Title
Lake dynamics in Central Asia in the past 30 years

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Publication Date
2020

UNIVERSITY OF CALIFORNIA

Los Angeles

Lake dynamics in Central Asia in the past 30 years

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geography

by

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2020

ABSTRACT OF THE DISSERTATION

Lake dynamics in Central Asia in the past 30 years

by

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Doctor of Philosophy in Geography
University of California, Los Angeles, 2020
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Water is a key resource in arid Central Asia (CA) and is heavily affected by climate change and human activities. Temperature across the region has increased drastically especially in the mountain region while precipitation change is less homogeneous. The increased temperature has caused increased melting of glacier and snow which has a large contribution to the runoff in rivers. Human activities such as agriculture irrigation and reservoir management also affect water availability. In the Soviet era, agriculture in CA expanded continuously and large amount of water was extracted from rivers for irrigation. This has caused the catastrophic decline of the Aral Sea. In the post-Soviet era, countries in CA have reorganized their agriculture structure to be self-sufficient. It is important to understand how these changes affect water availability in CA especially under climate change. This dissertation uses lakes as proxy indicators of water availability and assesses how climate and human activities have affected lakes in CA. Seventeen lakes located in three former Soviet republics and western China from seven basins are examined using remote sensing and hydrologic modeling to estimate their changes in area, water level and volume. Agriculture area changes in these basins from seven countries are also examined using remote sensing. It is found that 1) lakes located in the mountains have generally expanded due to the melting glaciers and snow; 2) lakes located in the lowlands have remained relatively stable due to the relative stability of agriculture area; 3) reservoirs exhibit different seasonal patterns due to their major function as power generation reservoirs release water during the winter while irrigation reservoirs release water during the summer; 4) agriculture area in the former Soviet Central Asia republics is highly dependent on precipitation due to the lack of efficient irrigation infrastructure while agriculture in China has continuously expanded due to the adoption of drip irrigation and groundwater extraction. In conclusion, climate is the more dominant factor affecting water availability especially in the mountains causing the lakes to expand while agriculture irrigation has offset some of the surplus in the lowlands causing the lakes to remain relatively stable.

The dissertation of Shengan Zhan is approved.

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ACKNOWLEDGEMENTS

I received tremendous advice and support from numerous colleagues and friends along this arduous yet rewarding journey. First, I would like to thank my advisor and committee co-chair Prof. Yongwei Sheng for his endless support financially, academically as well as emotionally. He has provided valuable guidance and resource without reservation whenever they are needed. I would like to thank my committee co-chair Prof. Dennis Lettenmaier for providing advice and resource to conduct numerous hydrologic modeling experiments which are the most challenging aspects of my dissertation. I would like to thank other committee members Prof. Yongkang Xue and Prof. An Yin for their advice on my experiment design as well as results.

I also want to thank Solomon Vimal, Mu Xiao and Qian Cao for providing specific guidance on hydrologic modeling experiment designs and troubleshooting without reservation. I thank Dr. Junli Li, Yan Huang as well as numerous colleagues at the Chinese Academy of Sciences Research Center for Ecology and Environment of Central Asia I Kyrgyzstan for providing data and support on a field trip that led me to a new understanding of the region. I thank Marcel Kleinherenbrink for providing methods and codes on the processing of CryoSat data. I thank Yanhong Gao for providing important data that drove model experiments. I also thank Prof. Michael Shin for providing professional guidance throughout this journey.

I am eternally grateful to Zhuang Cai for keeping me spirited when I am at my lowest points. Finally, I would like to thank my parents for their unconditional love and support.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Central Asia (CA), as defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO), mainly includes the former Soviet Central Asian republics (i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan), Afghanistan, northeastern Iran, northern and central Pakistan, northern India, western China, Mongolia (Dani et al., 1992, Figure 1.1). The region is home to over 100 million people (Frenken, 2013) and the economy heavily depends on agriculture (Qushimov et al., 2007). The region is also arid due to its distance from moisture sources. About 90% of Central Asia receives less than 400 mm of precipitation per year (Mueller et al., 2014). Nevertheless, Central Asia is home to the Tianshan and Pamir mountains, which are commonly known as the "water tower" in this region (Viviroli et al., 2003; Voviroli and Weigartner, 2004; Immerzeel et al., 2010). These mountains are estimated to contribute to 50-90% of total runoff in Central Asia (Voviroli and Weigartner, 2004) through orographic effects and meltwater runoff generated by glaciers and snowpacks (Kehrwald et al., 2008; Kaser et al., 2010; Sorg et al., 2012).

Climate change has caused glaciers in the Tianshan to shrink in area and mass by 18% and 27% respectively since the 1960s (Farinotti et al., 2015). While temperature in Central Asia has increased in the 20th century and is projected to continue increasing in the 21st century, precipitation changes are more ambiguous. It is also debatable whether river runoff will increase or decrease in the future (Siegfried et al., 2012; Unger-Shayesteh et al., 2013). Additionally, humans have a great impact on the water here as they extract large amounts of water from rivers for agriculture. The upstream countries also depend heavily on hydropower during the winter. All these aspects have major impacts on water availability in the countries in Central Asia.

Despite its aridity, Central Asia is home to many lakes (Lehner and Doll, 2004). Lakes are a natural storage of water resources and they are vulnerable to climate change and human disturbances (Arnell et al., 2001). Endorheic lakes (lakes with no outflow) are particularly sensitive to disturbances because they are dependent on the balance between inflow and evaporation. Increasing temperature and/or decreasing precipitation as well as the diversion of upstream water for human use may cause the water level in lakes to change drastically (Micklin, 1988; Robertson and Ragotzkie, 1990; Mason et al., 1994; De Wit and Stankiewicz, 2006; Gao et al., 2011). Thus, these lakes are important indicators of climate change and human disturbances.

Lakes in Central Asia have experienced drastic changes over the past decades (Birkett, 1995; Bai et al., 2011; Li et al., 2011; Micklin, 2014a). The Aral Sea in particular has shrunk over 80% since 1960 mostly due to the diversion of water from the rivers that feed it for agriculture (Micklin, 2007, Cretaux and Berge-Nguyen, 2014; Micklin, 2014b). Other lakes have experienced spatially heterogeneous patterns of changes as well (Bai et al., 2011; Li et al., 2011; Bai et al., 2012). While changes in some of the lakes have been documented, attribution of the cause of changes have has been highly generalized and qualitative (Bai et al., 2011; Li et al., 2011; Bai et al., 2012). Therefore, it is important to understand how and more crucially why these lakes are changing in order to better understand the water resources in Central Asia.

1.2 Climate in Central Asia

This section will provide a description of the present climate of Central Asia and how it has changed over the past 100 years. Temperature and precipitation will be discussed in detail as they are two important climate factors affecting water resources. The section provides a general background and leads to the discussion of how climate have and will affect water resources in the region.

1.2.1 Temperature and its changes over the instrumental record period

Temperature is affected by solar radiation and atmospheric circulation (Surkova, 2010). In Central Asia, solar radiation is the dominant factor controlling the air temperature in the region especially during the summer due to the large number of cloud-free days (Schiemann et al., 2008; Surkova, 2010). Atmospheric circulation plays a smaller role, but it can cause shorter scale weather variations through the following four processes (Schiemann et al., 2008; Surkova, 2010). 1) cyclonic intrusions from the south bring warm air across southern Central Asia and causes warm winter weather and precipitation; 2) Cold northern and north-eastern intrusions causes cooler summer and cold winter weather as well as precipitation; 3) anticyclonic weather created by the Siberian High causes little precipitation and 4) Mid-latitude (50-55°N) cyclonic activity in northern Central Asia causes cooling and winter precipitation. As a result, the region has large air temperature variations both diurnally and seasonally (Surkova, 2010). In the arid lowland regions, air temperature can reach over 40°C in the summer and below -30°C in the winter. Atmospheric circulation plays a stronger role during the winter when cold air intrusions from the north interact more frequently with warmer air from the south. As a result, the interannual variation of air temperature is greatest during the winter and smallest during the summer (Surkova, 2010). There is also a strong north-south gradient in the mean annual temperature in Central Asia (Mannig et al., 2013).

Unger-Shayesteh et al. (2013) conducted an extensive review on the climatic, cryospheric and river runoff changes in the mountain ranges of Central Asia. The statistically significant rates of temperature changes in literatures that they reviewed range from 0.18 to 0.42°C per decade in the mountains although different studies reveal contradicting seasonal trends. Huang et al. (2012) revealed enhanced warming during the cold season (November to March) in the entire Central Asia at 0.24°C per decade and the rate is more pronounced than other semi-arid regions in the world, while the rate during the warm season (May to September) is 0.08°C per decade. Many studies on the mountain regions of Central Asia also revealed largest increases in mean air temperature during the winter (Podrezov et al., 2001; Podrezov et al., 2002; Ministry of Ecology and Emergencies of the Kyrgyz Republic, 2003; Giese and Mossig, 2004; Romanovskij and Kuz'micenok, 2005; Mamatkanov et al., 2006; Siegfried et al., 2012). On the other hand, studies focusing on stations in the lowland regions show largest warming rates during the summer and fall (Bohner, 1996; Spektorman, 2006 and Chub, 2007). Some studies also found cooling trends in certain months in the year especially during late winter and spring (Bohner; 1996; Finaev, 1999; Giese and Mossig, 2004; Mamatkanov et al., 2006; Bolch and Marchenko, 2009; Zhang et al., 2009). Meteorological stations in Uzbekistan show that warming is associated with a decreasing range between minimum and maximum mean annual temperatures as most of the stations show an increase in minimum mean annual temperature while fewer stations show an increase in maximum mean annual temperature (Chub, 2007).

Unger-Shayesteh et al. (2013) concluded that generally at elevations above 1,500 m significant warming rates tend to occur during winter and fall while at elevations below 1,500 m significant warming rates tend to occur during summer and fall. They also attributed the different findings from different studies to 1) lack of significance assessment; 2) neglecting short-term and long-term autocorrelation; 3) the high sensitivity of trends to the selection of study period and 4) the lack of assessment on the spatial representativeness of trends. In general, the entire Central Asia is experiencing warming temperatures and the rates are more pronounced in higher elevations and during winter and fall; however, a more detailed spatial pattern of warming rates is inconclusive.

1.2.2 Precipitation and its changes over the instrumental record period

Since Central Asia is located in the heart of Eurasia and far away from moisture sources, the region experiences small amount of annual precipitation especially in the lowland areas (Gafurov, 2010; Surkova, 2010). The westerlies bring most of the moisture to the region from the Atlantic Ocean. However, the air masses quickly become dry as they move across the continent. The high Pamir, Hindu-Kush Tianshan and Himalayan mountains to the southeast of Central Asia blocks most of the moisture coming from the Indian Ocean (Schiemann et al., 2008). As a result, the precipitation in Central Asia exhibits strong spatial heterogeneity. The Aral Sea and most of the lowland regions receive merely 90-120 mm of annual precipitation and the foothills of the surrounding mountains receive around 200 mm (Surkova, 2010; Micklin, 2014a). On the other hand, annual precipitation can reach over 1000 mm in the Tianshan and Pamir mountains (Bolch, 2007; Williams and Konovalov, 2008; Micklin, 2014a) due to the orographic effects of mountain ranges. The wetter region of northern Central Asia receives around 300-400 mm per year (Williams and Konovalov, 2008). In general, precipitation decreases from north to south in the lowland regions and increases with elevation in the mountain ranges. The precipitation seasonality is essentially the same across Central Asia except for the northern part. Most of the region (including the mountain ranges) has precipitation peaking in spring and fall, little precipitation during the summer and moderate precipitation during the winter (Schiemann, 2008). The northern part has a more even distribution of precipitation throughout the year with a relative peak during the summer (Schiemann, 2008).

The spatial patterns of seasonal and annual changes in precipitation are even less consistent among different studies compared to the changes in temperature (Seneviratne et al., 2012; Unger-Shayesteh et al., 2013). In the mountain regions of Central Asia (where most precipitation falls), some studies found no significant trends in annual precipitation (Giese and Mossig, 2004; Bolch, 2007; Chub, 2007; Bolch and Marchenko, 2009; Kutuzov and Shahgedanova, 2009). Depending on the location of stations, some show increasing trends (Bohner, 1996; Aizen et al., 1997; Romanovsky, 2002; Mamatkanov et al., 2006; Zhang et al., 2009); and some show decreasing trends (Podrezov et al., 2001; Romanovsky, 2002; Mamatkanov et al., 2006; Zhang et al., 2009; Kriegel et al., 2013). In general, stations in the foothills and higher altitudes of Tianshan show increasing trends while stations in the inner Tianshan show decreasing trends. Changes rates of annual precipitation can range from -30 to + 50 mm per decade (Unger-Shayesteh et al., 2013). In most of the lowland regions, little change in precipitation was found (IPCC, 2001). However, significant increase in precipitation was observed by many stations located near irrigated lands compared to stations located in the nearby quasi-pristine sandy desert (Lioubimtseva et al., 2005; Lioubimtseva and Henebry, 2009). This reflects the micro-regional changes in climate induced by human activities and is consistent with other similar regions in the world (Diem and Brown, 2003; Lioubimtseva et al., 2005; Pielke et al., 2005). Seasonal changes in precipitation and their spatial patterns are also inconclusive across the mountain regions in Central Asia. Some studies found increasing precipitation in the cold season for some regions (Bohner, 1996; Aizen et al., 1997; Finaev, 1999; Romanovskij and Kuz'micenok, 2005; Zhang et al., 2009) while others found increasing precipitation in the warm season for other regions (Romanovsky, 2002; Karandaeva and Tsarev, 2005; Romanovskij and Kuz'micenok, 2005; Mamatkanov et al., 2006; Zhang et al., 2009). Neither conclusive is the elevation dependency of precipitation changes (Finaev, 1999; Dikich, 2004 and Zhang et al., 2009).

Even though there is great ambiguity in the long-term trend of precipitation, there are significant increasing trends in the year-to-year variability of precipitation shown in many stations in Uzbekistan (Chub, 2007). Paleo-records show increased precipitation during warmer periods such as the Early and Mid-Holocene and more arid conditions during cooler periods such as the Younger Dryas (Lioubimtseva et al., 2005; Lioubimtseva, 2014), providing some insight into future changes in precipitation in the region.

1.3 Agriculture in Central Asia

Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (i.e. the former Soviet Central Asia republics) were governed by the Union of Soviet Socialist Republics (USSR) from 1922 to 1991 during which the focus of agriculture was cotton production. The centralized USSR government began massive collectivization of agriculture in 1929 in which individual farms were combined into collective farms (Micklin, 2014c). The goal was to reach "cotton independence" by 1933 under collective effort (Karimov, 1995; Pankova et al., 1996). Over 50% of irrigated area was devoted to cotton plantings and by 1933, 97% of national cotton needs were grown domestically (Micklin, 2000). However, soil conditions declined rapidly over time as a result of over-irrigation and lack of proper drainage systems which caused cotton yields to decline (Micklin, 2014c). To keep up with production, irrigated area saw steady growth since the 1950s until the end of the Soviet period. Earlier expansion of irrigated area already occupied most of the fertile lands such as the alluvial fans and downstream river deltas (Karimov, 1995; Pankova, 1996). Since the 1950s, irrigation expansion extended to areas less suitable for agriculture such as the Golodnaya (Golodnaya meaning hungry) and Karshi Steppes as well to the Karakum Desert. Construction of the Karakum Canal began in 1954. This is one of the longest irrigation canals in the world at 1375 km and crossed the vast Karakum Desert. During 1913 - 1950, irrigated area in the Aral Sea basin merely expanded from 3.2 to 3.8 million hectares while the area expanded drastically from 3.8 to over seven million hectares during 1950 – 1990 (Table 1.1).

After the collapse of the Soviet Union in 1991, the former Soviet Central Asia republics broke into five independent countries each with their own agricultural agendas. Uzbekistan became the country having the largest irrigated area (4.28 million ha) as well as the largest share of irrigation water withdrawal (53.0%) in the Aral Sea basin in 1995 (Table 1.2; World Bank, 1998). The expansion rate of irrigated area greatly decreased since 1995 and irrigated area became stable since 2000. Associated with changes in irrigation area are changes in the type of crops being planted. During the first five years of the collapse of the Soviet Union, Uzbekistan which was the largest cotton producer shrank its area of cotton plantation by 19% (Index 2012a) while tripling its area of wheat plantation (Index 2012b). During 1995-2011, Uzbekistan further reduced its cotton area by 10% while increasing its wheat area by 8%. Turkmenistan, which was the second largest cotton producer, shrank its cotton area by 28% during 1990-1995 (Index, 2012c) while sextupling its wheat area (Index, 2012d) and again doubling the 1995 wheat area by 2011. These changes are driven by the need to strengthen the countries' food bases (Micklin 2014c). Kazakhstan and Uzbekistan being major rice producers, also dropped their rice plantation area by 23% between 1990-1995 and 72% between 1990-2001 respectively (Index, 2012e; Index, 2012f).

In western China, agriculture has been developed since the 1950s and has been rapidly expanding (Sun and Gao 2010). Similar to development elsewhere, agriculture in western China started around river channels and oases and gradually expanded towards less fertile lands such as barren and shrubland (Wang et al., 2017). The widespread irrigation combined with inefficient water management strategies has led to severe desertification and ecological deterioration in Ebinur lake basin in Xinjiang (Zhang et al., 2015). In efforts to restore ecological stability in Ebinur basin, Ebinur lake wetland nature reserve was established in the late 1990s (Bai, 2007). Highly efficient drip irrigation was also introduced around the late 1990s (Xu et al., 2003).

As can be seen from the discussion above, agriculture in Central Asia depends heavily on irrigation. Not only does expanding agricultural area demand more water being withdrawn but also does the decreasing efficiency of water use over time. Even though irrigated area only increased by 25% from 1913-1950, total water withdrawal increased by over 60% (Table 1.1). The amount of water withdrawn per unit of irrigated area increased from roughly 10,750 m^3/ha in 1913 to 15,000 m3/ha in 1950 and peaked in the 1980s to around 20,000 m^3/ha. The increase in unit area water use is caused by serious soil salinization in the irrigated area of Central Asia (Micklin 2014c). When plants absorb water in the soil, they leave the salts dissolved in water behind in the soil and over time the salts accumulate leading to the salinization of soil. The situation in Central Asia is worsened by over-irrigation and the lack of proper drainage systems to keep the water table low. The rising saline groundwater thus further deteriorates soil conditions. Over 50% of irrigated areas in the Aral Sea basin suffered from soil salinization (Pankova et al. 1996). Salts needed to be flushed out from the soil prior to planting of crops which increased water consumption. Also, as irrigated land expanded into drier areas not suited for agriculture, water use increased due to higher evaporation as well as the need to fill pore spaces in the drier soils and to leach the salts. Therefore, soil salinization combined with expansion of irrigation into steppes and deserts greatly increased the withdrawal of water per unit of irrigated area from in the Soviet period from 1950 to 1990 (Table 1.1; Micklin, 2000). After the collapse of the Soviet Union, there is a drastic decline in per area irrigation water use. This is mostly because the planted area of water-intensive cotton (the dominant crop in the Soviet period) and rice, was greatly reduced by the independent countries since 1990.

1.4 Lakes in Central Asia

Overall, studies on changes in lakes and reservoirs in Central Asia other besides the Aral Sea are limited. Li et al. (2011a) examined the water level changes in nine lakes in Central Asia, Xinjiang and Mongolia from 2003-2009 using satellite altimetry. Li et al. (2011b) further extended the study to 24 lakes in the region. Bai et al. (2011) examined the areal changes of nine lakes in a similar region from 1975-2007 using optical satellite imagery. Klein et al. (2014) examined the seasonal fluctuations of over 10 lakes in the past 27 years using satellite altimetry. These are the only regional studies on lake area and water level changes in Central Asia that were found in the literature. A few studies focusing on individual lakes and reservoirs in the region were also found (e.g. Ma et al., 2007; Propastin, 2008; Hwang et al., 2011; Cretaux et al., 2015; Kouraev et al., 2009; Birkett, 1995). Table 1.3 lists changes in the lakes that were found in the literature with sources. Note that the Caspian Sea is not reviewed here because the feeding rivers (i.e., the Volga and Ural rivers) do not originate in the Central Asian mountains and the rivers are much less affected by agriculture in Central Asia.

These lakes in Central Asia show a spatially heterogeneous pattern of change. Alpine lakes (elevation > 1,000 m) are generally stable or expanding. Lakes in northern Tibetan Plateau (i.e. Ayakkum Lake and Aqqikkol Lake) are expanding. Lakes in the Tianshan (i.e. Karakul Lake, Lake Issykkul, Sayram Lake) are stable or expanding. Lakes in the Altai mountains (i.e. Uureg Lake, Uvs Lake, Khyargas Lake, Khar-Us Lake, Teletskoye Lake) are stable or shrinking. This pattern follows a north-south gradient where northern lakes are stable or shrinking while southern lakes are expanding. The pattern is likely caused by the difference in the number of glaciers in the catchments of the lakes. More glaciers are feeding the lakes in the northern Tibetan Plateau and the Tianshan while fewer glaciers are feeding lakes in the Altai Mountains.

Lakes in the lowland regions are generally stable or shrinking. Changes in open lakes in these regions depend on whether dam or irrigation projects exist in their upstream catchments. Those affected (Bosten Lake, Zaysan Lake, Kairakum reservoir, Kapshagay reservoir) are shrinking while those not affected (Ulungur Lake, Markakol Lake, Teletskoye lake, Khar-Us Lake) are generally stable. The closed terminal lakes are mostly shrinking with a few exceptions. Affected by dams and irrigation projects, most terminal lakes (Lake Balkhash, all the Aral Sea except the north Aral Sea) are shrinking. Sarykamish Lake, a notable exception, expanded drastically as much of the irrigation water diverted from rivers drained into its basin. Those not affected by water projects (i.e. Alakol Lake, and Uvs Lake) are rather stable.

1.5 Motivations and objectives of this dissertation

In light of the above discussion, it is important to understand how water resources are changing in Central Asia and what is causing the changes. Lakes, especially endorheic lakes, are particularly sensitive to climatic and anthropogenic impacts. Endorheic lakes are the terminus of a hydrologic system and their storage variations are direct responses to the climatic changes and human activities in the basin. Thus, endorheic lakes can be used as proxy indicators of climate and anthropogenic change. Nevertheless, aside from the Aral Sea, studies on lake changes in Central Asia are lacking. Such an assessment is important to reduce the uncertainties associated with future projections of water availability in the region since it can identify whether water in a region is more affected by the climate or the people. It provides insight on future water management strategies regarding changing water availability, seasonality as well as human interventions in transnational river basins.

The scientific goals of this dissertation are to examine the natural and anthropogenic impacts on lake dynamics in the various basins in Central Asia. Lakes in these will be examined and compared regarding the climatic and anthropogenic impacts affecting their water level, areal extent and storage. Specifically, the scientific questions sought are:

1. How have lakes changed in the past 30 years in Central Asia?
2. What are the climatic impacts (precipitation and temperature) on water storage in lakes in Central Asia?
3. How have human activities (irrigation and water management) affected water storage in lakes in Central Asia?

These questions are addressed in the following chapters. Chapter 2 is a pilot study that uses remote sensing and hydrologic modeling to examine the changes of a pair of adjacent lakes in Xinjiang, China. It also uses remote sensing to derive agriculture extent over the basin to assess the influence of agriculture on lake changes. This study serves as a methodological guideline for the subsequent chapters. Chapter 3 expands the study area to include the most populated regions in Central Asia. It examines the changes of 17 lakes across Central Asia and discusses their changes in relation to the climate and human activities. Chapter 4 focuses specifically on agriculture changes in seven basins that covers the seven countries across Central Asia and discusses the effect of agriculture on lake changes.

