification of Central Asia in the short term is not probable, the seasonal distribution of water could change dramatically. This will have implications for the management of water resources in the region. Changes in water flow will negatively affect the productivity of hydropower stations, and thus energy generation efficiency, as well as seasonal water availability, and hence agriculture. The effects are not evenly distributed; northern and eastern Kazakhstan will, most likely benefit from longer growing seasons but western Turkmenistan and Uzbekistan could suffer from increased water demands for irrigation as temperatures rise [109]. The increase in air temperatures will increase PET and open water evaporation, while terrestrial actual ET rates will depend on moisture availability and thus on future changes in precipitation amounts and intensities which are highly uncertain. Improvements in landuse and landcover management practices, with efficient water use in agriculture in particular, can help mitigate the negative effects of climate change through land-atmosphere feedbacks.

4.3. Implications for Water Resource Research and Management in CA Region

While integrated water resources, evapotranspiration, groundwater management and studies in CA have been supported by international organizations since the early 1990s [25], systematic progress is relatively slow because of: (i) weak institutional development; (ii) the lack of cross-disciplinary hydroclimatoecological research; (iii) the difficulties encountered when establishing academia-business collaborations; and (iv) lack of consistent implementations of applied technology projects (that address one or more sectors of the water–energy–food nexus) throughout the entire region [25,132].

Managing transboundary water resources and basins is a daunting tasks, especially in the context of global climate change. While most of the research and practical efforts of the international community to improve water management in CA is aimed at the state and government level, working at the grassroots level would perhaps be a more effective approach.

The involvement of CA water research and management organizations in global network initiatives can help to build a foundation for stronger research cooperation and implementation of effective water use strategies. GLEON, the Global Lake Observatory Network [133], is a community of lake experts whose aim is the improvement of lake research worldwide, but CA is not represented in the group [63]. Another example is FLUXNET, a global network of regional networks of micrometeorological towers which used the Eddy Covariance Method [134] to measure the fluxes of greenhouse gases and energy (including evapotranspiration) between the biosphere and the atmosphere (again, CA is poorly represented) [135]. The long-term observations and data from the micrometeorological towers are useful in themselves, but also instrumental in the verification of various climate, hydrological, and ecological models, together with remote sensing products, applied over the CA region. Being connected to these kinds of networks is essential for CA to improve its efforts in monitoring and forecasting of water resources and related ecosystem services [134].

With regards to integrated water management and underpinning research; thus far, transboundary programs have only focused on surface water resources; they lack cooperative programs and research projects related to groundwater resources. Cooperation through transparent international initiatives for research and management of groundwater resources, such as IGRAC MAR [112], that encourage data sharing and publication on public web sites, would facilitate developments in this area.

This paper demonstrates that political and water management policy/strategy aspects related to the water–energy–food nexus are of key importance in endorheic CA. This complex nexus requires cooperation between countries that share a common past and should work together to build a secure future where resources are concerned. Guillaume et al. [136] reviewed the history of transboundary water use in CA using the nexus concept, and concluded that governments, scientists, civil societies and consumers must all play a role in the transformation of the water–energy–food security framework in order for it to be successful. Such a transformation will only be possible through considerable institutional changes and reforms in the region.

Programs similar to Central Asia Water [137] and Indus Basin Forum [138], which are dedicated to knowledge sharing, regional cooperation expansion, and advanced technologies adaptation, are powerful components for successful CA regional climate change adaptation efforts. These efforts are supported by the local governments and international donors such the British Council, British Aid, Newton Fund, German GIZ, Royal Academy of Engineers, USAID PEER, World Bank, and UNDP. However, these initiatives and funding schemes operating in CA need to be unified to provide the much-needed synergy and momentum for the critical improvement of water resources management, as well as closely linked food and energy sector concerns. While endorheic Central Asia is at a crossroads, the pressures caused by climate change and aggravated by human mismanagement of natural resources leave very little time for hesitation.

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