Figure 1.1: Central Asia as defined by the United Nations Educational, Scientific and Cultural Organization

Table 1.1: Irrigated area and water withdrawal in the Aral Sea basin over the 100 years (Micklin, 2000; Micklin 2014).

Year	Irrigated area (million ha)	Irrigation withdrawal (km^3)	Irrigation withdrawal (m^3/ha)
1913	3.2	25.6-43.2	8,000-13,500
1922	1.7	16	9,400
1933	3.5	40	11,500
1940	3.8	49	13,000
1945	N/A	N/A	15,000
1950	3.8	57	15,000
1965	4.8	82	17,000
1980	6.3	107-126	17,000-20,000
1985	7	112-133	16,000-19,000
1990	7.25	109	14,600-17,000
1995	7.94	100	12,594
2000	8.1	75	9,180
2005	8.1	91	11,258
2010	8.2	92	11,169

Table 1.2: Irrigated area and water withdrawal from the Aral Sea basin by country in 1995 (World Bank, 1998)

Country	Irrigated area (million ha)	% of irrigation withdrawal
Uzbekistan	4.28	53.0
Turkmenistan	1.74	22.4
Tajikistan	0.72	10.3
Kazakhstan	0.74	9.7
Kyrgyzstan	0.46	4.6
Total	7.94	100.0

Table 1.3: List of lakes and their changes investigated in the literature

Lake	Coordinates (latitude N, longitude E)	Period	Area variation		Level variation (m)	Source
			km^2	%		
Karakul Lake	39.03, 73.4	2002-2009	1.8	0.45	+0.816	Li et al. (2011b)
Kairakum reservoir	40.30, 70.0	2002-2009	-18.69	-6.78%	-2.852	Li et al. (2011b)
Ayakkum Lake	37.56, 89.39	2002-2009	110.63	14.84%	+1.716	Li et al. (2011b)
Bosten Lake	41.97, 87.04	2002-2009	-190.32	-17.24%	-2.66	Li et al. (2011b)
		1975-2007	-96.93	-9.18%	N/A	Bai et al. (2011)
Lake Issykkul	42.44, 77.27	2002-2009	17.55	0.28%	+0.018	Li et al. (2011b)
		1975-2007	-41.02	-0.66%	N/A	Bai et al. (2011)
		1992-1994	N/A	N/A	No change	Birkett (1995)
Lake Balkhash	46.29, 75.63	2002-2009	-8.31	-0.05%	-0.258	Li et al. (2011b)
		1975-2007	-449.5	-2.61%	N/A	Bai et al. (2011)
		1992-1994	N/A	N/A	No change	Birkett (1995)
		1992-2007	N/A	N/A	+1.679	Hwang et al. (2011)
Zaysan Lake	48.00, 83.92	2002-2009	-223.09	-7.36%	-1.745	Li et al. (2011b)
		1975-2007	165.81	5.85%	N/A	Bai et al. (2011)
Ebinur Lake	45.00, 83.00	1998-2005	-253	-50.30%	N/A	Ma et al. (2007)
		1975-2007	-50.5	-8.37%	N/A	Bai et al. (2011)
Sarykamish Lake	41.94, 57.4	2002-2009	152.2	4.09%	+1.001	Li et al. (2011b)
		1992-2006	N/A	N/A	+6.6	Kouraev et al. (2009)
Aqqikkol Lake	37.08, 88.42	2002-2009	85.46	22.29%	+1.716	Li et al. (2011b)
Aral Sea (whole)	44.99, 59.48	1975-2007	-4,4862.2	-75.70%	N/A	Bai et al. (2011)
		1993-2001	-13,000	-37.14%	-4.5	Peneva et al. (2004)
		2002-2009	N/A	-62%	N/A	Singh et al. (2012)
		1981-2013	-22,000	-46.81%	N/A	Shi et al. (2014)
		1957-2008	-56,700	-84.5%	N/A	Kravtsova et al. (2010)
Aral Sea (south)	44.90, 59.35	2002-2009	-12,399.96	-71.65%	-2.948	Li et al. (2011b)
		1993-2013	-21,000	-72.41	-9	Shi et al. (2014)
		1957-2008	-54,000	-88.24%	N/A	Kravtsova et al. (2010)
		1992-2006	N/A	N/A	-7.2	Kouraev et al. (2009)
Aral Sea (west)	45.13, 58.47	2002-2009	N/A		-4	Singh et al. (2012)
		1989-2008	-5,400	-57.45%	N/A	Kravtsova et al. (2010)
Aral Sea (east)	44.90, 59.87	2002-2009	N/A	-94%	-3.5	Singh et al. (2012)
		1989-2008	-25,800	-88.97%	N/A	Kravtsova et al. (2010)
Aral Sea (north)	46.45, 60.65	2002-2009	382.29	13.11%	+1.37	Li et al. (2011)

		1992-1994	N/A	N/A	0.5	Birkett (1995)
		2002-2009	N/A	N/A	+1.5	Singh et al. (2012)
		1957-2008	-2,700	-45.76%	N/A	Kravtsova et al. (2010)
		1992-2006	N/A	N/A	No change	Kouraev et al. (2009)
Tengiz Lake	50.42, 69.02	2002-2009	-478.13	-35.48%	-0.738	Li et al. (2011)
Seletyteniz Lake	53.25, 73.20	2002-2009	-233.62	-58.48%	-0.247	Li et al. (2011)
Teke Lake	53.83, 72.95	2002-2009	-2.61	-1.38%	N/A	Li et al. (2011)
Kapshagay reservoir	43.82, 77.62	2002-2009	-68.83	-5.52%	-0.442	Li et al. (2011)
Sayram Lake	44.60, 81.17	2002-2009	1.33	0.29%	0.3	Li et al. (2011)
		1975-2007	3.31	0.72%	N/A	Bai et al. (2011)
Khar-Us Lake	48.06, 92.24	2002-2009	-0.77	-0.08%	-0.014	Li et al. (2011)
Alakol Lake	46.13, 81.72	2002-2009	46.37	1.59%	-0.131	Li et al. (2011)
		1975-2007	-22.71	-0.76%	N/A	Bai et al. (2011)
Ulungur Lake	47.26, 87.29	2002-2009	-4.72	-0.56%	< -0.3	Li et al. (2011)
Markakol Lake	48.75, 85.76	2002-2009	0.18	0.04%	-0.034	Li et al. (2011)
Khyargas Lake	49.18, 93.31	2002-2009	-48.32	-3.08	-2.088	Li et al. (2011)
Uvs Lake	50.32, 92.75	2002-2009	-21.02	-0.58%	-0.064	Li et al. (2011)
Uureg lake	50.15, 91.02	2002-2009	0.11	0.04%	0.063	Li et al. (2011)
Teletskoye lake	51.59, 87.67	2002-2009	0.11	0.05%	-0.31	Li et al. (2011)
Sasykkol Lake	46.50, 81.00	1975-2007	0.91	0.12%	N/A	Bai et al. (2011)
		1992-1994	N/A	N/A	No change	Birkett (1995)

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CHAPTER 2

ASSESSING ANTHROPOGENIC AND NATURAL CONTRIBUTIONS TO DECADAL LAKE CHANGES IN CENTRAL ASIA: A PILOT STUDY IN EBINUR AND SAYRAM BASINS

2.1 Introduction

As defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the geographic area of Central Asia contains Afghanistan, northeastern Iran, northern and central Pakistan, northern India, western China, Mongolia and the former Soviet Central Asian republics (Dani et al., 1992). Climatically, it is a semiarid to arid region in the vast Eurasian hinterlands with a strong continental climate characterized by hot and dry summers and cold and relatively moist winters (Schiemann et al., 2008; Lioubimtseva and Henebry, 2009; Surkova, 2010). Mountains are the “water tower” in this region (Viviroli et al., 2003; Viviroli and Weigartner, 2004; Immerzeel et al., 2010). The westerlies bring moisture from the Atlantic Ocean to the region and most of the precipitation falls in the mountain ranges while the lowland regions are exceptionally dry. Meltwater runoff thus serves a crucial role in the downstream hydrology (Kehrwald et al., 2008; Kaser et al., 2010; Sorg et al., 2012;). The Tianshan and the Pamir mountains are estimated to contribute to 50-90% of total runoff in Central Asia which is significantly higher than the percentage contribution of mountain runoff in humid regions (Viviroli and Weigartner, 2004). Climate change has caused glaciers in the Tianshan to shrink in area and mass by 18% and 27% respectively since the 1960s (Farinotti et al., 2015). While temperature in Central Asia has increased in the 20th century and is projected to continue increasing in the 21st century (Unger-Shayesteh et al., 2013), precipitation changes are more ambiguous (Seneviratne et al., 2012; Unger-Shayesteh et al., 2013). It is also debatable whether river runoff will increase or decrease in the future (e.g. Aizen et al., 1997; Kezer and Matsuyama, 2006; Khan and Holko, 2009; Duethmann et al., 2015).

Additionally, humans have a great impact on the water in Central Asia as they extract large amounts of water from both surface and ground water for agriculture. Over 90% of water extracted from rivers is used for irrigation (World Bank, 1998). The area of irrigated agricultural lands has increased drastically in the past 100 years. These aspects have major impacts on water availability in Central Asia which affects the livelihood of over 100 million people.

Nevertheless, the contributions of climate change and human impacts on endoreic lakes in Central Asia are not well understood. This study intends to select a pair of representative lakes (i.e., Ebinur Lake and Sayram Lake) in Central Asia to examine changes in the two lakes using a combination of remote sensing and hydrologic modeling. By comparing the changes in these lakes, we examine the impact of the changing climate and human activities on water resources in the two basins as a pilot study of the broad Central Asia.

2.2 Study Area

Ebinur Lake and Sayram Lake are two typical lakes suitable for the study of climate and human influences on water resources. They both are major endorheic lakes in northeastern Xinjiang, China (Figure 2.1). As a province in western China, Xinjiang is home to nearly 22 million people. Its climate and hydrology are similar to elsewhere in Central Asia. Over 80% of surface runoff originates in the mountains in Xinjiang and over 45% of that is meltwater from glaciers and snowpack (Shen et al., 2013). Climate change is having major impacts on water resources in Xinjiang as it is causing the glaciers and snowpack to retreat and shifts peak runoff earlier in the year (Yao et al., 2004; Shen et al., 2013). This greatly influences water availability for human use and has great implications on water management and water security in the region.

These hydrologic changes are associated with a general shift in the climate of Xinjiang from warm-dry to warm-wet (Shi et al., 2007). Figure 2.2 shows the mean annual precipitation (A) and temperature (B) at three meteorological stations from 1953 to 2010. Both precipitation and temperature at all stations show statistically significant increasing trends over the past six decades. Bole station, being the highest station at 1,650 m above sea level (asl), experienced the highest rate of both precipitation and temperature increase among the three stations.

The mean surface air temperature in northwestern China between 1961 and 2006 has a warming rate of 0.35°C/decade with evidence of accelerated warming since the 1980s (Shi et al., 2007; Chen et al., 2010; Shen et al., 2013). Precipitation in north Xinjiang has increased by 22% from 1987-2000 compared to 1961-1986 with the greatest seasonal increase in winter (Shi et al., 2007). Warming in the region has caused a widespread retreat of glaciers and changes in the snowpack. Glacier area was reduced by 1,400 km^2 (5%) in northwestern China from 1960 to 1995 (Liu et al., 2002). Snow depth across Xinjiang and especially in Tianshan is increasing while snow cover duration is decreasing (Hu et al., 2013). As a result of this ongoing warming and shift in precipitation patterns, river runoff has been increasing since the second half of the 20st century (Yao et al., 2004; Shi et al., 2007; Shen et al., 2013; Yao, et al., 2014; Wang et al., 2017). Nevertheless, observations show the runoff seasonality and peak flow has shifted toward earlier in the year which has significant implications on water management in the region (Shen et al., 2013).

Despite its apparent aridity, Xinjiang is home to many endorheic lakes (lakes with no outlet). Endorheic lakes are particularly sensitive to disturbances because they are dependent on the balance between inflow and net evaporation (evaporation minus precipitation) (Arnell et al., 2001). Increasing temperature and/or decreasing precipitation as well as the diversion of upstream water for human use can cause the water level in lakes to change drastically (Micklin, 1988;

Robertson and Ragotzkie, 1990; Mason et al., 1994; Gao et al., 2011). Thus, these lakes are important indicators of climate change and human disturbances.

The selected lakes in this study are located in proximity and are affected by similar changes in climate yet drastically different degrees of human disturbance. Ebinur Lake, located in an agricultural basin experienced large water level declines between the 1950s and the 1970s, remained relatively stable in the 1980s and 1990s before increasing rapidly around 2000 and then declining again since 2003 (Yao et al., 2014). Its changes were thought to be relevant to irrigation development (Wang et al., 2003; Ma et al., 2014). In contrast, Sayram Lake has been expanding steadily since the 1970s (Chai et al., 2013). Since there is little human present surrounding Sayram Lake, the expansion was attributed to the increased precipitation and glacier melt (Chai et al., 2013; Cheng et al., 2016).

Despite the significant changes in these lakes, only one study (Ma et al., 2014) has attempted to quantify the relative contribution of climatic and human factors to changes in this lake region, and focuses entirely on Ebinur Lake. Other studies have assessed causes of the differences qualitatively (Sun and Gao, 2010; Yao et al., 2014; Zhang et al., 2015; Wang et al., 2017). Quantitative assessment of the relative importance of climate and human factors on lake changes could help to reduce the uncertainties associated with future projections of water availability in the region.

2.3 Methods

This study utilized both remote sensing and hydrological modeling. Remote sensing was used to derive observed lake area and water level as well as agriculture extent in the basins. Hydrologic modeling was used to simulate natural changes of the lakes without human impacts. Figure 2.3 shows the overall workflow of this study.

2.3.1 Observing lake changes using remote sensing

We used Landsat and MODIS imagery to derive lake area changes and satellite altimetry from ICESat and CryoSat to derive lake water level changes. We extracted lake area using the Normalized Difference Water Index (NDWI) and object-based image segmentation at multiple scales (Sheng et al., 2016). Table 2.1 lists the images used to derive lake areas.

The measured lake surface elevations were derived from ICESat and CryoSat products. We used the ICESat-derived inland water surface spot heights (IWSH) product from (O'Loughlin et al., 2016). The product was derived from the GLAS/ICESat GLA14 Global Land Surface Altimetry Data (Zwally et al., 2012). It contains surface water body heights from 2003 to 2009. The CryoSat product was derived from CryoSat-2 Level 1B SARIn data provided by the European Space Agency (ESA). We retracked the Level 1B waveform product using the algorithm proposed by Kleinherenbrink et al. (2014). The algorithm effectively reduces the effects of surrounding topography, which often contaminates the water surface elevation in the Level 2 ESA product.

The two products were then reconciled using lakes around Central Asia that have data from both products since they use different geodetic reference systems and contain various biases (Song et al., 2015). We selected ten lakes in Central Asia, including lakes in Tianshan, the Tibetan Plateau and other lowland regions for this purpose. We found a systematic bias between the ICESat-derived product and CryoSat derived-product, which we removed for Sayram Lake and Ebinur Lake.

We interpolated the lake area and water level records temporally to obtain coincident lake area and water level measurements which we then used to construct the lake hypsometry. We used the hypsometry curve to produce a historical records of lake changes since the 1980s, including lake volume change time series. The volume change between two time periods was calculated as:

$$\Delta V = \frac{(h1 - h2) \times (A1 + A2)}{2}$$

where h1, h2, A1, A2 are the lake level and area measurements at time 1 and 2 respectively.

2.3.2 Modeling lake changes using the Variable Infiltration Capacity (VIC) model

We used the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) to simulate changes in lake storage under natural conditions (i.e., absent extractions for uses such as irrigation). VIC is a physically based semi-distributed macroscale hydrology model. It has been applied in many different environments and spatial scales ranging from 1/16th degree to 2 degree (e.g., Nijssen et al., 2001; Livneh et al., 2013; Xiao et al., 2016). Bowling and Lettenmaier (2010) extended the model to include a lake and wetland algorithm, which is a key feature that makes the model suitable for this study. The lake and wetland algorithm treats all water bodies within a grid cell as one effective lake that exchanges water with its surrounding wetland. A wetland in this context is the land surrounding a lake that is periodically flooded and dried as the lake expands and contracts. The lake and wetland receives runoff from the surrounding land. As the lake expands, it first saturates the soil in the wetland and then the lake extent is updated based on the lake's depth-area relationship. Excess lake water discharges into the channel as a function of the water level.

The algorithm has been shown to successfully capture the delay of streamflow in an arctic environment caused by lakes and wetlands and to reproduce the seasonality of saturated area surrounding lakes (Bowling and Lettenmaier, 2010). It was also applied to reconstruct changes in Lake Chad, including a multi-decadal reduction in storage initiated by the Sahel drought of the 1980s and extended by long-term increases in irrigation of the surrounding areas (Gao et al., 2011).

2.3.2.1 Precipitation data processing

Precipitation generally is acknowledged to be the most important forcing variable for hydrologic models. However, high quality spatially-gridded precipitation data are not available in regions like Central Asia where meteorological stations are lacking. Here, we circumvented this issue by using output from the Weather Research and Forecasting (WRF) model (Gao et al., 2015), adjusted with limited station to create a model forcing data set. The workflow used in production of the data set is shown in Figure 2.4.

We first resampled the gridded precipitation output from WRF, which is for the period from 1979 through 2011, from its native 30-km spatial resolution to 1/4 degrees. The basin contains 131 cells after resampling. We then aggregated the data temporally into monthly averages. For months from April to September when precipitation rates are high especially in the mountains, we divided the grid cells to two groups to better capture precipitation variability at higher altitudes (Figure 2.5). We plotted the monthly averages for each grid cell against the cell's average elevation to obtain empirical precipitation lapse rates for the entire basin (Figures 2.6 to 2.16). These lapse rates are then used in conjunction with station values to develop adjustments to the WRF-derived precipitation fields.

There are three precipitation gauges in the basin that collected daily data for the period from 1951 to 2010. We used these estimates to adjust each grid cell's values to a fixed elevation (1,000 m) based on the corresponding lapse rates. We then extrapolated the monthly averages from the gauges to all 131 grid cells within the basin. Finally, we adjusted these values back to the grid cells' original elevation using the lapse rates calculated from the WRF data set. As a final step, we disaggregated the monthly grid cell values to daily based on the day to month proportions from the WRF data set. The comparison between the final precipitation data set and the WRF data set is shown in Figure 2.17.

2.3.2.2 Model setup

We set up the model to run at 1/4 degree spatial resolution. We took model input parameters such as elevation, soil and vegetation parameters from Nijssen et al. (2014). Meteorological forcings (including daily max/min temperature and wind speed) are the daily 0.25-degree records from 1948-2016 were from Sheffield et al. (2006). Creation of the precipitation forcing is described in the following section. We ran the model at a daily time step for the period 1979 to 2010. As implemented, the VIC model does not account for human water consumption. Therefore, the model simulations only represent natural changes in the lakes, that would have occurred absent, for instance, diversion of inflows for irrigation.

The model implementation for both Sayram and Ebinur lakes consists of two steps. In the first step the lake is not simulated, rather runoff is generated for all grid cells within the lake basins respectively. The resulting streamflow is then computed and fed into the second step (as lake inflow) along with other forcings to simulate the lake water and energy balances.

We estimated model parameters for Sayram Lake by comparing the predicted and observed lake areas (the latter from remote sensing). There has been relatively little human disturbance in the Sayram Lake basin in recent decades, so observed changes should be caused almost entirely by natural climate variability. On the other hand, we did not attempt to calibrate model parameters for Ebinur Lake, since the observed changes are likely associated with both natural variability and human influence. We used the default parameters from Nijssen et al., (2014) instead.

2.3.3 Agriculture changes

Agricultural land in the basins has mostly been converted from grass/barren through irrigation (Wang et al., 2017). There are significant changes of normalized difference vegetation index (NDVI) between grass/barren land and agricultural land that are apparent from satellite imagery. We estimated these changes quantitatively using the Terra MODIS NDVI time series data (Didan, 2015). The data set is a 16-day composite at 250 m spatial resolution for the period 2000 through 2017. To measure the expansion of agriculture in the region, we used a simple thresholding technique based on the annual mean NDVI as in Rembold and Maselli (2006). A pixel is considered to be agricultural if its annual mean NDVI value is greater than 0.25 and abandoned if the value falls below 0.25. We evaluated the results through manual inspection using Google Earth high resolution imagery. From our results, we evaluated the yearly extent and expansion rate of agricultural land within the two basins from 2000 through 2017.

2.4 Results

Observed and modeled lake changes are presented and compared for both lakes. Agriculture changes in the Ebinur Lake basin are also presented to provide context for changes in Ebinur Lake.

2.4.1 Observed lake changes

Sayram Lake and Ebinur Lake have experienced different patterns of area and water level changes in recent decades (Figures 2.18 and 2.19). Sayram Lake expanded more or less steadily since the 1970s. Its area increased from 453 km^2 to 462 km^2 (~2%) between 1977 and 2016 and its water level increased about 1.5 m between 2004 and 2018. Ebinur Lake, in contrast, experienced more fluctuation since the 1990s. Its area increased from 550 km^2 to 950 km^2 (45%) between 1990 and 2003 and declined to 600 km^2 (25%) in 2016. The water level decreased 2.5 m between 2004 and 2018.

The hypsometry curves of the two lakes constructed based on coincident lake area and water level measurements are shown in Figure 2.20. We used a linear relationship to describe the hypsometry. The correlation coefficients were around 0.6 for both lakes and root mean square errors (RMSEs) for the lake levels are around 0.13 m. The volume changes of the two lakes reconstructed based on the hypsometry curves are shown in Figure 2.21. Sayram Lake had a volume increase of about 0.5 km^3 since 1970s. Ebinur Lake experienced a dramatic increase of about 0.2 km^3 between 1999 and 2003 and declined to pre-1999 volumes in 2010. It increased again since 2010 by about 0.35 km^3.

2.4.2 Modeled lake changes

The comparison between modeled and observed volume changes are shown in Figures 2.22 and 2.23. Both lakes had similar trends in modeled and observed volume changes. Model results for Sayram Lake had an overall increasing trend as in the observations but the model volumes had greater inter-annual as well as intra-annual variability. For example, the modeled volume remained relatively constant between 1989 and 2002 but increased dramatically between 2002 and 2005. It remained relatively steady since 2005 as well. The modeled results showed up to 0.3 km^3 of intra-annual variability while the observed show less than 0.1 km^3 though there were no year-round observations. The model showed a greater overall increase in volume (i.e., 0.35 km^3) between 1989 and 2016 than the observations (0.25 km^3).

The modeled volume changes for Ebinur Lake had a much larger intra- and inter-annual variability compared to the observed as well. The lake volume had a decreasing trend between 1990 and 2001 of 0.35 km^3. It increased between 2001 and 2003 by 0.7 km^3 and declined again 2003 and 2010 by 0.55 km^3. Even without considering irrigation, the model showed a decline of 0.2 km^3 between 1990 and 2010 while the observed volumes remained rather steady.

2.4.3 Agriculture changes

Agriculture extent increased steadily since 2000 (Figure 2.24). Over 8,700 km^2 (16.7% of the basin area) were converted to agriculture in 2017, more than doubling the 2000 irrigated area of around 4,000 km^2. In contrast, the Sayram basin had no agriculture at all. The conversion from barren and grassland to agriculture started near river channels and gradually expanded to less and less fertile regions (Figure 2.24). This is similar to agriculture expansion patterns seen elsewhere in Central Asia (Karimov, 1995; Pankova, 1996). As a result, soils suffer from salinization in many parts of Central Asia (Pankova, 1996). Water use efficiency declines as additional water is needed to flush salts in the soil and fill pore spaces in the drier soils (Micklin, 2000). Nevertheless, drip irrigation has been adopted in Xinjiang since the late-1990s which drastically improves water use efficiency (Xu et al., 2003).

2.5 Discussion

The limitations of methods used in the study are discussed. They include limitation of volume change estimation from both remote sensing and hydrologic modeling as well as the uncertainty of agriculture extent estimation. Finally, the implications of the findings for water resources in Xinjiang are discussed as well.

2.5.1 Limitations of methodology

Limitations of the methodology mainly consist of the uncertainties of the lake hypsometry derived from remote sensing observations as well as the precipitation data set that forces the VIC model.

2.5.2 Volume change estimation from remote sensing

The reliability of volume change estimation from remote sensing depends on the accuracy of lake hypsometry curves constructed from coincident area and water level observations. While lake area changes estimated from satellite imagery have fairly low uncertainty (~2%), the water level changes are more uncertain because satellite altimetry (especially CryoSat) is affected by the surrounding topography even after retracking. The standard deviation for the CryoSat retracking algorithm is about 0.1 m while the range of elevation change for Sayram Lake over 15 years is about 1 m.

Moreover, the dates of area and water level observation rarely coincide. While the water level observations are more frequent, there is usually a few days to two weeks of difference to the closest area observation. Area and water level observations are matched to the closest dates as long as the time difference is less than 15 days. As a result, there is a small range of area and water level difference in the hypsometry curves especially for Sayram Lake (Figure 2.20). The uncertainty in the volume change estimates ranges from 0.035 to 0.12 km^3.

2.5.3 Volume change estimation from modeling

Precipitation is the primary forcing driving the results of volume change estimation in the model. While the best available precipitation data sets were gathered and reprocessed to obtain a gauge-based gridded precipitation data set for the basins, we were unable to verify the accuracy of the reprocessing results other than at the small number of precipitation gauges (and even this is complicated by the fact that the in situ observations were used in the adjustment process). Moreover, the model requires a lake hypsometry profile in order to calculate the lake area from its water balance. The hypsometry curves obtained from remote sensing were used for both lakes which contains some uncertainty. Finally, there is no observed data that can be used to evaluate the modeled results for Ebinur Lake inflows.

2.5.4 Agriculture changes

We empirically identified agricultural lands as having mean annual NDVI of greater than 0.25. We inspected the delineations visually and removed non-agricultural lands such as forests manually. Nevertheless, there is uncertainty associated with the inspection process as well as the Google Earth imagery used to validate the results for each year from 2000 to 2017.

2.6 Implications for water resources in Central Asia

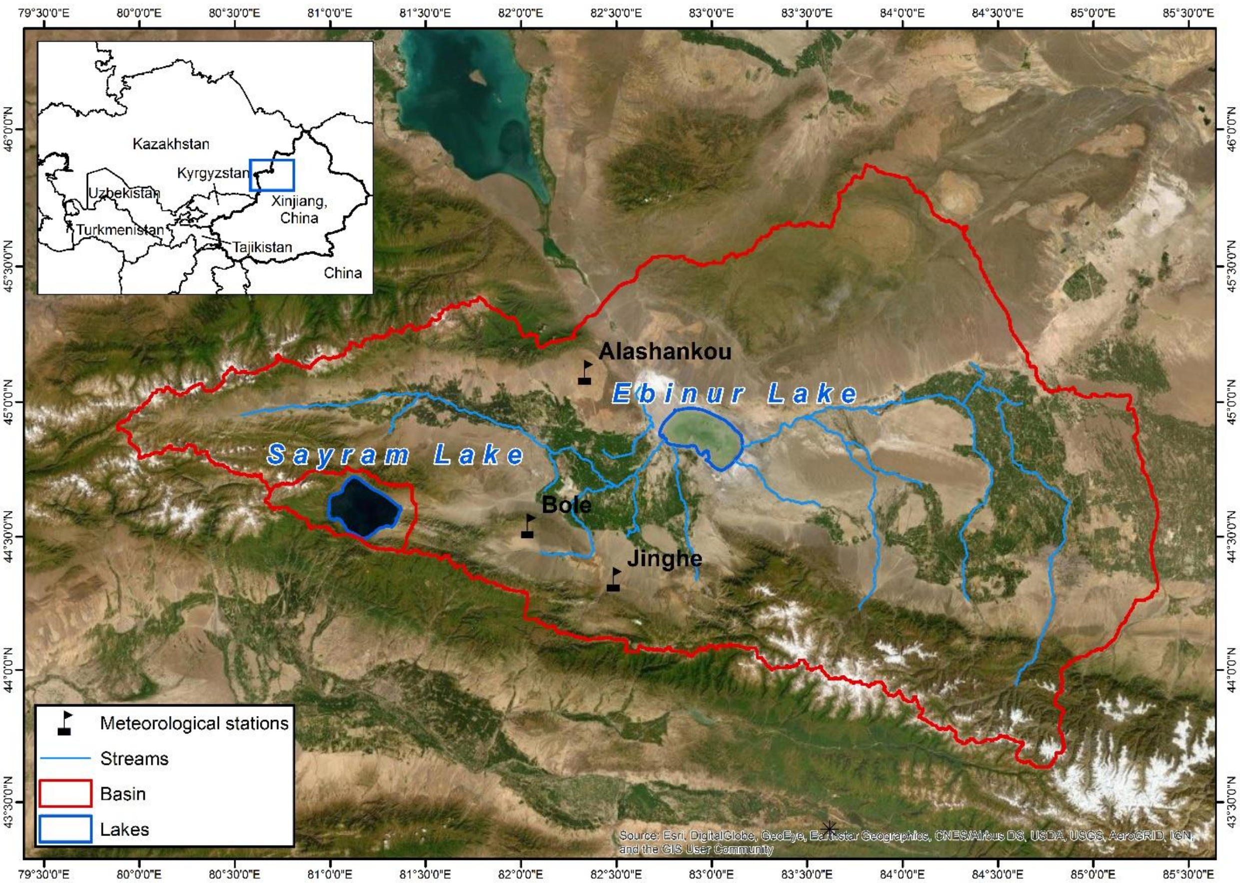
The steady expansion of Sayram Lake is consistent with limited previous studies. Cheng et al. (2016) found that, between 1972 and 2011, the lake area expanded 12 km^2, the water level increased 2.8 m and its volume increased 1.3 km^3. Our observed lake area, water level and volume change are 8.5 km^2, 1.9m and 0.4 km^3 respectively between 1972 and 2016. This is likely because of the different lake hypsometry profiles used to estimate the volume changes. The results for Sayram Lake revealed by both satellite observations and hydrologic modeling as well as observed precipitation over the past decades suggest that the north slope of Tianshan in northwestern Xinjiang is getting wetter. This expansion of Sayram Lake is likely caused by the increase of precipitation and melting of glaciers as a result of increased temperature in the mountain region (Shi et al., 2007; Chai et al., 2013; Wang et al., 2014; Wang et al., 2016). This suggests that the climate is getting wetter in the region. It also supports the hypothesis that the climate in northwestern China is switching from warm-dry to warm-wet (Shi et al., 2007), at least in the mountain region.

Nevertheless, results from Ebinur Lake which lies in the lowlands show that there is not much change in lake volume even under natural conditions. The observed changes of the lake area and water level follow a similar pattern as the modeled natural changes. It suggests that, while agriculture area has been expanding, irrigation water consumption has not changed much between 2000 and 2010 in Ebinur Lake basin. This is possibly related to the widely spreading adoption of drip irrigation in Xinjiang since the late-1990s which drastically improves water use efficiency compared to sprinkler irrigation that is commonly used prior (Xu et al., 2003). Su (2014) show that the adoption rate of drip irrigation increased from virtually none in 1996 to 60.95% in 2010 on lands cultivated by the Xinjiang Production and Construction Corps. The results also suggest that human water consumption in Ebinur Lake basin has come to an equilibrium with available water even under agriculture expansion. Contrary to common belief, changes in Ebinur Lake in the past two decades are more likely to have been caused by natural climate variability than increased water extraction due to agriculture expansion.

2.7 Conclusions

Water is a crucial resource in Xinjiang and its availability in the future under climate change has profound influence on the local ecosystem as well as the livelihood of the local residents. Here, we used remote sensing and hydrologic modeling to examine the changes of Sayram Lake and Ebinur Lakes in northwestern Xinjiang to reveal trends of water availability in the region. We found that the mountain region is getting wetter as evidenced by the continual expansion of Sayram Lake under little human influence.

We also found that the lowland region has experience little change in water availability in the past two decades as evidenced by the lack of trends in the observed lake volume changes. Ebinur Lake’s drastic decline between the 1950s and 1970s as shown in past studies is likely caused by large scale agriculture irrigation projects (Wang et al., 2003; Ma et al., 2014). The changes of Ebinur Lake in the recent two decades, however, are unlikely caused by agriculture expansion as evidenced by the consistent patterns between the modeled natural changes and observed changes in Ebinur Lake. This suggests that the local agriculture practices since the 1990s have greatly improved water use efficiency and Ebinur Lake has come to a new balance with available water in the basin at a smaller volume.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2.1: Ebinur Lake and Sayram Lake in Xinjiang, China.

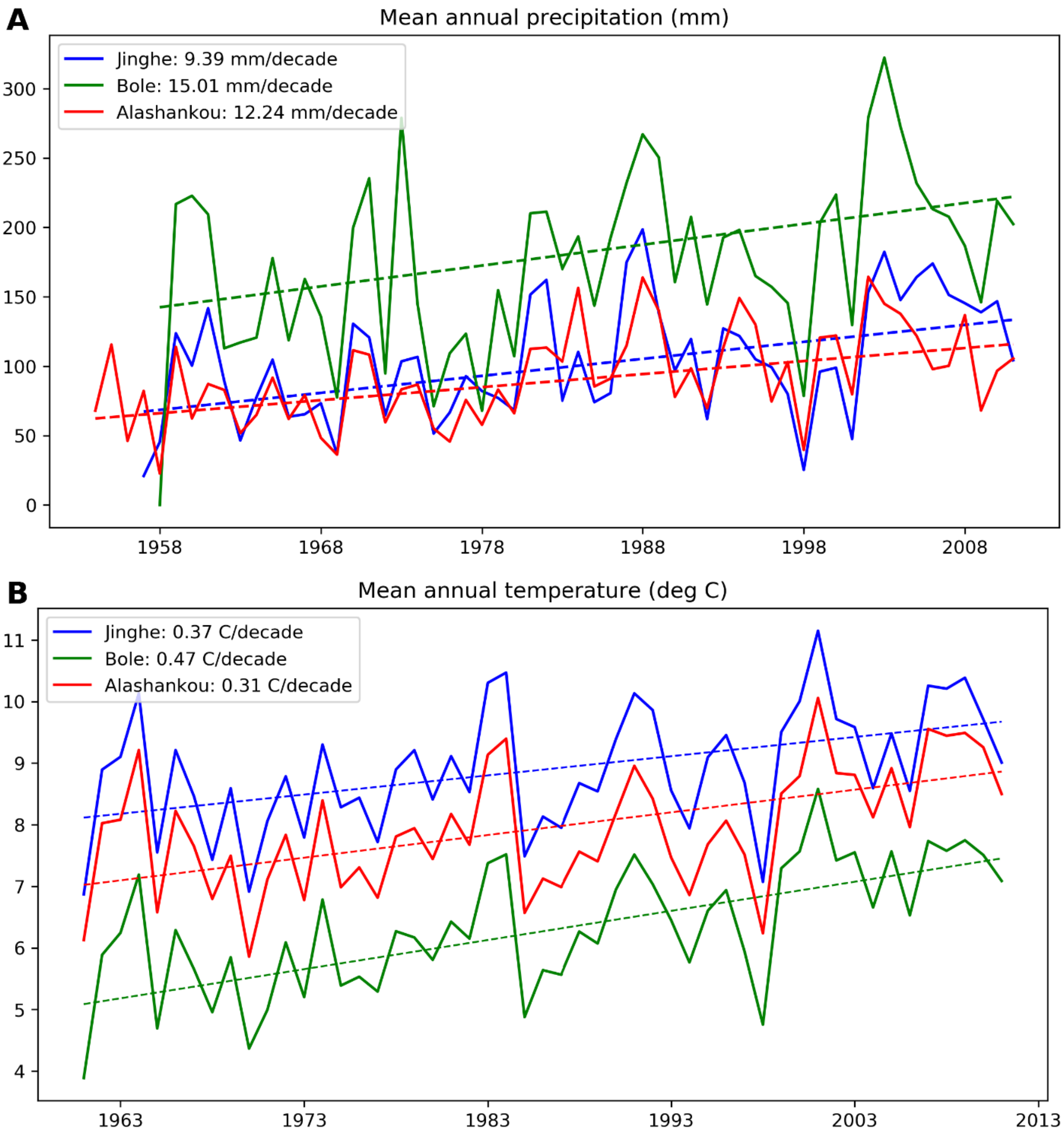


Figure 2.2: Mean annual precipitation (A) and Mean temperature precipitation (B) at three meteorological stations from the Chinese Meteorological Administration

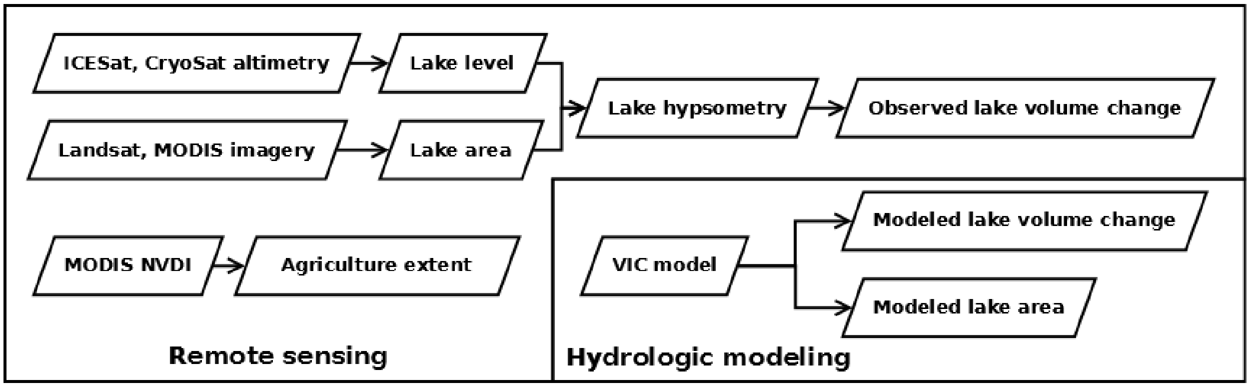


Figure 2.3: Workflow of the methodology

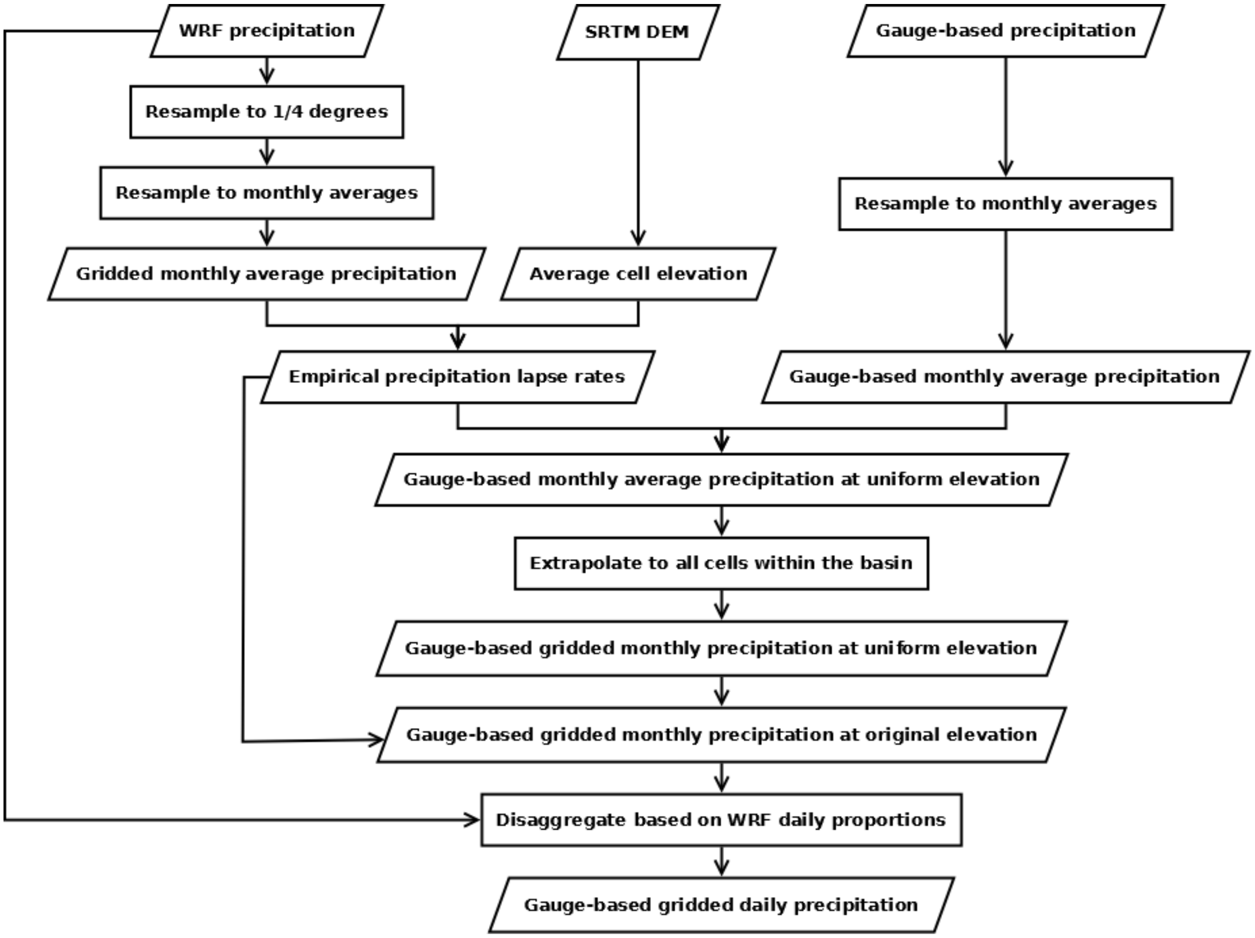
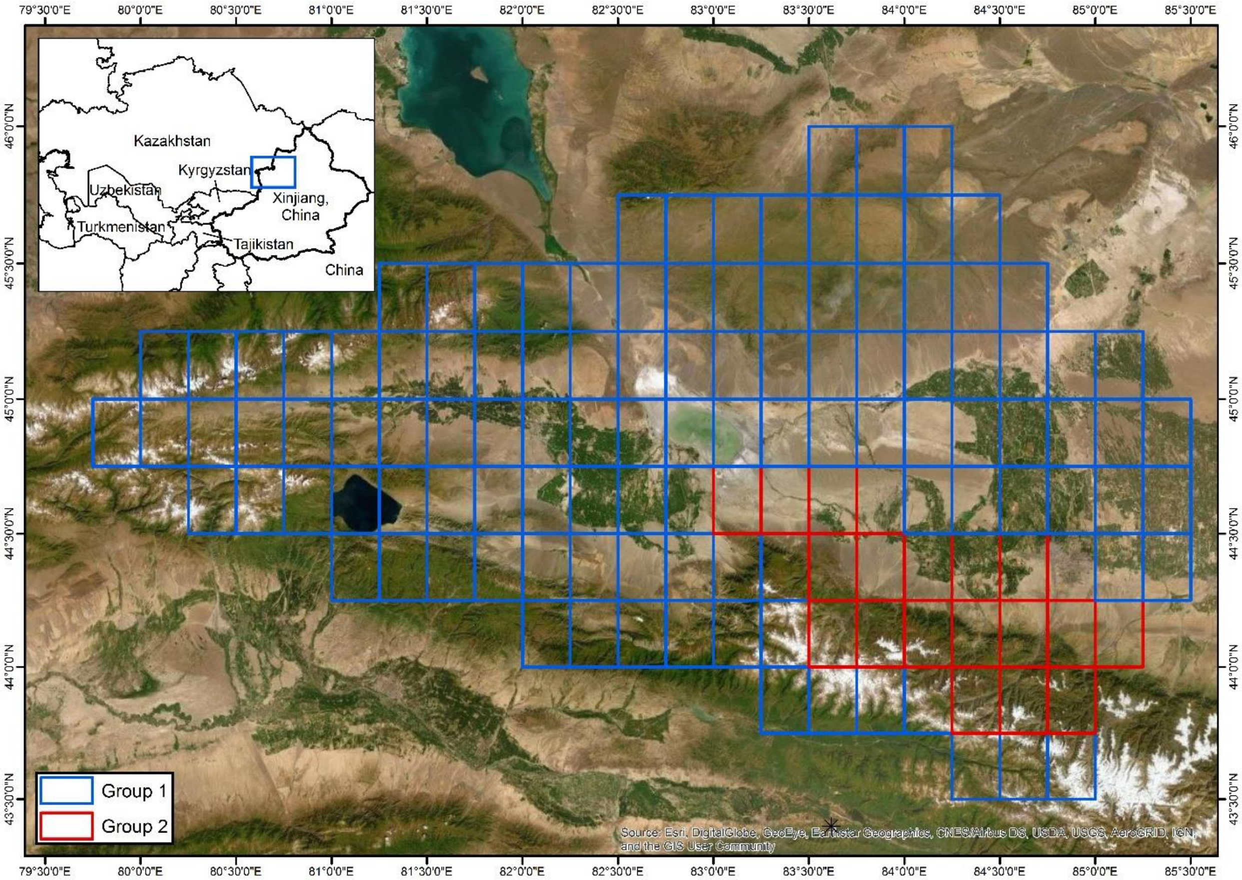


Figure 2.4: Workflow for precipitation data processing



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2.5: Grid cells used in the VIC model with red showing higher altitude grids.

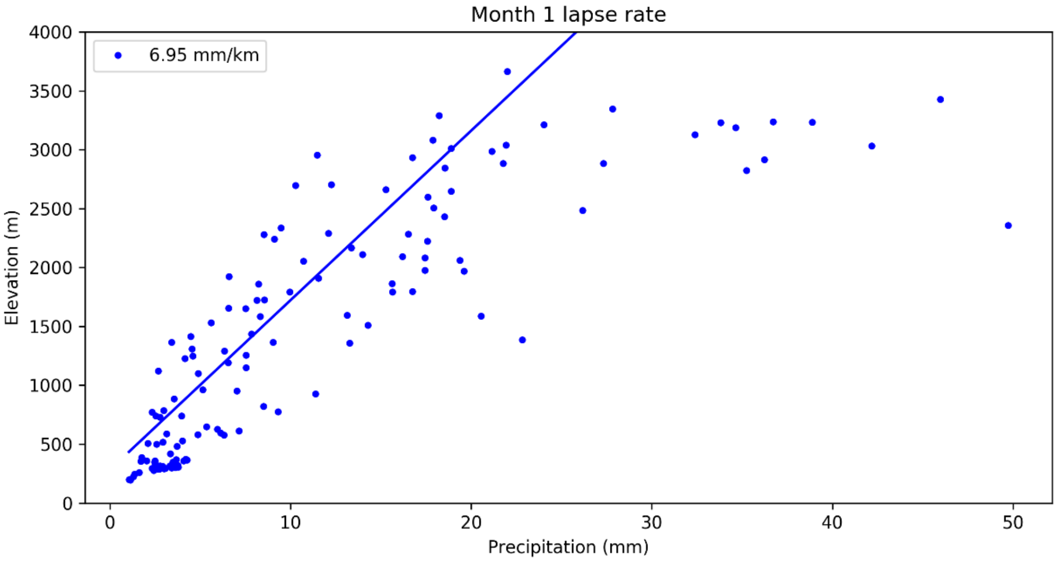


Figure 2.6: Precipitation lapse rate for January

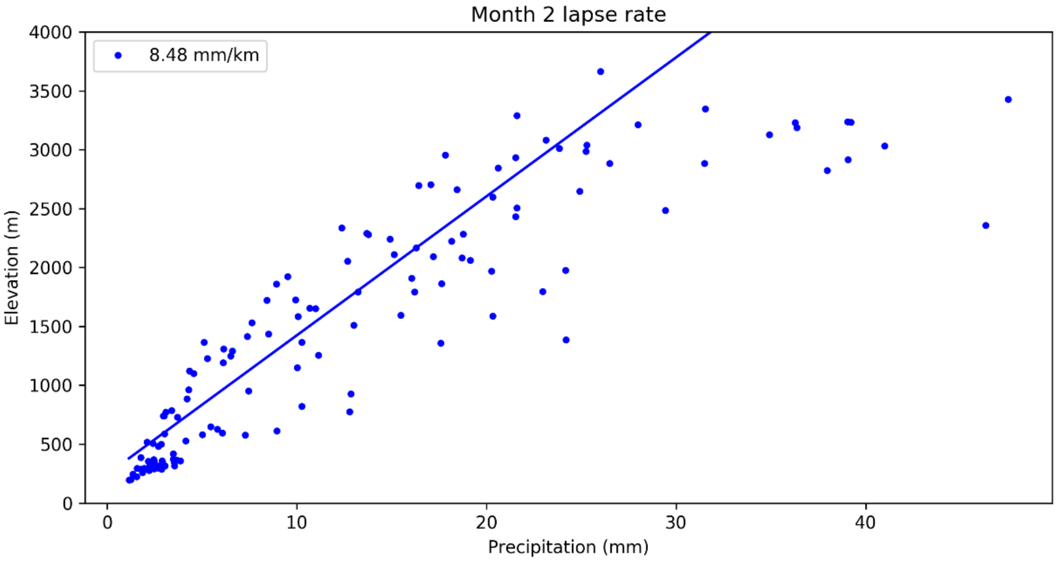


Figure 2.7: Precipitation lapse rate for February

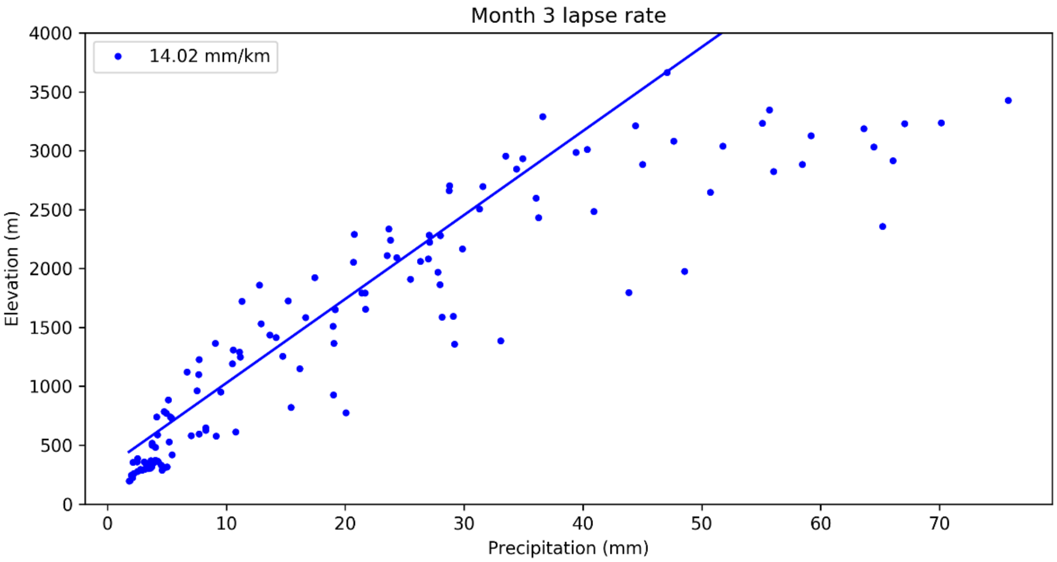


Figure 2.7: Precipitation lapse rate for March

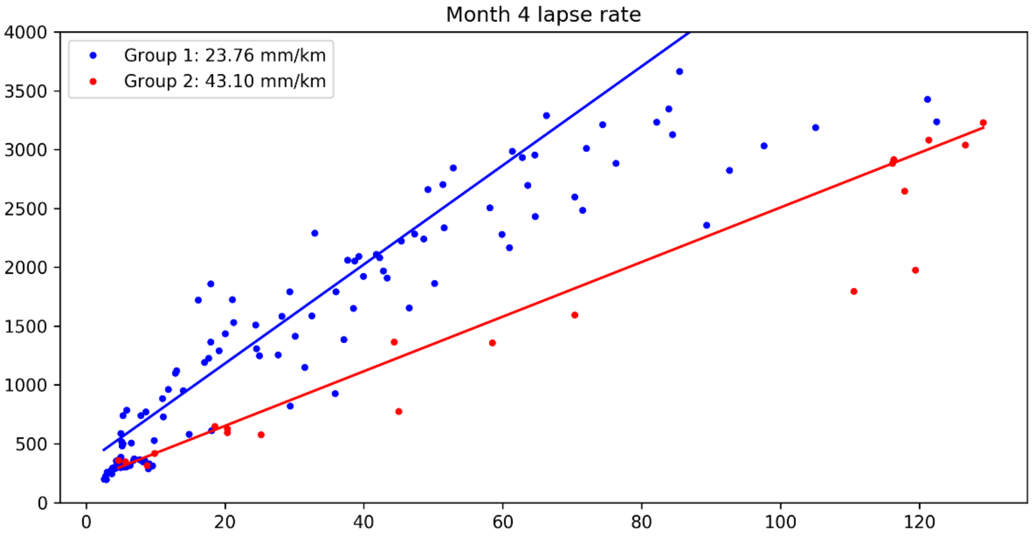


Figure 2.8: Precipitation lapse rates for April

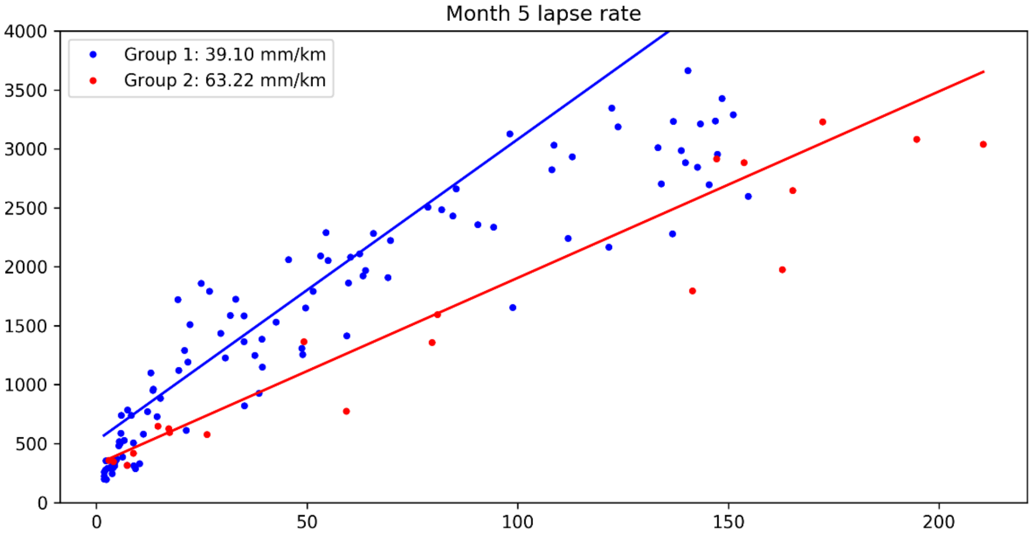


Figure 2.9: Precipitation lapse rates for May

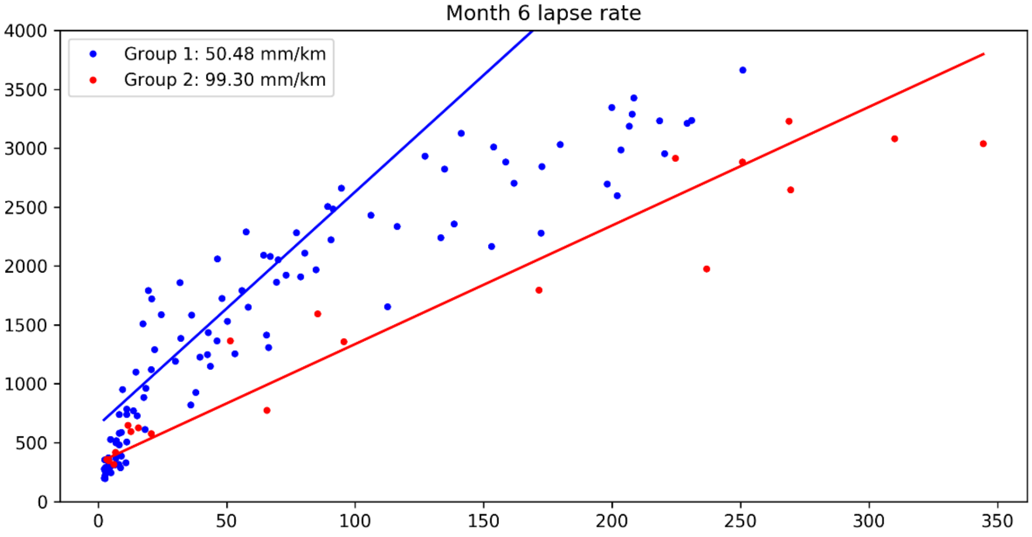


Figure 2.10: Precipitation lapse rates for June

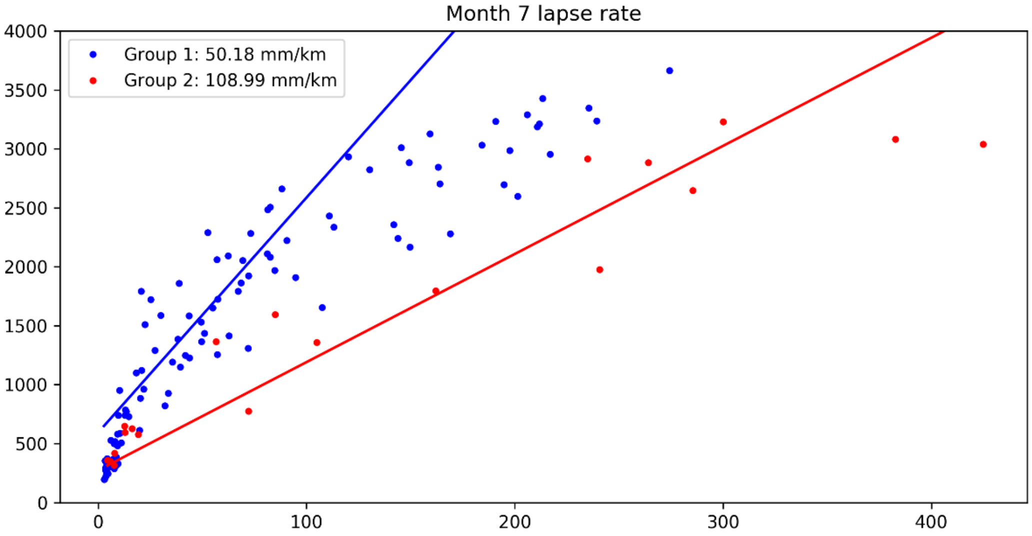


Figure 2.11: Precipitation lapse rates for July

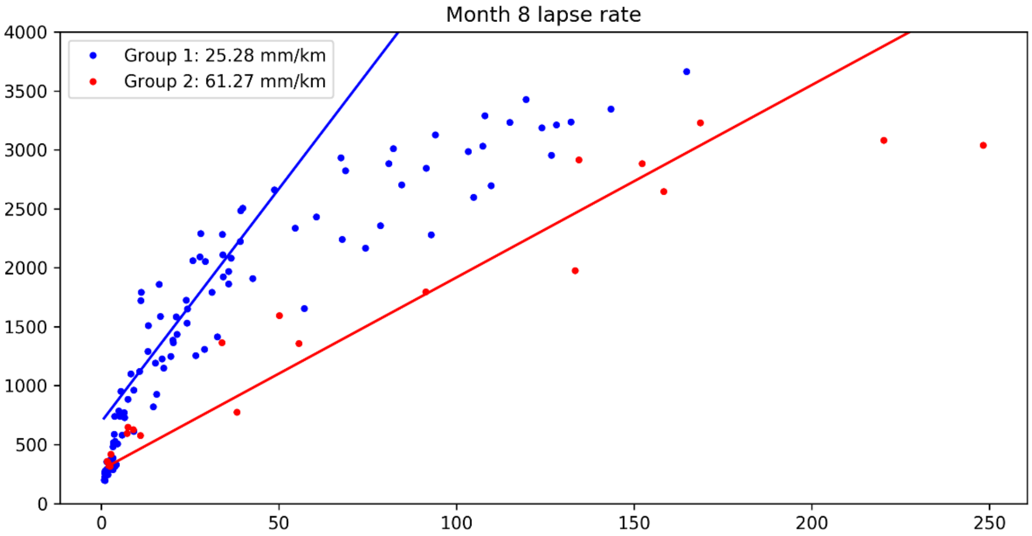


Figure 2.12: Precipitation lapse rates for August

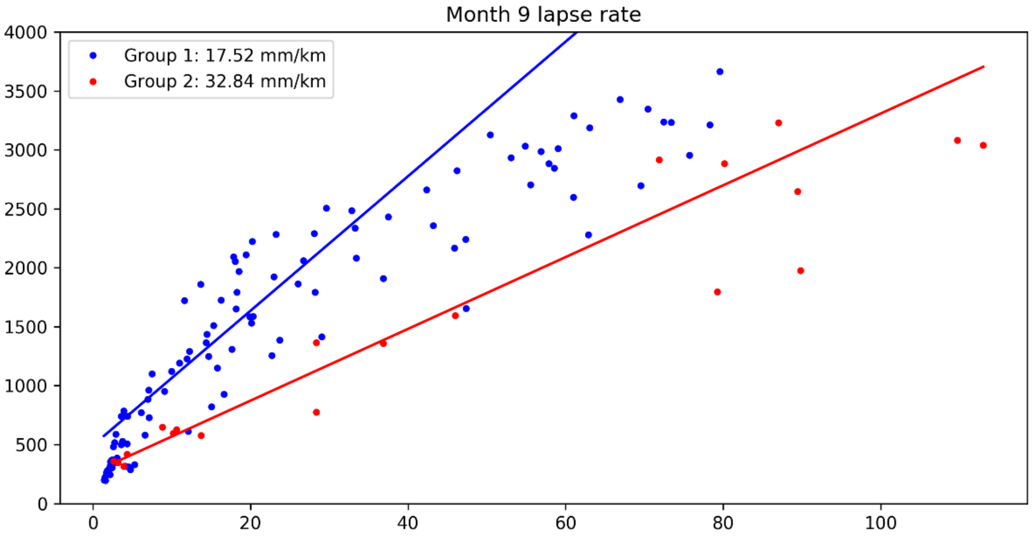


Figure 2.13: Precipitation lapse rates for September

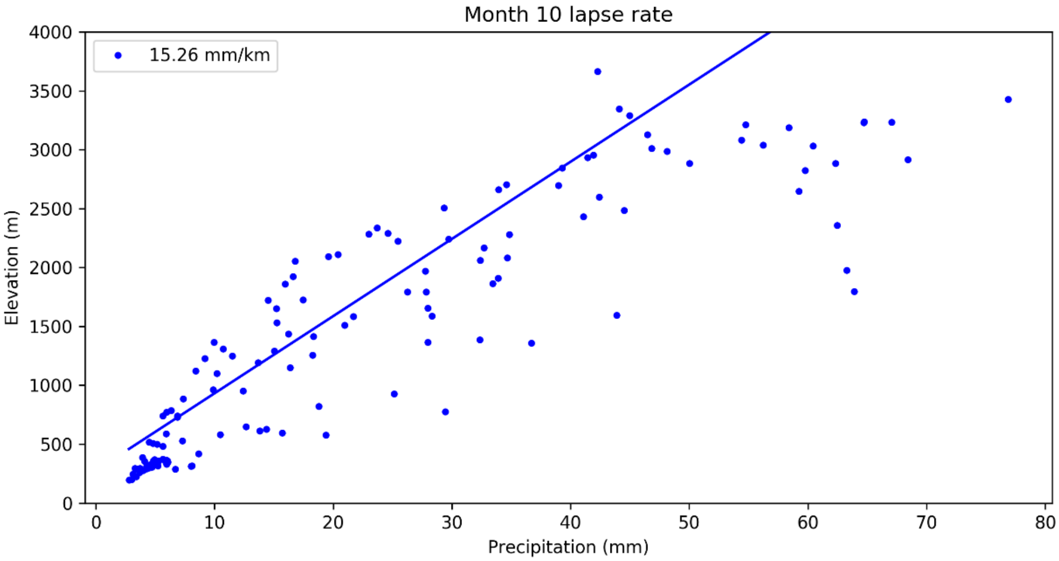


Figure 2.14: Precipitation lapse rate for October

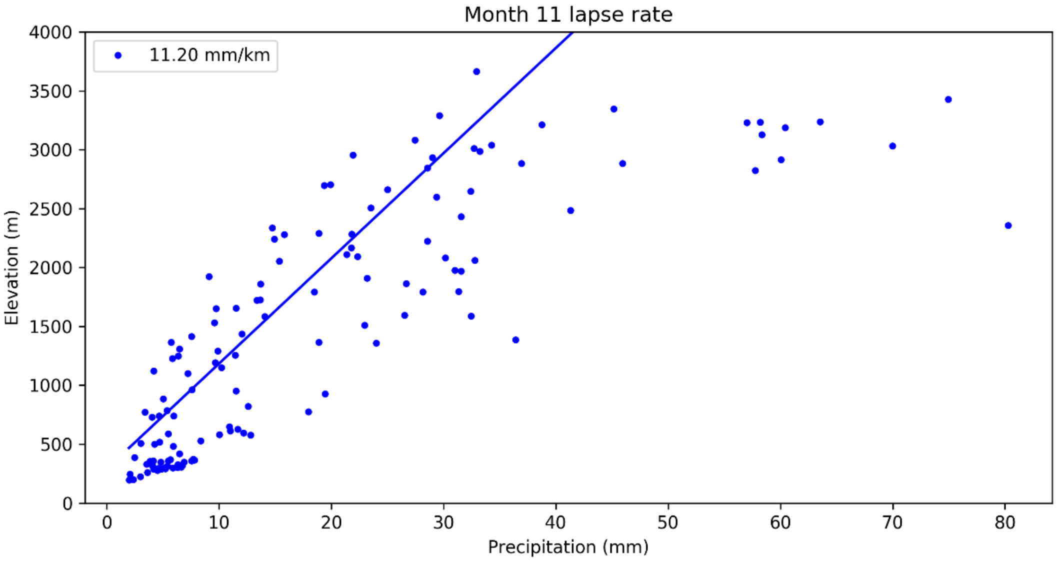


Figure 2.15: Precipitation lapse rate for November

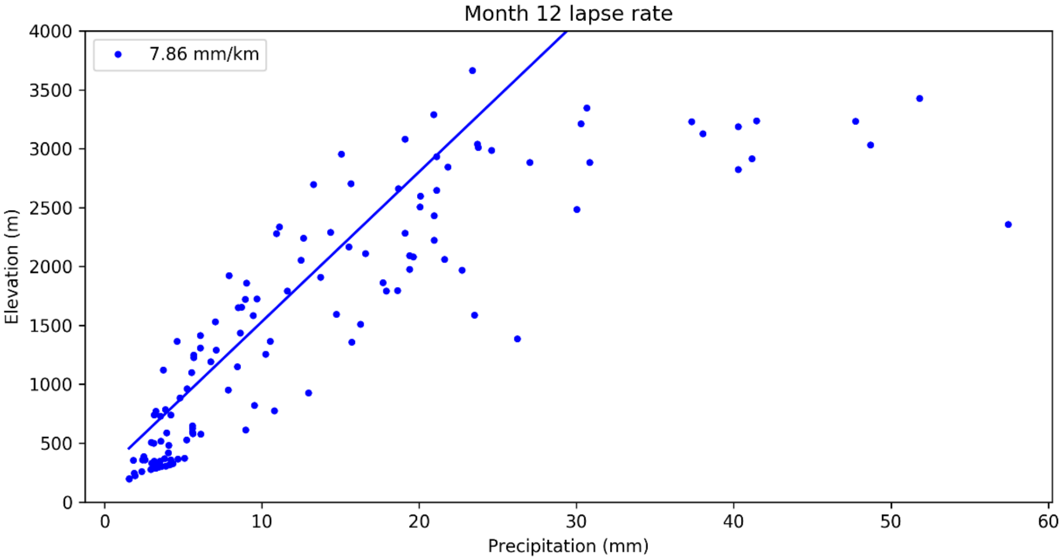


Figure 2.16: Precipitation lapse rate for December

Figure 2.17: Comparison between adjusted precipitation and WRF precipitation

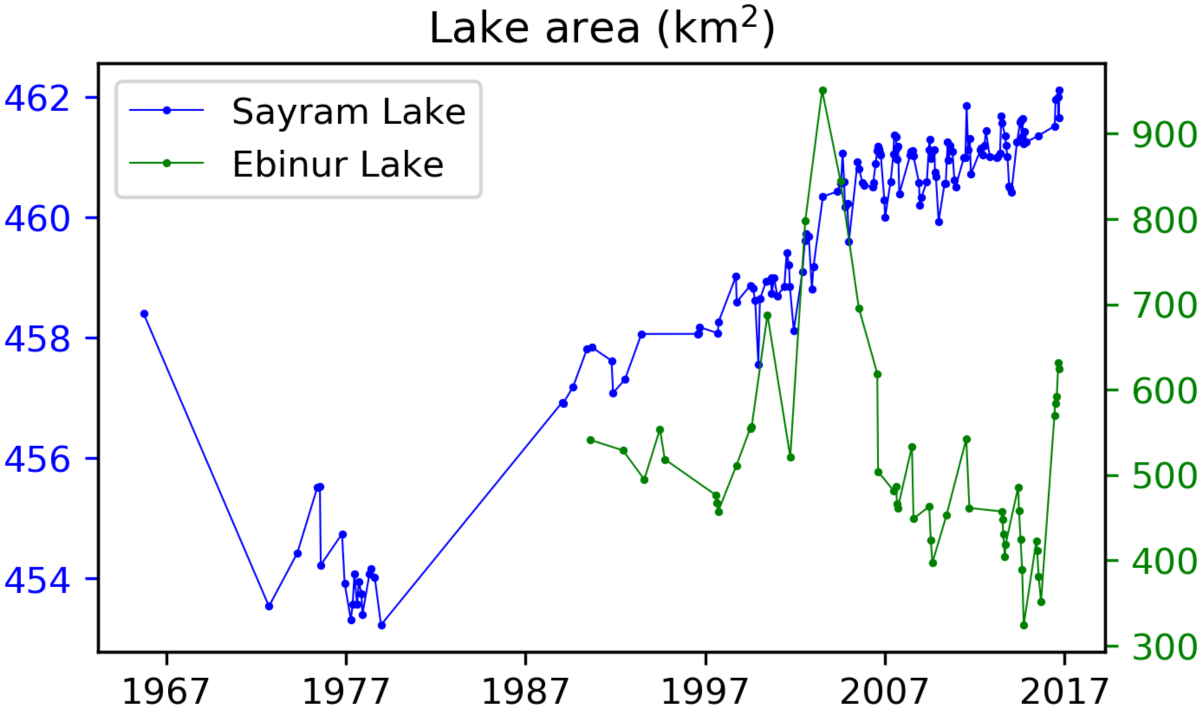


Figure 2.18: Area changes of Sayram and Ebinur Lakes from Landsat and MODIS imagery

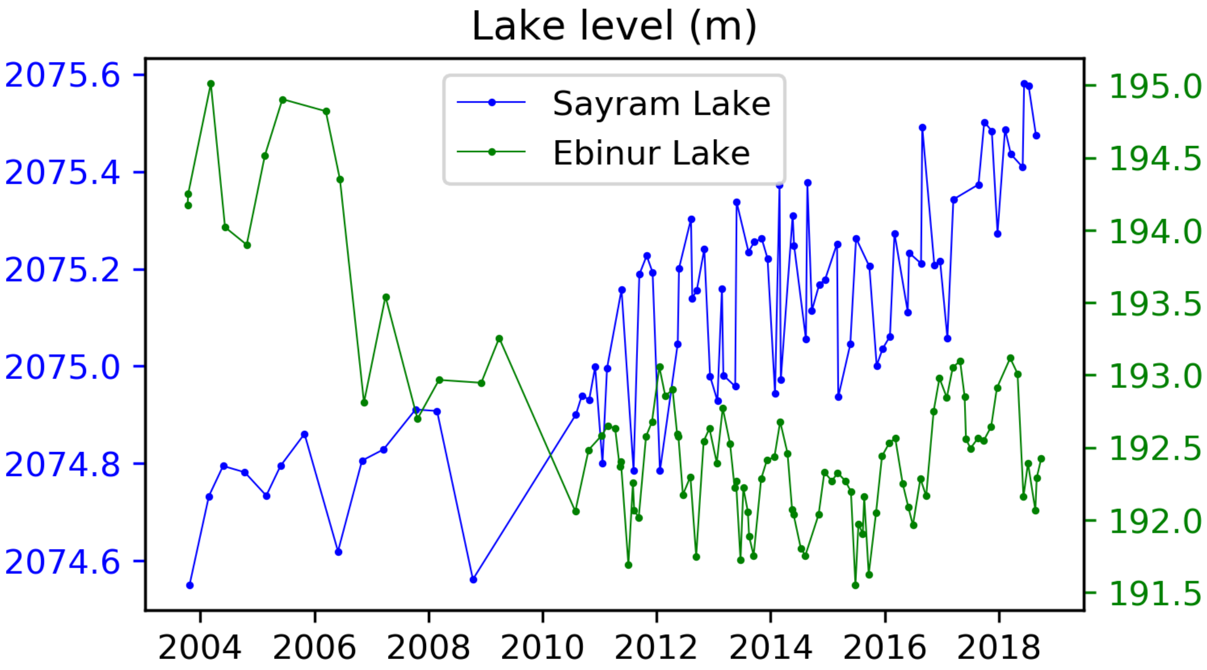


Figure 2.19: Water level changes of Sayram and Ebinur Lake from ICESat and CryoSat altimetry

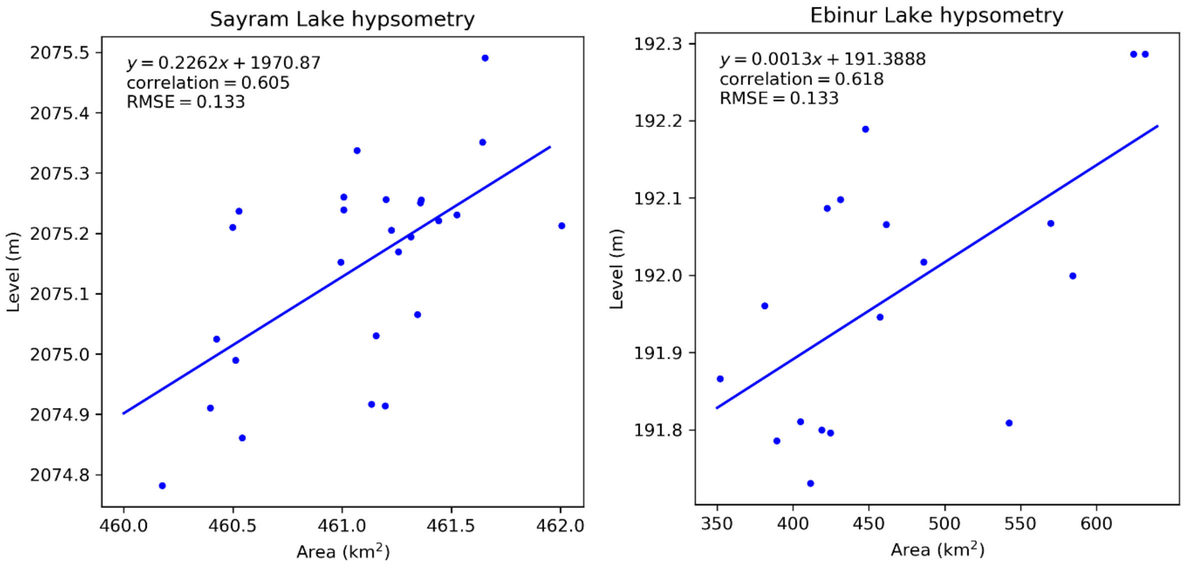


Figure 2.20: Hypsometry of Sayram and Ebinur Lakes

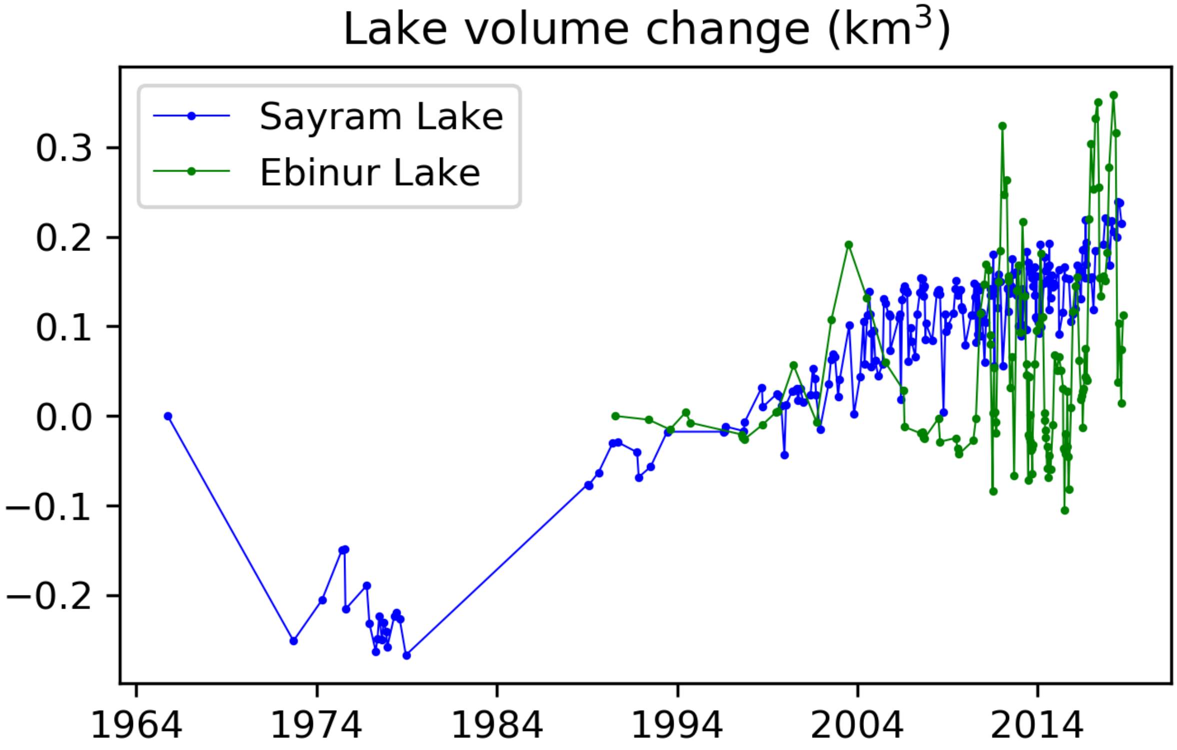


Figure 2.21: Volume changes of Sayram and Ebinur Lake derived from lake hypsometry

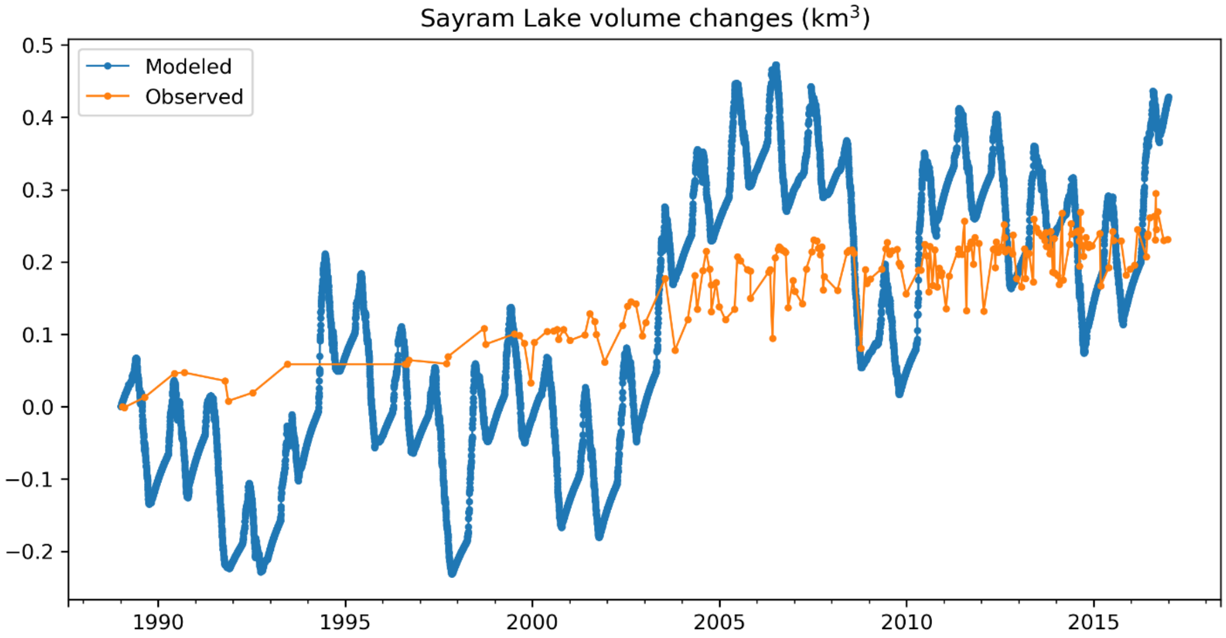


Figure 2.22: Comparison between modeled and observed volume changes of Sayram Lake

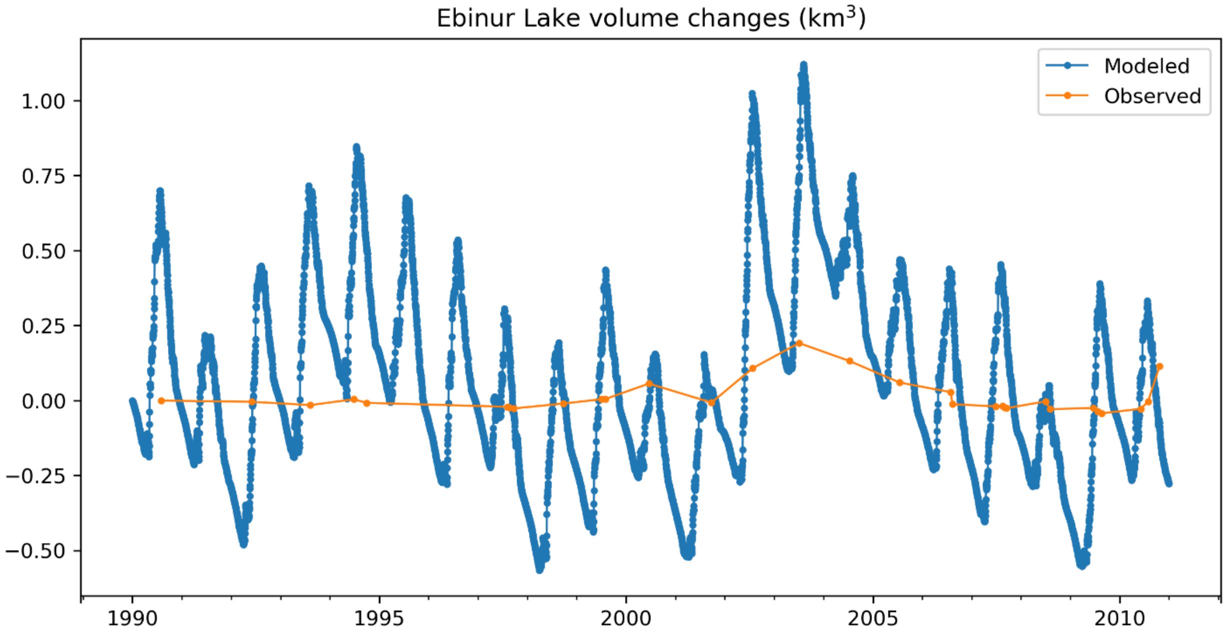


Figure 2.23: Comparison between modeled and observed volume changes of Ebinur Lake

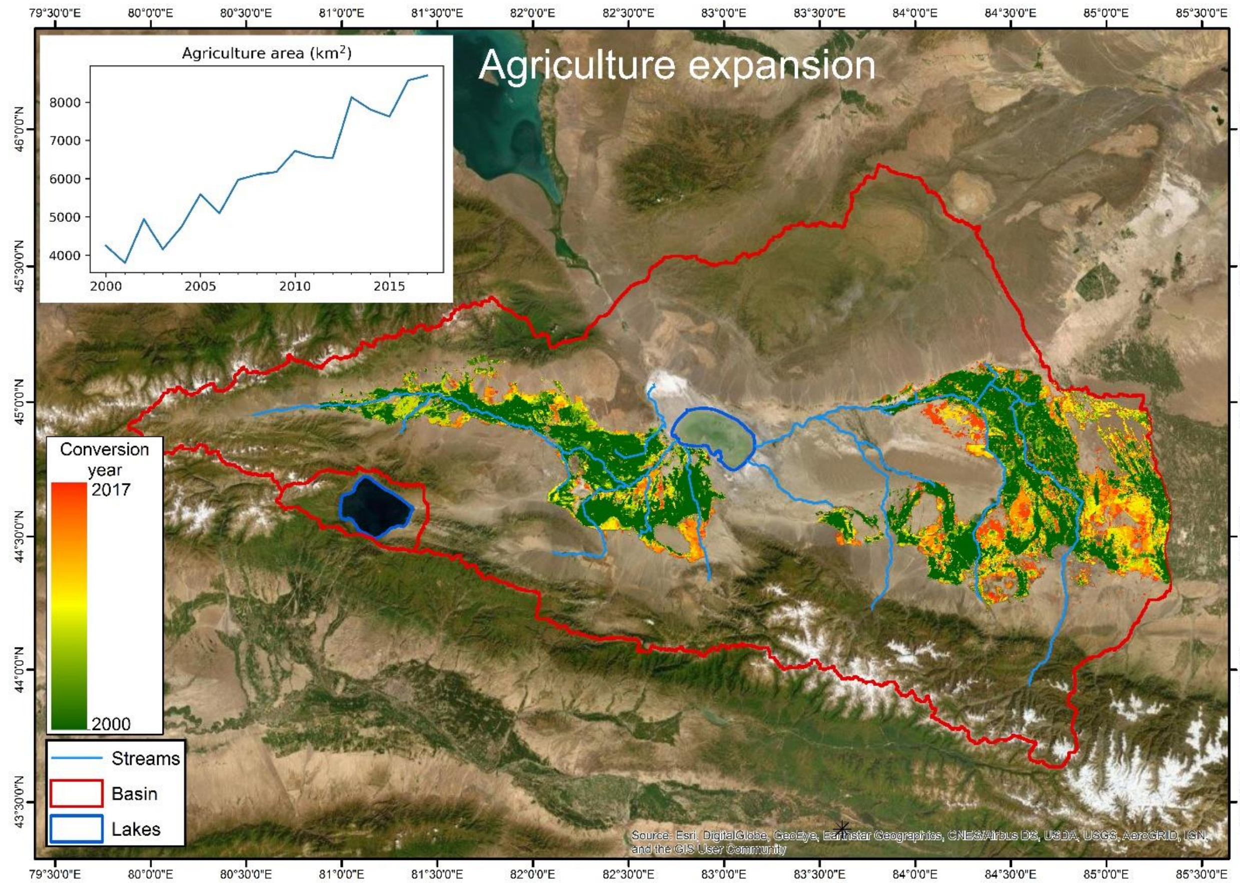


Figure 2.24: Annual agriculture expansion in Ebinur Lake basin from 2000 to 2017

Table 2.1: Summary of collected optical imagery

	Acquisition date	Sensor	Image ID
Sayram Lake	10/01/1965	Panoramic camera	Corona_19651001
	09/22/1972	Landsat 1 MSS	P158R029_LM1D19720922.dat
	04/21/1974	Landsat 1 MSS	P158R029_LM1D19740421.dat
	05/31/1975	Landsat 2 MSS	P158R029_LM2D19750531.dat
	07/24/1975	Landsat 2 MSS	P158R029_LM2D19750724.dat
	08/11/1975	Landsat 2 MSS	P158R029_LM2D19750811.dat
	10/16/1976	Landsat 2 MSS	P158R029_LM2D19761016.dat
	12/09/1976	Landsat 2 MSS	P158R029_LM2D19761209.dat
	04/14/1977	Landsat 2 MSS	P158R029_LM2D19770414.dat
	05/20/1977	Landsat 2 MSS	P158R029_LM2D19770520.dat
	06/25/1977	Landsat 2 MSS	P158R029_LM2D19770625.dat
	08/18/1977	Landsat 2 MSS	P158R029_LM2D19770818.dat
	09/23/1977	Landsat 2 MSS	P158R029_LM2D19770923.dat
	11/16/1977	Landsat 2 MSS	P158R029_LM2D19771116.dat
	12/04/1977	Landsat 2 MSS	P158R029_LM2D19771204.dat
	04/27/1978	Landsat 2 MSS	P158R029_LM2D19780427.dat
	06/02/1978	Landsat 2 MSS	P158R029_LM2D19780602.dat
	08/13/1978	Landsat 2 MSS	P158R029_LM2D19780813.dat
	12/17/1978	Landsat 2 MSS	P158R029_LM2D19781217.dat
	8/22/1989	Landsat 5 TM	P147R029_LT5D19890822.JP2
	6/6/1990	Landsat 5 TM	P147R029_LT5D19900606.JP2
	7/13/1992	Landsat 5 TM	P147R029_LT5D19920713.JP2
	6/14/1993	Landsat 5 TM	P147R029_LT5D19930614.JP2
	8/9/1996	Landsat 5 TM	P147R029_LT5D19960809.JP2
	8/25/1996	Landsat 5 TM	P147R029_LT5D19960825.JP2
	9/10/1996	Landsat 5 TM	P147R029_LT5D19960910.JP2
	9/13/1997	Landsat 5 TM	P147R029_LT5D19970913.JP2
	9/29/1997	Landsat 5 TM	P147R029_LT5D19970929.JP2
	7/9/1999	Landsat 7 ETM+	P147R029_LE7D19990709.JP2
	8/26/1999	Landsat 7 ETM+	P147R029_LE7D19990826.JP2
	7/27/2000	Landsat 7 ETM+	P147R029_LE7D20000727.JP2
	8/28/2000	Landsat 7 ETM+	P147R029_LE7D20000828.JP2
	9/13/2000	Landsat 7 ETM+	P147R029_LE7D20000913.JP2
	7/14/2001	Landsat 7 ETM+	P147R029_LE7D20010714.JP2
	9/16/2001	Landsat 7 ETM+	P147R029_LE7D20010916.JP2
	7/17/2002	Landsat 7 ETM+	P147R029_LE7D20020717.JP2
	8/18/2002	Landsat 7 ETM+	P147R029_LE7D20020818.JP2
	8/5/2006	Landsat 5 TM	P147R029_LT5D20060805.JP2
	8/21/2006	Landsat 5 TM	P147R029_LT5D20060821.JP2
	9/6/2006	Landsat 5 TM	P147R029_LT5D20060906.JP2
	9/22/2006	Landsat 5 TM	P147R029_LT5D20060922.JP2
	6/21/2007	Landsat 5 TM	P147R029_LT5D20070621.JP2
	7/7/2007	Landsat 5 TM	P147R029_LT5D20070707.JP2
	8/8/2007	Landsat 5 TM	P147R029_LT5D20070808.JP2
	8/24/2007	Landsat 5 TM	P147R029_LT5D20070824.JP2
	9/9/2007	Landsat 5 TM	P147R029_LT5D20070909.JP2
	6/26/2009	Landsat 5 TM	P147R029_LT5D20090626.JP2
	8/13/2009	Landsat 5 TM	P147R029_LT5D20090813.JP2
	9/30/2009	Landsat 5 TM	P147R029_LT5D20090930.JP2
	7/15/2010	Landsat 5 TM	P147R029_LT5D20100715.JP2

	8/16/2010	Landsat 5 TM	P147R029_LT5D20100816.JP2
	7/18/2011	Landsat 5 TM	P147R029_LT5D20110718.JP2
	8/19/2011	Landsat 5 TM	P147R029_LT5D20110819.JP2
	9/20/2011	Landsat 5 TM	P147R029_LT5D20110920.JP2
	6/21/2013	Landsat 8 OLI	P147R029_LC8D20130621.JP2
	9/9/2013	Landsat 8 OLI	P147R029_LC8D20130909.JP2
	9/25/2013	Landsat 8 OLI	P147R029_LC8D20130925.JP2
	7/10/2014	Landsat 8 OLI	P147R029_LC8D20140710.JP2
	7/26/2014	Landsat 8 OLI	P147R029_LC8D20140726.JP2
	8/11/2014	Landsat 8 OLI	P147R029_LC8D20140811.JP2
	8/27/2014	Landsat 8 OLI	P147R029_LC8D20140827.JP2
	9/12/2014	Landsat 8 OLI	P147R029_LC8D20140912.JP2
	7/13/2015	Landsat 8 OLI	P147R029_LC8D20150713.JP2
	6/13/2016	Landsat 8 OLI	P147R029_LC8D20160613.JP2
	6/29/2016	Landsat 8 OLI	P147R029_LC8D20160629.JP2
	8/16/2016	Landsat 8 OLI	P147R029_LC8D20160816.JP2
	9/1/2016	Landsat 8 OLI	P147R029_LC8D20160901.JP2
	9/17/2016	Landsat 8 OLI	P147R029_LC8D20160917.JP2
Ebinur Lake	6/26/1994	Landsat 5 TM	P146R029_LT5D19940626.JP2
	9/30/1994	Landsat 5 TM	P146R029_LT5D19940930.JP2
	8/5/1997	Landsat 5 TM	P146R029_LT5D19970805.JP2
	8/21/1997	Landsat 7 ETM+	P146R029_LT5D19970821.JP2
	9/22/1997	Landsat 7 ETM+	P146R029_LT5D19970922.JP2
	9/25/1998	Landsat 7 ETM+	P146R029_LT5D19980925.JP2
	7/2/1999	Landsat 7 ETM+	P146R029_LE7D19990702.JP2
	8/3/1999	Landsat 7 ETM+	P146R029_LE7D19990803.JP2
	6/18/2000	Landsat 7 ETM+	P146R029_LE7D20000618.JP2
	9/25/2001	Landsat 7 ETM+	P146R029_LE7D20010925.JP2
	07/04/2003	MODIS Terra	MOD09GQ.A2003185.h23v04.006.2015159134211
	07/11/2004	MODIS Terra	MOD09GQ.A2004192.h23v04.006.2015091081849
	07/18/2005	MODIS Terra	MOD09GQ.A2005199.h23v04.006.2015106015230
	7/26/2002	Landsat 7 ETM+	P146R029_LE7D20020726.JP2
	7/29/2006	Landsat 5 TM	P146R029_LT5D20060729.JP2
	8/14/2006	Landsat 5 TM	P146R029_LT5D20060814.JP2
	6/30/2007	Landsat 5 TM	P146R029_LT5D20070630.JP2
	8/17/2007	Landsat 5 TM	P146R029_LT5D20070817.JP2
	9/2/2007	Landsat 5 TM	P146R029_LT5D20070902.JP2
	9/18/2007	Landsat 5 TM	P146R029_LT5D20070918.JP2
	6/19/2009	Landsat 5 TM	P146R029_LT5D20090619.JP2
	7/21/2009	Landsat 5 TM	P146R029_LT5D20090721.JP2
	8/22/2009	Landsat 5 TM	P146R029_LT5D20090822.JP2
	6/6/2010	Landsat 5 TM	P146R029_LT5D20100606.JP2
	7/11/2011	Landsat 5 TM	P146R029_LT5D20110711.JP2
	9/13/2011	Landsat 5 TM	P146R029_LT5D20110913.JP2
	6/30/2013	Landsat 8 OLI	P146R029_LC8D20130630.JP2
	7/16/2013	Landsat 8 OLI	P146R029_LC8D20130716.JP2
	8/1/2013	Landsat 8 OLI	P146R029_LC8D20130801.JP2
	9/2/2013	Landsat 8 OLI	P146R029_LC8D20130902.JP2
	9/18/2013	Landsat 8 OLI	P146R029_LC8D20130918.JP2
	6/1/2014	Landsat 8 OLI	P146R029_LC8D20140601.JP2
	6/17/2014	Landsat 8 OLI	P146R029_LC8D20140617.JP2
	7/19/2014	Landsat 8 OLI	P146R029_LC8D20140719.JP2
	8/20/2014	Landsat 8 OLI	P146R029_LC8D20140820.JP2

	9/21/2014	Landsat 8 OLI	P146R029_LC8D20140921.JP2
	6/4/2015	Landsat 8 OLI	P146R029_LC8D20150604.JP2
	6/20/2015	Landsat 8 OLI	P146R029_LC8D20150620.JP2
	7/22/2015	Landsat 8 OLI	P146R029_LC8D20150722.JP2
	9/8/2015	Landsat 8 OLI	P146R029_LC8D20150908.JP2
	6/6/2016	Landsat 8 OLI	P146R029_LC8D20160606.JP2
	6/22/2016	Landsat 8 OLI	P146R029_LC8D20160622.JP2
	7/24/2016	Landsat 8 OLI	P146R029_LC8D20160724.JP2
	8/25/2016	Landsat 8 OLI	P146R029_LC8D20160825.JP2
	9/10/2016	Landsat 8 OLI	P146R029_LC8D20160910.JP2

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CHAPTER 3

LAKE CHANGES ACROSS CENTRAL ASIA IN THE PAST 30 YEARS OBSERVED FROM REMOTE SENSING

3.1 Introduction

Central Asia is located in the heart of Eurasia that includes the former Soviet Central Asian republics, northeastern Iran, Afghanistan, northern and central Pakistan, northern India, western China and Mongolia (Dani et al., 1992). Water is a crucial resource to over 100 million people in this region. However, Central Asia is far away from moisture sources and is characterized by hot and dry summers and cold and relatively moist winters (Schiemann et al., 2008; Lioubimtseva and Henebry, 2009). The Himalayan mountains to the south block moisture coming from the Indian Ocean and most precipitation is brought by the westerlies coming from the Atlantic Ocean (Schiemann et al., 2008), leading to strong spatial heterogeneity of precipitation patterns. For example, the Aral Sea and most of the lowland regions receive merely 90-120 mm precipitation annually while the foothills of the Tianshan and Pamir mountains in these regions receive around 200 mm (Surkova 2010; Micklin et al., 2014). In contrast, the high Tianshan and Pamir mountains can receive over 1000 mm annually due to the orographic effects (Bolch, 2007; Williams, 2008). Temperature has been rising significantly at 0.24°C per decade across Central Asia (Huang et al., 2012) while more pronounced warming has been observed during the winter especially in the mountains (Siegfried et al., 2012). Figures 3.1 and 3.2 show the precipitation and temperature trends in Central Asia from 1985-2015 derived from the Climate Research Unit data set (Harris et al., 2014). While precipitation trends are highly variable across the region, there is widespread increase in temperature. As a result, glaciers in the region are declining (e.g. Aizen et al., 2007; Bolch, 2007; Armstrong, 2010; Cogley, 2016) and snow cover area and snow depth are decreasing

(Aizen et al., 1997) and snow is starting to melt earlier in the spring (Dietz et al., 2013). The generated meltwater provides crucial water source to the downstream arid lowland regions where most populations are located. Depending on the location and abundance of glaciers in the catchments, some studies have found increases in annual runoff in certain Tianshan catchments (e.g. Kriegel et al., 2013; Xu et al., 2013; Deng et al., 2015; Duethmann et al., 2015) while others have found decreases (Aizen et al., 1997; Kezer and Matsuyama, 2006) or no significant changes (Aizen et al., 1997). Given these hydrologic changes, there is great uncertainty on how water resources will change under the undertaking climate change (Bernauer and Siegfried, 2012; Siegfried et al., 2012).

Apart from climatological changes, humans also have great influences on water availability in Central Asia. Over 90% of water extracted from rivers is used for irrigation (World Bank, 1998). With the exception of Kazakhstan, irrigated agriculture accounts for 80% of total agriculture in the former Soviet Central Asia republics including Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (Micklin et al., 2014). The drastic expansion of agriculture lands in the 20th century has caused the Aral Sea to experience devastating shrinkage which is commonly known as the Aral Sea disaster (Micklin, 2007). During the Soviet period, water in the former Soviet Central Asia republics was managed by the central government. Hydroelectric facilities were constructed in upstream regions (Kyrgyzstan and Tajikistan) to mainly to store water during the winter and provide water during the summer for agricultural irrigation in the downstream regions (Uzbekistan, Turkmenistan and Kazakhstan). After the collapse of the Soviet Union however, this regional arrangement fell apart as the region broke into various countries each with their own agenda. This created conflicts between upstream and downstream countries on how much water should be released from dams in the winter for power generation versus how much should be released in the summer for irrigation. These international conflicts on water and energy management will likely exacerbate water security in Central Asia (Siegfried and Bernauer, 2007; Bernauer and Siegfried, 2012; Mukhammadiev, 2014).

In light of the above discussion, it is important to understand how water resources are changing in Central Asia and what is causing the changes. Lakes, especially endorheic lakes, are particularly sensitive to climatic and anthropogenic impacts. Endorheic lakes are the terminus of a hydrologic system and their storage variations are direct responses to the climatic changes and human activities in the basin. Central Asia is home to many such lakes (Lehner and Döll, 2004), despite its apparent aridity. Thus, lakes in Central Asia can be used as proxy indicators of climate and anthropogenic change. This study selects some representative lakes in the region and uses remote sensing to examine how their area, level and volume are changing in the past 30 years. It also assesses the possible climatic and anthropogenic causes that lead to the changes in these lakes to provide insight into future water availability in the region under climate and population change.

3.2 Materials and methods

3.2.1 Study area

Figure 3.3 shows the study area which is located in the most populated area of Central Asia. Seven major basins were selected including the most notable Amu Darya, Syr Darya and Ili river basins. The basins cover about 1.7 million km^2 and about 20% are in the high mountains (elevation > 2,000 m). Extensive agriculture has been developed in all but three mountain lake basins (Chapter 4). Seventeen representative lakes were selected from these basins. Table 3.1 shows their basic characteristics of the lakes. These lakes form a hierarchy from high altitude, high precipitation, little human disturbance to low altitude, low precipitation, considerable human disturbance. Chatyr, Karakul, Sayram and Songkul are mountain lakes located at altitudes greater than 2,000 m.

Kapchagay, Kayrakkum, Shardara and Toktogul are reservoirs located near population centers and agriculture lands. The rest are lowlands lakes located at or near the terminus of their respective basins. Therefore, the chosen lakes provide a representative view of how water resources are changing in Central Asia.

3.2.2 Observing lake area from optical satellite imagery

We collected over 330 satellite imagery from Landsat and MODIS archives (https://earthexplorer.usgs.gov/) ranging from 1986 to 2016. Lakes were mapped from these images using an automated adaptive mapping algorithm based on the Normalized Difference Water Index (NDWI) (Li and Sheng, 2012; Sheng et al., 2016). The NDWI is defined using the green and near infrared bands as:

$$NDWI = \frac{Green - Near\ infeared}{Green + Near\ infeared} \tag{1}$$

Regions of potential lakes were first located by applying a loose global threshold (-0.05) to the entire NDWI image. A buffer was then extended from the region so that each region contained lakes pixels and lands pixels. A NDWI histogram was then generated for each region and a second local NDWI threshold was identified from the histogram to extract the lake pixels. This adaptive mapping algorithm is more effective and robust than using a single NDWI threshold because complex water conditions such as turbidity, mineral content, presence of vegetation and snow/ice may cause the lake to have different NDWI values that cannot be captured by a single threshold. The algorithm has been shown to be effective in various terrains and water conditions (Li and Sheng, 2012; Wang et al., 2014; Sheng et al., 2016).

The algorithm was applied to the acquired satellite images to derive lakes automatically. The derived results were then validated manually by comparing the results to the original image to remove cloud and shadow contamination. Over 360 area observations were derived for 17 lakes.

3.2.3 Observing lake water level from satellite altimetry

We measured lake water level from ICESat and CryoSat altimeters. The ICESat data was collected from the ICESat derived inland water surface spot heights (IWSH) product (O'Loughlin et al., 2016). This product contains the mean and median elevations of each transect that overpasses a lake from 2003 to 2009. Over 850 observations were collected from this product.

We also collected the CryoSat Level 1B product (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat) operated in synthetic aperture radar interferometry (SARIn) mode from 2010 to 2018. This product contains waveforms received by the sensor. The standard retracker used for the Level 2 product can only detect one peak in the waveform and thus provide one elevation estimate. However, in mountain areas the surrounding topography may product multiple peaks in the waveform. The standard retracker may detect a peak corresponding to the surrounding terrain instead of the water surface. As a result, water level estimates in the Level 2 product may be off by tens to even hundreds of meters (Kleinherenbrink et al., 2015). We conducted our own retracking on the L1B product using an algorithm proposed by Kleinherenbrink, Ditmar, and Lindenbergh (2014). The proposed retracker is able to detect multiple peaks and multiple elevation estimates. The multiple elevation estimates were then filtered to only contain measurements from the water surface since water surface elevation does not vary as much as the surrounding terrain. This approach can effectively remove terrain reflections from a satellite overpass.

Finally, results from both products have to be reconciled because they use different geodetic reference systems and contain various biases. Since they do not have temporal overlap, other lakes in the region that contains ICESat, CryoSat and a third HYDROWEB product (http://hydroweb.theia-land.fr/) with elevation measurement from 2003 to 2018 were examined.

We selected ten lakes in Central Asia, including lakes in Tianshan, the Tibetan Plateau and other lowland regions and used the HYDROWEB product as a baseline to assess the bias between ICESat and CryoSat. We found that CryoSat was consistently underestimating elevation than ICESat in nine out of ten lakes. We took the median difference at those nine lakes (0.687 m) and applied to all lakes in the study area.

3.2.4 Combining lake area and water level observations to estimate lake volume changes

A lake hypsometry (area-level relationship) needs to be derived before volume changes of the lake can be estimated. The satellite area observations started around late 1980s and early 1990s for most lakes while the lake level observations started in 2003. There were too few coincidental area and level measurements to derive hypsometry for lakes in our study area. Therefore, we had to use a digital elevation model (DEM) for this purpose.

3.2.4.1 Deriving lake hypsometry from digital elevation model

We used the Multi-Error-Removed Improved-Terrain Hydro (MERIT Hydro, http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/) DEM to derive lake hypsometry. This DEM is based on the MERIT DEM which removed multiple errors including absolute bias, stripe noise, speckle noise and tree height bias from the Shuttle Radar Topography Mission (SRTM) DEM and developed specifically for hydrologic studies.

We obtained the maximum extent for each lake in our study area from the 30-year satellite observations and calculated a lake area within the maximum extent for each 0.5-meter elevation intervals. We also derived a mean shoreline elevation using the DEM based on the remote-sensing-derived lake boundaries. We used both derivations to fit a polynomial relationship between lake area and water level, which is used as the basis for estimating lake area from level measurements and vice versa. The relationships are shown in Table 3.2 and scatterplots are shown in Figures 3.4 – 3.20.

Lake level given an area observation (and vice versa) is estimated using the equations in Table 3.2. We found systematic biases between the estimated levels from area observations and the observed levels from ICESat/CryoSat. The estimated levels are greater than the observed levels for most of the lakes. Therefore, we used pairs of estimated levels and observed levels taken within 15 days apart to estimate the bias between the two data sources. We then subtracted the bias of each lake from the estimated levels to derive a consistent record of water level changes in all lakes from 1980s to 2010s. Similarly, we corrected the bias between the observed areas and estimated areas.

3.2.4.2 Estimating lake volume changes

With the area and level estimates, lake volume change between two time periods is then calculated as:

$$\Delta V = \frac{(h1 - h2) \times (A1 + A2)}{2}$$

where h1, h2, A1, A2 are the lake level and area measurements at time 1 and 2 respectively.

3.3 Results

Using the above data sets we generated, we analyze the observed lake area, level, and volume changes in the past ~30 years in the subsequent sections and examine the lake changes for various lake groups. Lakes are grouped by endorheic, open and reservoirs as these types of lakes are controlled by different physical processes. Endorheic lakes are usually the most sensitive ones to changes in inflow and can have drastic changes in area. On the other hand, open lakes can self-regulate through outflow and they are usually more stable. Reservoirs are controlled by human operations and can have drastic interannual fluctuations depending on the inflow and release schedules.

3.3.1 Endorheic lakes

Figures 3.21 - 3.23 show the area, level and volume changes of endorheic lakes. All lakes except Songkul, Sorbulaq and Issykkul experienced an overall increase in surface area (Figure 3.21). The increases range between 1.0% and 15.4% while the decreases are much less, between -0.04% and -4%. Chatyr, Karakul and Sayram showed consistent increase during the observed period. These three lakes are located in the mountain regions above 2,000 m in elevation. Alakol, despite located at 347 m, showed a consistent increase as well. Songkul, while located in the mountains at 3,011 m, experienced a decline of -1.3%. Issykkul remained rather stable with a slight overall decline of -0.03%.

Other lakes showed much greater interannual fluctuations. Ebinur lake in particular experienced the biggest fluctuations among all endorheic lakes as its area changed between -40% and 80%. The north part of the Aral Sea showed a decline between the late 1980s and 1990s and it recovered in the 2000s. Smaller lakes like Sorbulaq and Qamystybas showed some interannual variabilities as well between -5.0% and 6.6%.

All lakes except Aral Sea north, Songkul, Sorbulaq and Issykkul experienced an overall level increase during the observed period (Figure 3.22). Similar to area observations, mountain lakes such as Chatyr, Karakul and Sayram showed consistent increases in water level ranging from 3.5 m to 5.2 m. Alakol and Qamystybas showed increase of 2.7 m and 0.05 m respectively. Both Aral Sea north and Issykkul showed slight decline during the period of -1.9 m and -1.6 m respectively. Songkul and Sorbulaq remained relatively stable with slight declines overall.

Over half the lakes experienced increase in volume during the observed period (Figure 3.23). Alakol showed the greatest increase of 3.91 km^3. Qamystybas, Sayram, Karakul, Chatyr and Ebinur showed moderate increase between 0.13 and 1.04 km^3. Songkul and Sorbulaq showed slight decrease of -0.21 km^3 and 0.01 km^3 respectively while the north Aral Sea and Issykkul showed greater decline of -2.72 km^3 and -4.87 km^3 respectively.

3.3.2 Open lakes

Figures 3.24 - 3.26 show the area, level and volume changes of open lakes. All three open lakes examined in this study have experienced an increase during the observed period ranging between 0.8% and 1.4% (Figure 3.24). All three lakes drain into Alakol; and therefore, it's reasonable that they have the same consistent increasing trend.

All three lakes showed similar levels of increase during this period (Figure 3.25). Kosharkol, Sasykkol and Zhalanashkol increased by 0.8, 1.6 and 1.4 m respectively. This is consistent with the area increase.

All three lakes also experienced increase in volume (Figure 3.26). Kosharkol and Zhalanashkol increased by 0.05 km^3 and 0.03 km^3, respectively while Sasykkol had a greater increase of 0.58 km^3.

3.3.3 Reservoirs

Figures 3.27 – 3.29 show the area, level and volume changes of reservoirs. All four reservoirs experienced a slight 0.02% to 8.4% increase overall (Figure 3.27). They have little overall trend during the observation period, but they experience much interannual variability as expected from dam operations. Toktogul experienced the greatest interannual changes of up to 60%. The Toktogul dam is constructed in a mountain valley mainly for hydroelectric purposes while other three dams are constructed in relatively flat lowland regions mainly for irrigation purposes.

Similar to their area, reservoirs levels show little trend over the entire observed period (Figure 3.28). However, interannual fluctuations exists especially for Toktogul which fluctuates between -40.6 m and 20.0 m. Kapchagay, Kayrakkum and Shardara generally fluctuates between -7.2 m and 6.4 m. Both Kayrakkum and Shardara are located on the Syr Darya river while Toktogul is located on the Naryn river which is a major tributary of the Syr Darya river. It can be seen that the water level in Kayrakkum and Shardara are well correlated while they are in opposite phase with the level of Toktogul. This is implicated by the major functionality of the three dams as Toktogul release large amounts of water in winter and spring for power generation while Kayrakkum and Shardara releases water in summer for irrigation.

All reservoirs experienced increase in volume during the observed period except for Kayrakkum which showed a slight decrease of -0.17 km^3 (Figure 3.29). Kapchagay, Shardara and Toktogul increased by 1.17 km^3, 0.35 km^3 and 1.10 km^3 respectively. It can be seen from that Toktogul peaks in October and releases water throughout the winter months and reaches its lowest level in March. Shardara and Kayrakkum peaks in May and releases water during the summer and reaches their lowest levels in September/October.

3.4 Discussion

Interesting patterns can be found from the above results. Overall, natural lakes are increasing in volume regardless of their type and elevation. Reservoirs have remained stable with large amounts of interannual variability. Our results correspond well with other studies on individual lakes (Ma et al., 2007; Kravtsova et al., 2010; Bai et al., 2011; Li et al., 2011). Differences exist mainly due to the different time periods examined by various studies. For example, the north part of Aral Sea experienced drastic changes in the 1990s up to 2005 due to the construction and destruction of a dam in multiple occasions (Cretaux et al., 2005). Drastic increase since 2000 and stabilization since 2006 is due to the construction of a new dam that stopped the flow of water out of the north Aral Sea. Nevertheless, the overall volume of the lake still declined compared to the mid-1980s when the Aral Sea was not yet divided, and its volume was much larger.

3.4.1 Climatic causes of lake changes

Precipitation changes across Central Asia is highly heterogeneous. Stations in the foothills and higher altitudes of Tianshan show increasing precipitation trends while those in the inner Tianshan show decreasing trends. There is little difference overall between precipitation trends at high and low elevations (Figure 3.30). Nine out of twelve lakes that expanded are located in regions with increasing precipitation while only one out of five lakes that declined are located in regions with decreasing precipitation. Thus, ten out of seventeen lakes have the same direction of change as precipitation in their locale. This suggests a modest relationship between precipitation and lake change.

Temperature, on the other hand, has been increasing consistently across Central Asia. The rate of temperature change in Central Asia ranges between 0.18°C and 0.42°C per decade with evidence of exacerbated warming in winter though evidence for altitude-dependent warming is inconclusive (Unger-Shayesteh et al., 2013). As a result, the decline of glacier and snowpacks have been widely observed across the Tianshan (Unger-Shayesteh et al., 2013). The decline of glacier and snow generates more meltwater runoff that can feed lakes which explains the consistent expansion of lakes located above 2,000 m elevation such as Chatyr, Karakul and Sayram (Figure 3.31). The interesting exception to this is Songkul which showed a slight decline over the period.

This is possibly related to the small proportion of the lake basin being covered by snow and glacier. Issykkul also showed a slight decline over the period despite being at 1,600 m elevation and surrounded by mountains with glaciers and permanent snowpacks. However, the Issykkul basin has well developed irrigated agriculture fields. Human activities may have caused the decline of Issykkul though the decline of area is only -0.03%. Downstream lakes and reservoirs have generally expanded slightly as well as a result of more meltwater production.

3.4.2 Anthropogenic causes of lake changes

Humans have been practicing irrigated agriculture in the region for 3,000 years (Micklin, 2014). During the Soviet period (pre-1991), the Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan and Tajikistan were predominantly planting cottons which is a water intensive crop. The Soviets extensively built water management infrastructures including canals and dams between the 1950s and 1980s. All four reservoirs examined in this study were filled during this period. Agriculture expanded steadily since the 1950s and as a result the Aral Sea has undergone constant decline since the 1960s due to the extraction of water for irrigation from the Amu Darya and the Syr Darya rivers which supplies the sea. Figure 3.32 shows the monthly average volume change of each reservoir within a year. Kapchagay, Kayrakkum and Shardara, which are irrigation reservoirs, fills water up until May and releases water during the summer for irrigation. Toktogul, which is mainly a power generation reservoir releases water during the winter.

Most of the observations in this study were made after the collapse of the Soviet Union in 1991. During this period, agriculture expansion in the former Soviet states came to a halt and irrigated area remained largely unchanged between 1995 and 2010 (Micklin, 2014; Chapter 4 of this dissertation). However, agriculture continued to expand in Xinjiang, China (See Chapter 2). This may be why the majority of lakes and reservoirs at lower elevations remained relatively stable with little sign of decline during our observed period. Nevertheless, considering the expansion of high-altitude lakes under increased meltwater runoff, lakes in lowland regions should experience similar increasing trends if no agriculture were present.

3.4.3 Implications of transnational river management policies

Of the four reservoirs, Toktogul lies in Kyrgyzstan while Kapchagay and Shardara lies in Kazakhstan and Kayrakkum lies in Tajikistan. With the collapse of the USSR, the five countries of the former Soviet Central Asia republic undergone numerous negotiations on agreements over water sharing in the region (Agreement, 1992; Agreement, 1993; Agreement, 1996; Almaty Declaration, 1997; Agreement, 1998; Ashgabat Declaration, 1999; Agreement, 2000; Almaty Statement, 2009). They agreed to essentially keep the arrangements during the Soviet period. However, these agreements are poorly implemented (Siegfried and Bernauer, 2007) and attempts to solve the problem have largely failed (Bernauer and Siegfried, 2012). For example, even though downstream countries insisted on keeping the previous schedule of water releases from upstream hydroelectric facilities (Micklin, 1996; Micklin, 1997; Krutov and Lennaerts, 2000; Pannier, 2000; Gleason, 2001), they declined to offer compensating energy resource to upstream countries or offered them at market prices (Micklin, 2002; Bernauer and Siegfried, 2012). In response, the upstream countries modified their hydroelectric operation schedules to match their domestic energy demand during the winter (Siegfried and Bernauer, 2007; Bernauer and Siegfried, 2012) as shown in Toktogul whose volume kept declining during the winter (Figure 3.32). These nations view energy and water as a matter of national security and generally adopts a “self-sufficiency” policy which incurs substantial costs for all countries in the region (Micklin, 2002).

3.5 Conclusion

Water is a scarce yet essential resource in Central Asia. Here, we examined the changes of lakes and reservoirs across Central Asia in the past three decades to shed light on the changes of water resources in the region. We used satellite remote sensing to estimate lake area, water level and volume changes and found various interesting patterns that can guide future water management policies in the region.

First, lakes located in the remote high-elevation mountain regions are generally expanding throughout the period. This is likely caused by the increased melting of snow and glaciers due to a warming climate. This suggests that more water is being generated from the mountains and will have a positive effect on the local population. Second, despite the increased meltwater runoff, lakes in the downstream lowland regions have not seen similar expansion like the mountain lakes. Most downstream lakes have remained stable and, in some cases, declined. Many of these lakes are located near agriculture fields and irrigation is likely the cause of such difference. Third, reservoirs have generally remained stable during the past three decades though they have experienced different patterns depending on their location and major function. A reservoir located in the mountains has shown declines during the winter and spring suggesting a release of water for hydroelectric power generation. Reservoirs located in the agriculture regions have shown declines during the summer suggesting a release of water for irrigation.

Under climate change, more water has been generated from glaciers and snow and this trend is likely to continue to the near future (Siegfried et al., 2012); however, peak runoff will shift towards earlier in the spring (Bernauer and Siegfried 2012). This has great implications on water management especially in transnational rivers as countries will fight over the amount of water allocated for power generation versus agriculture irrigation. This calls for the cooperation between countries sharing the same watershed as increased meltwater production alone will not solve water conflicts in the region.

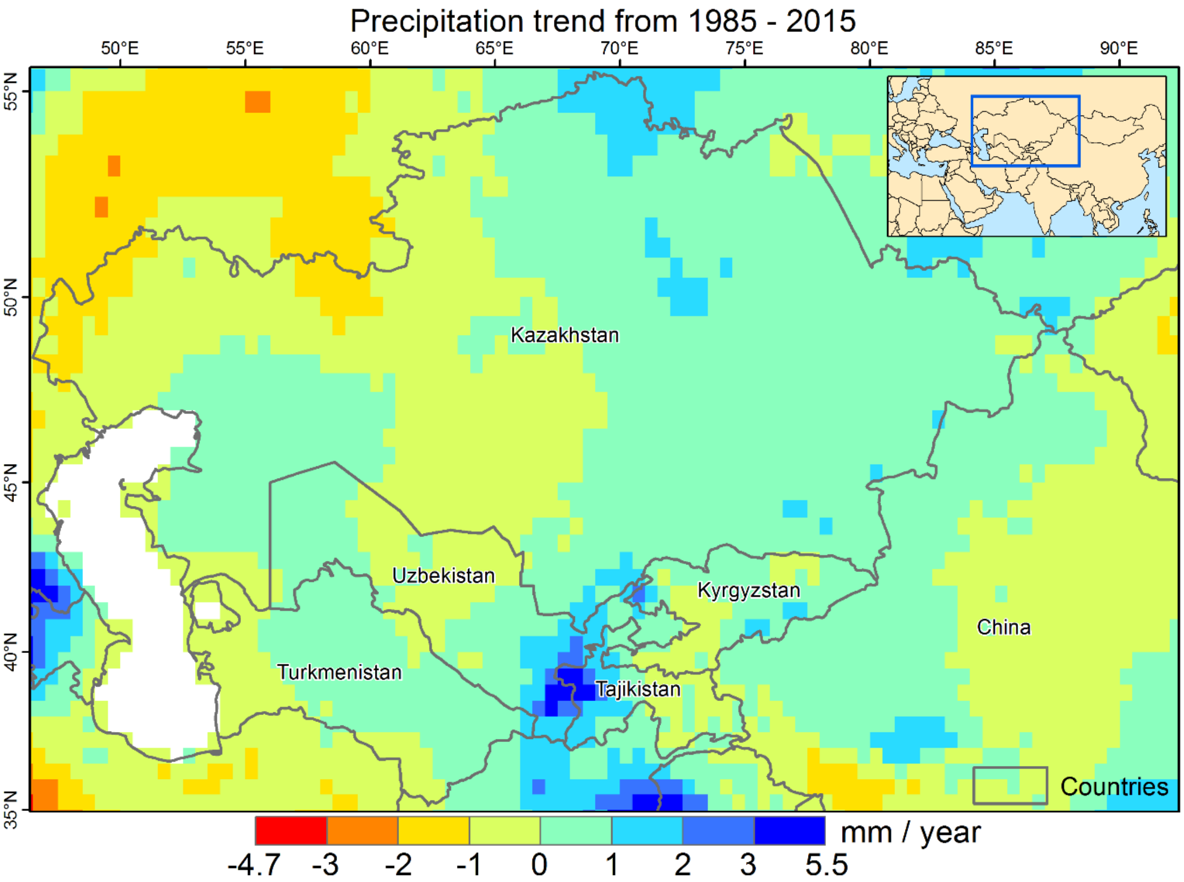

Figure 3.1: Precipitation trends in Central Asia from 1985-2015

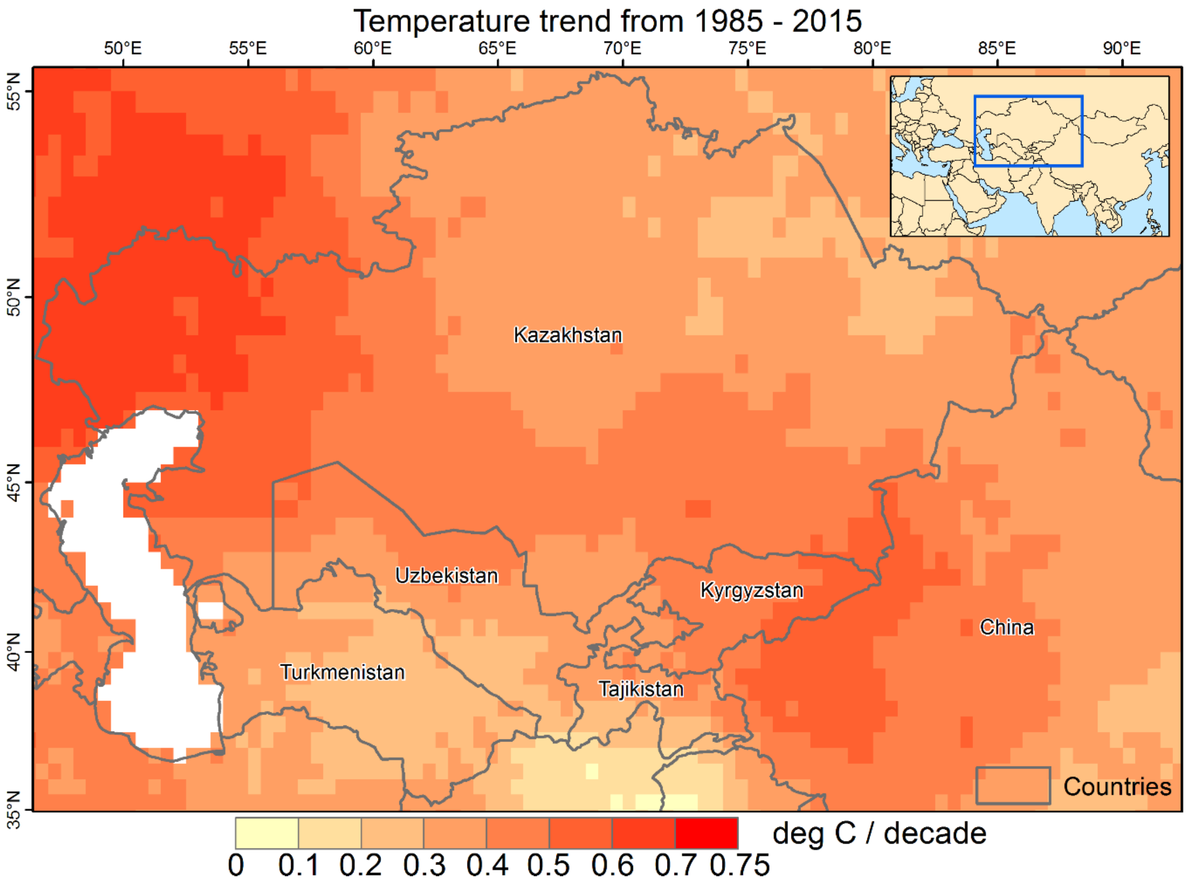

Figure 3.2: Temperature trends in Central Asia from 1985-2015

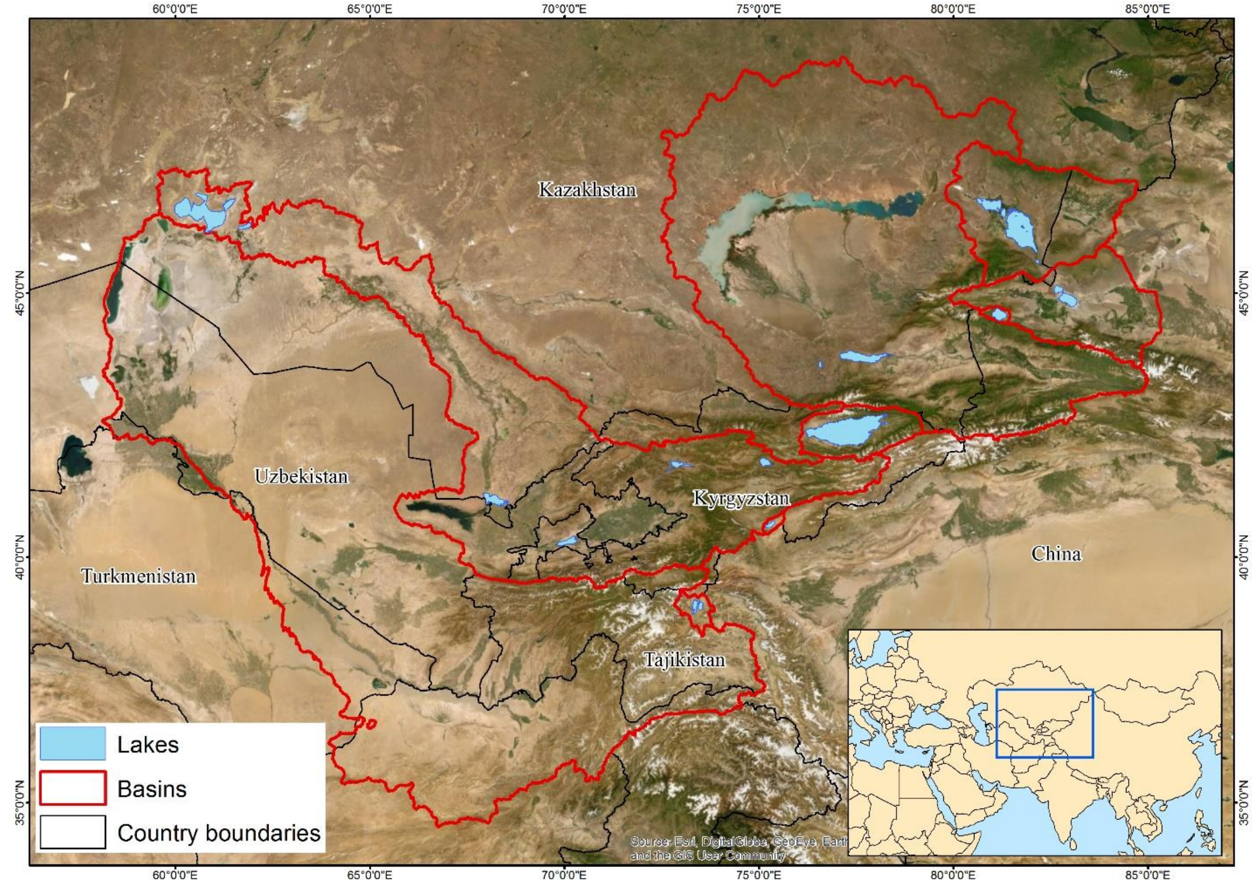

Figure 3.3: Lakes in study area

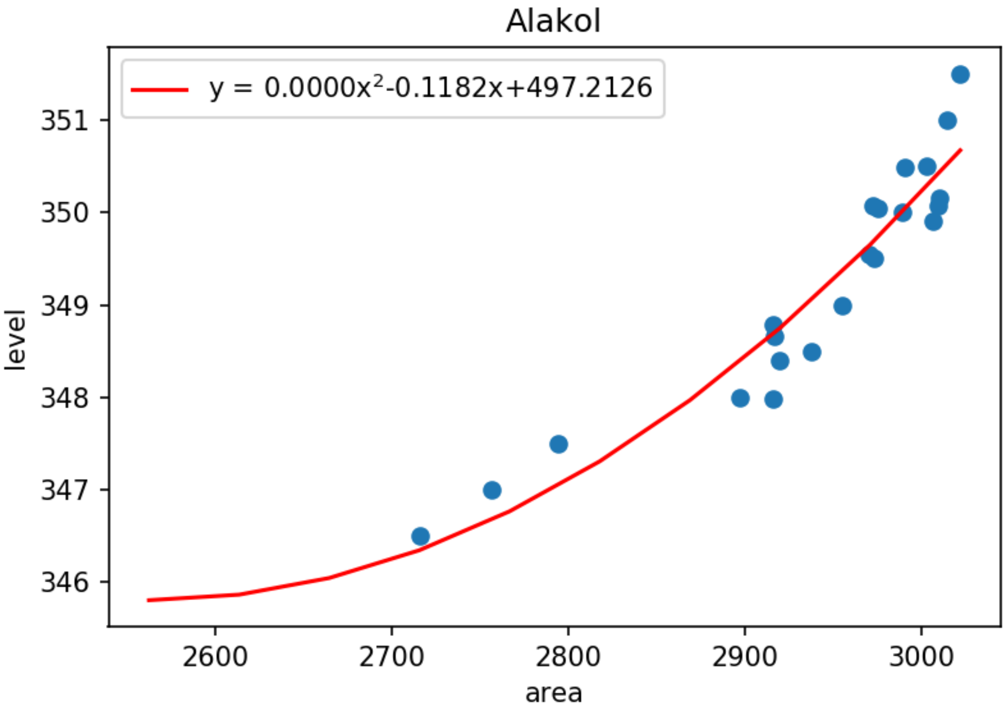

Figure 3.4: Hypsometry of Alakol

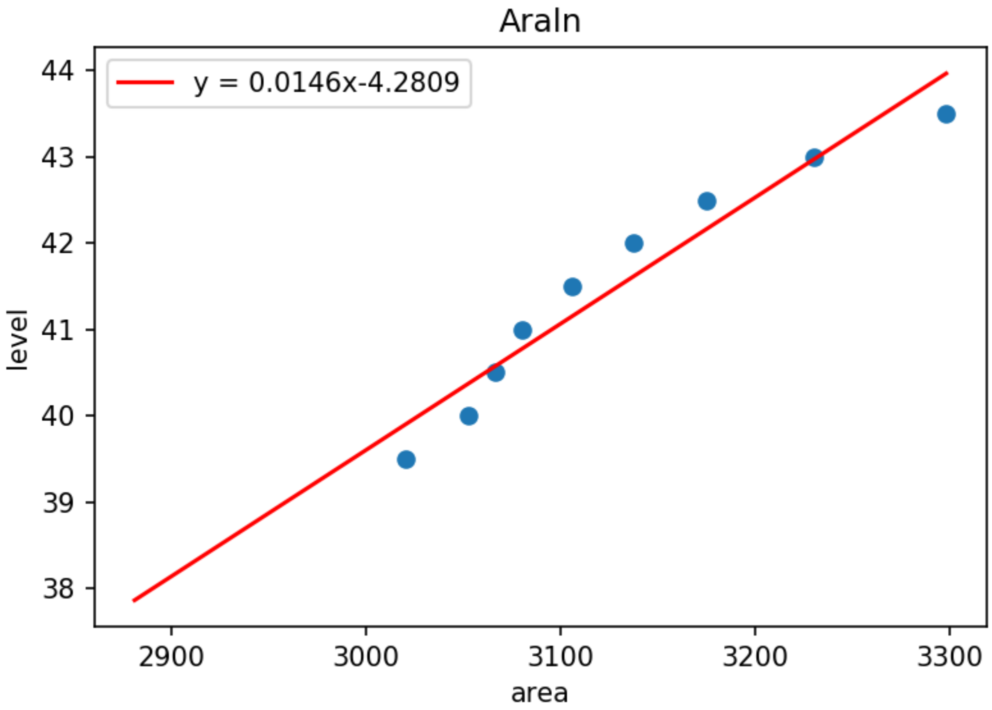

Figure 3.5: Hypsometry of Aral Sea north

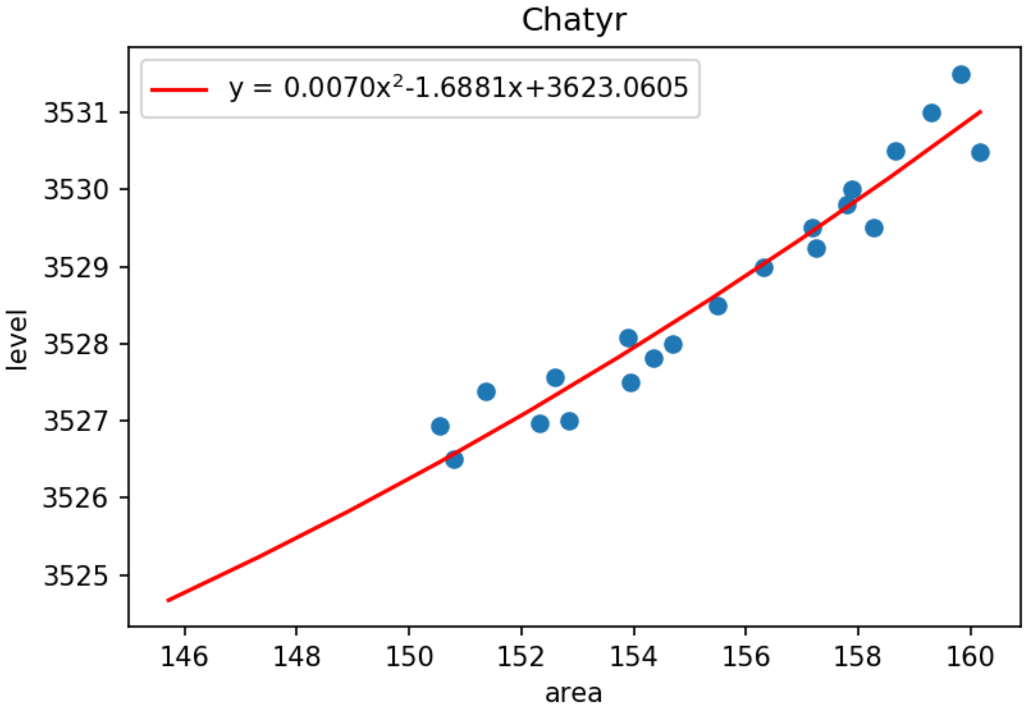

Figure 3.6: Hypsometry of Chatyr

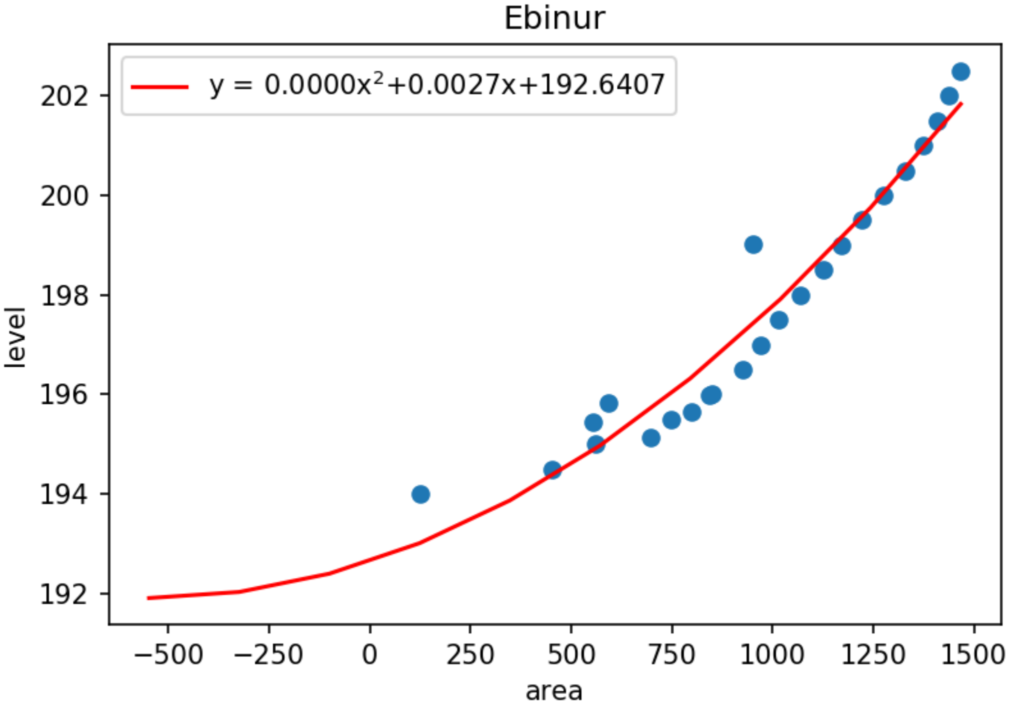

Figure 3.7: Hypsometry of Ebinur

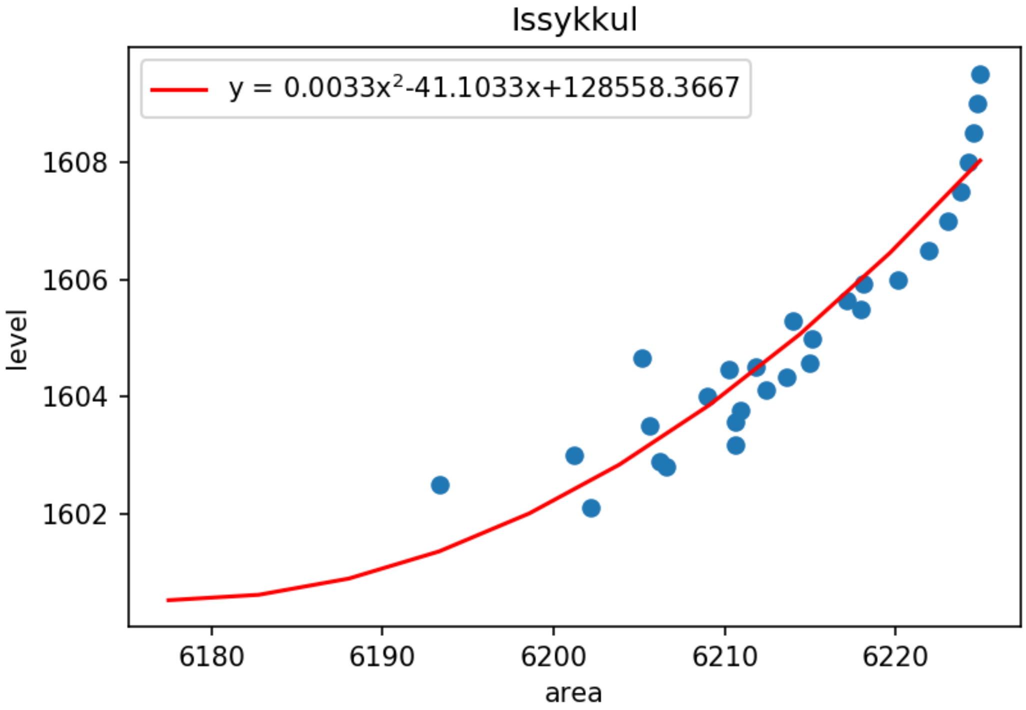

Figure 3.8: Hypsometry of Issykkul

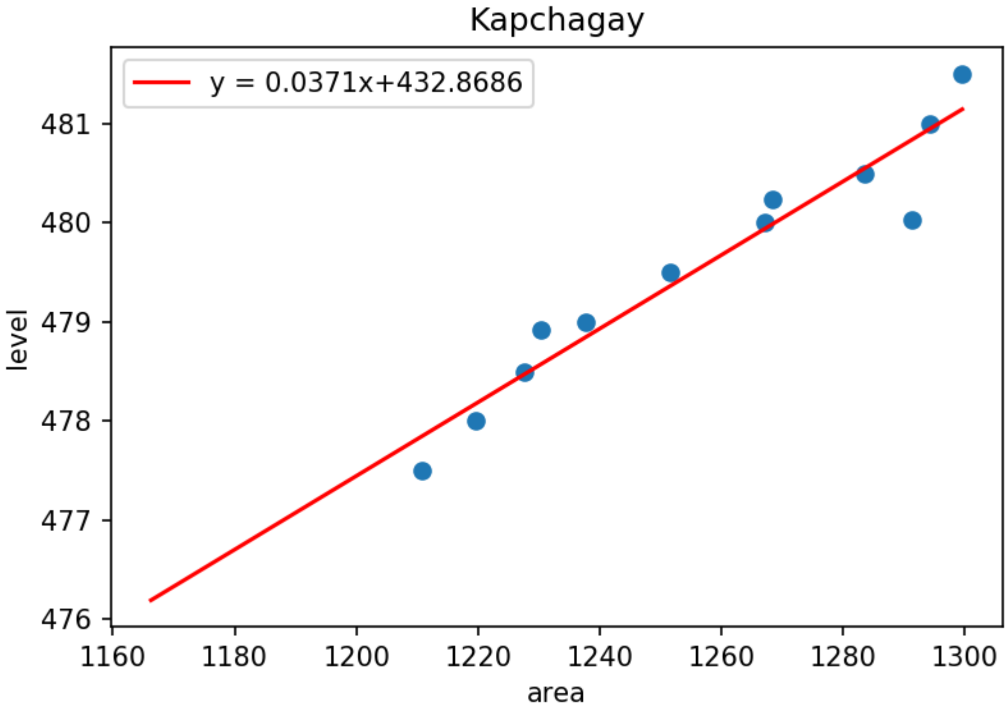

Figure 3.9: Hypsometry of Kapchagay

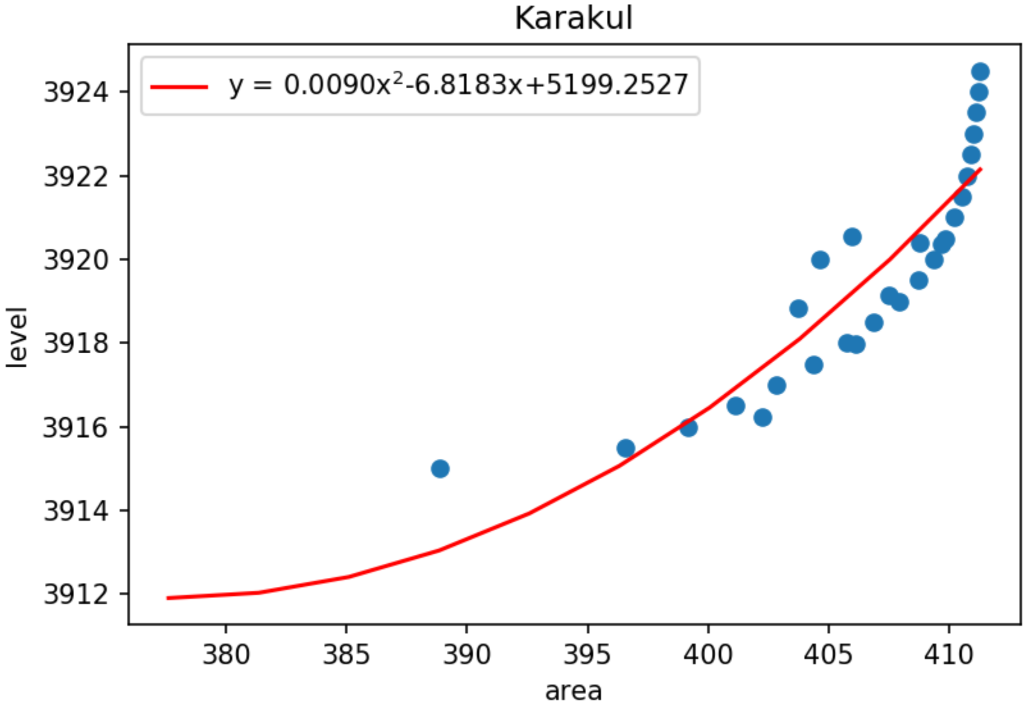

Figure 3.10: Hypsometry of Karakul

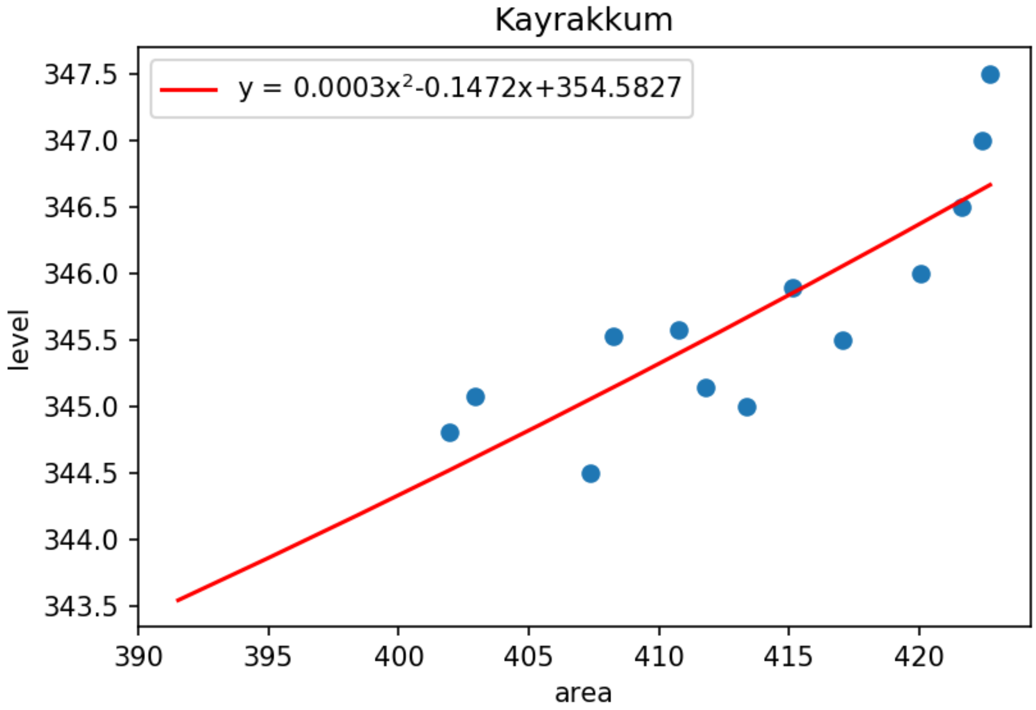

Figure 3.11: Hypsometry of Kayrakkum

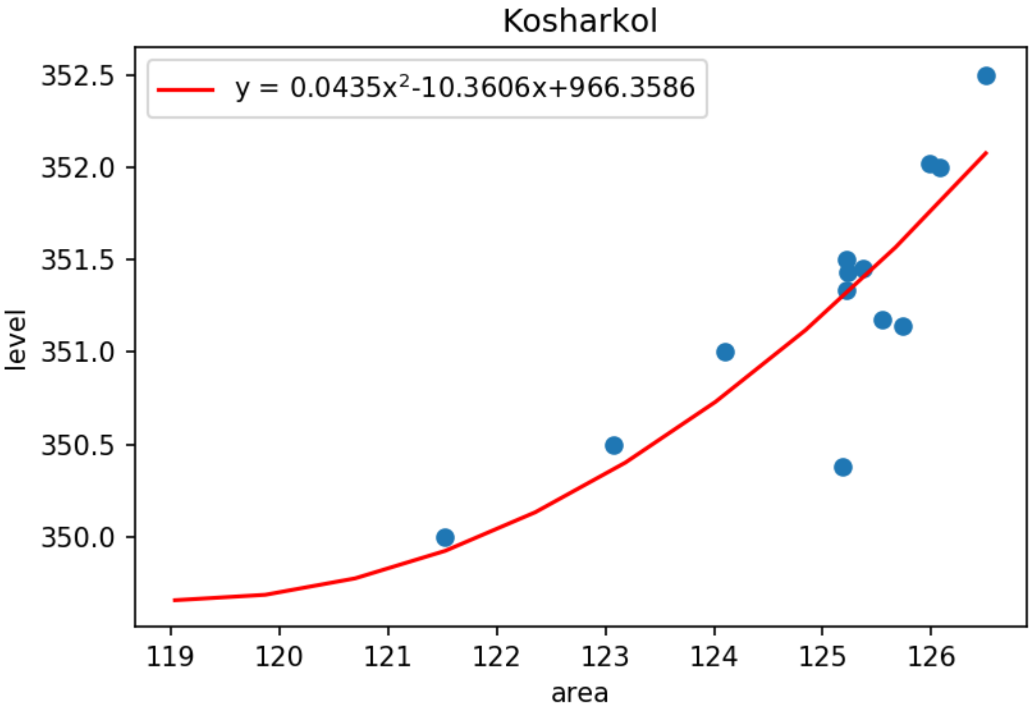

Figure 3.12: Hypsometry of Kosharkol

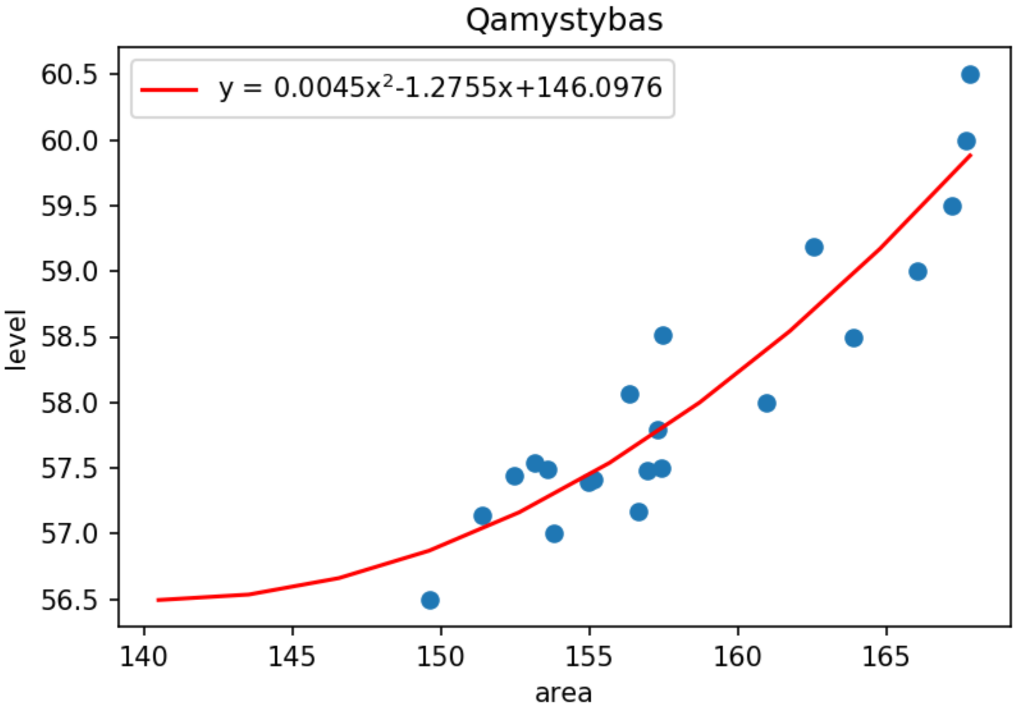

Figure 3.13: Hypsometry of Qamystybas

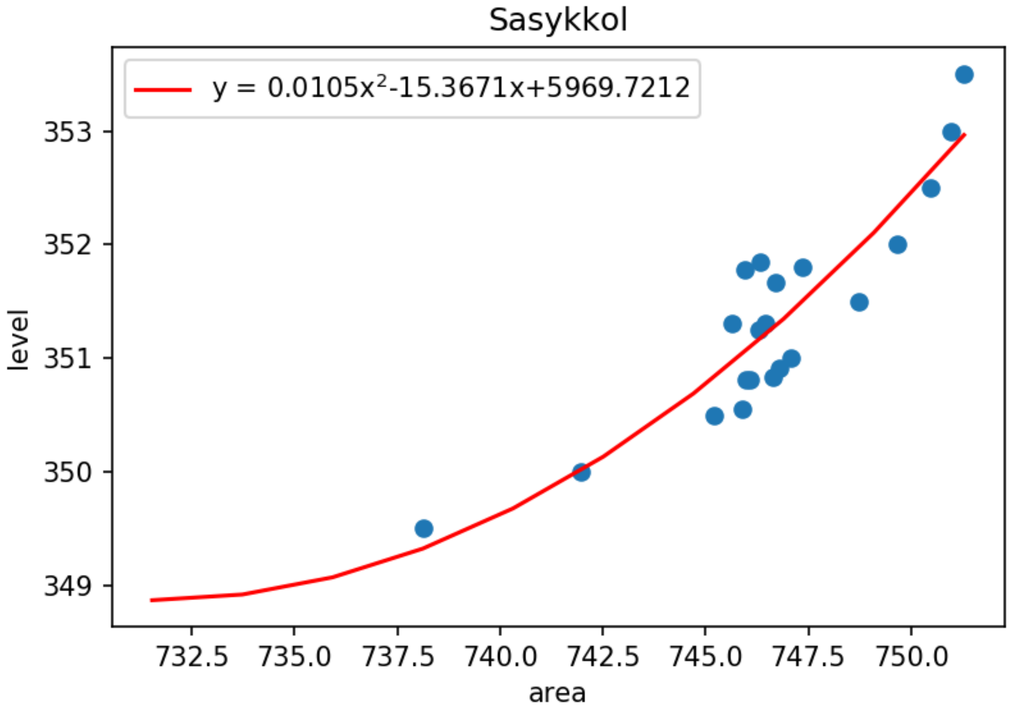

Figure 3.14: Hypsometry of Sasykkol

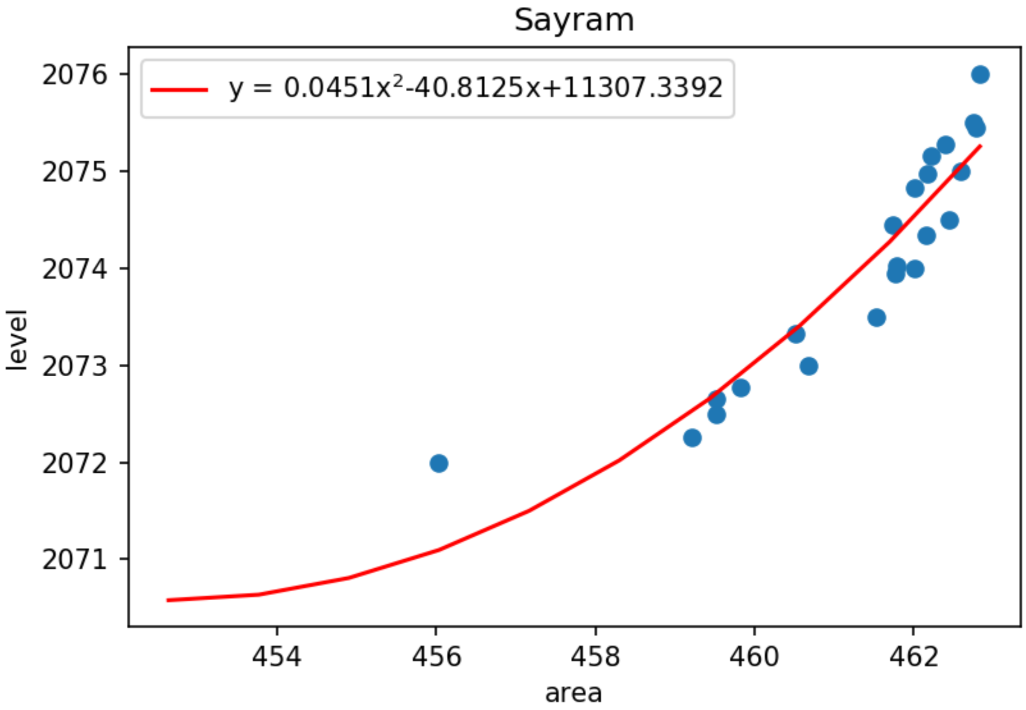

Figure 3.15: Hypsometry of Sayram

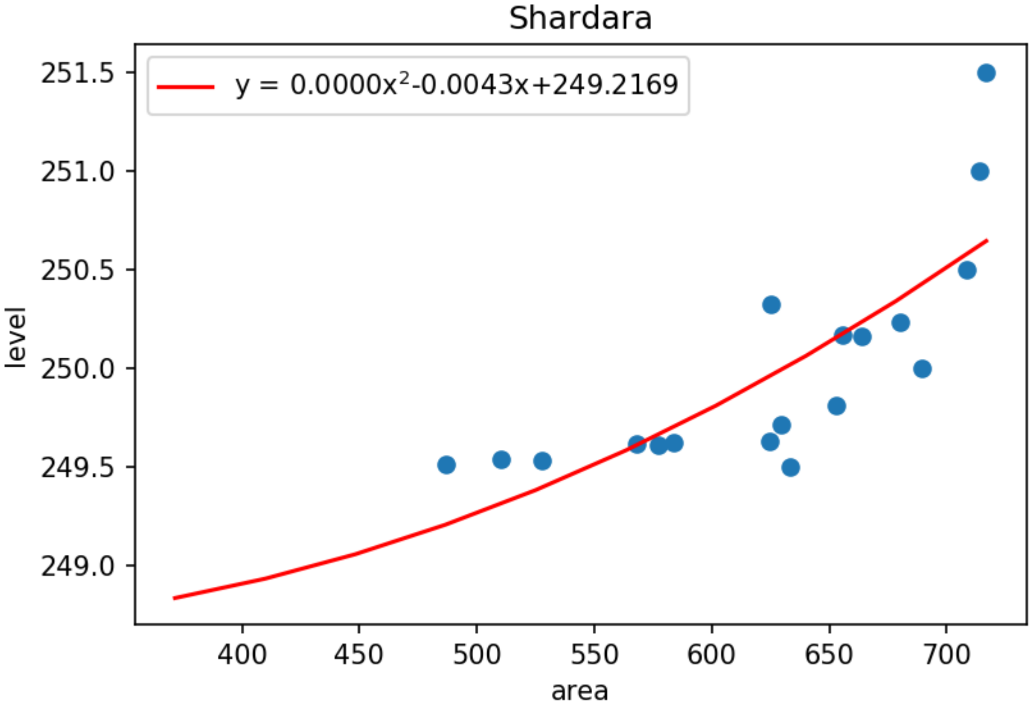

Figure 3.16: Hypsometry of Shardara

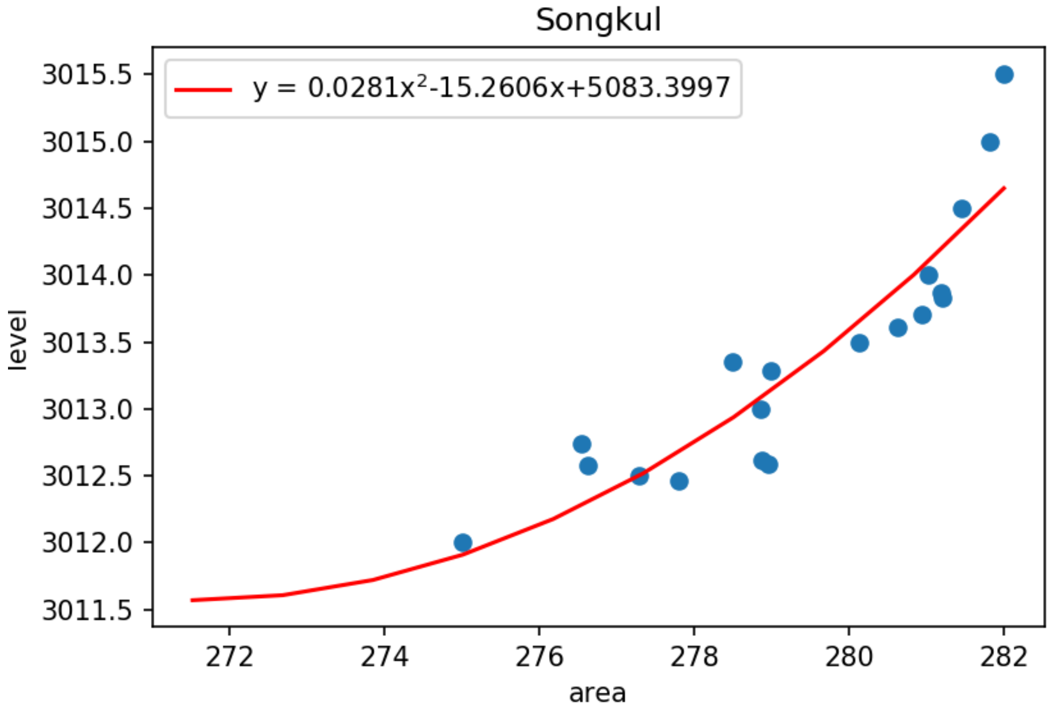

Figure 3.17: Hypsometry of Shardara

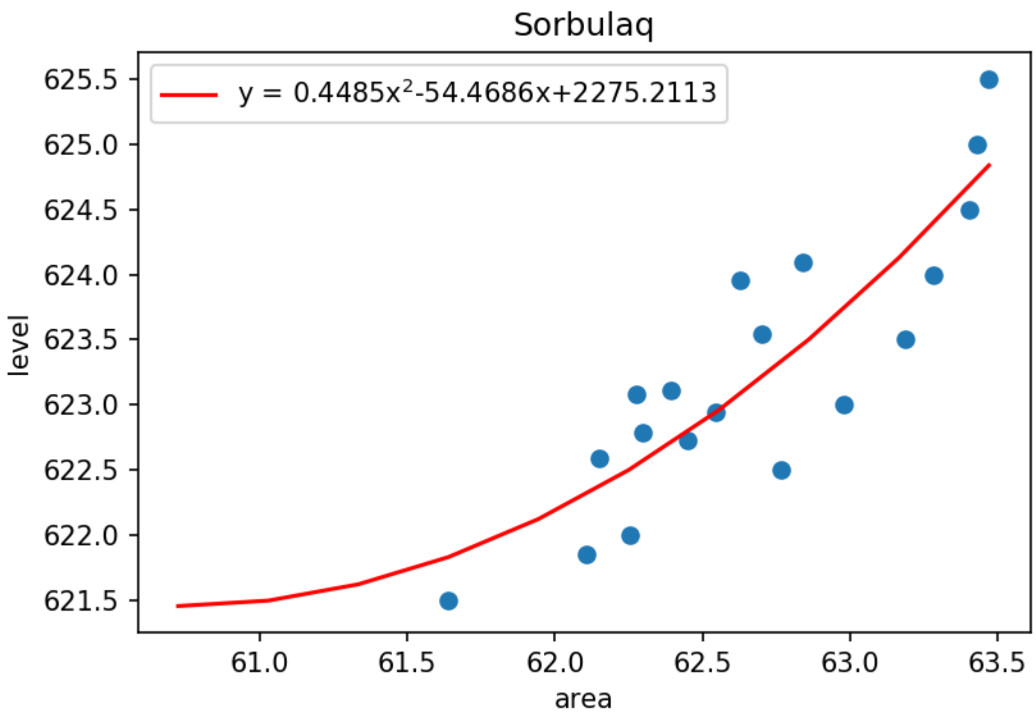

Figure 3.18: Hypsometry of Sorbulaq

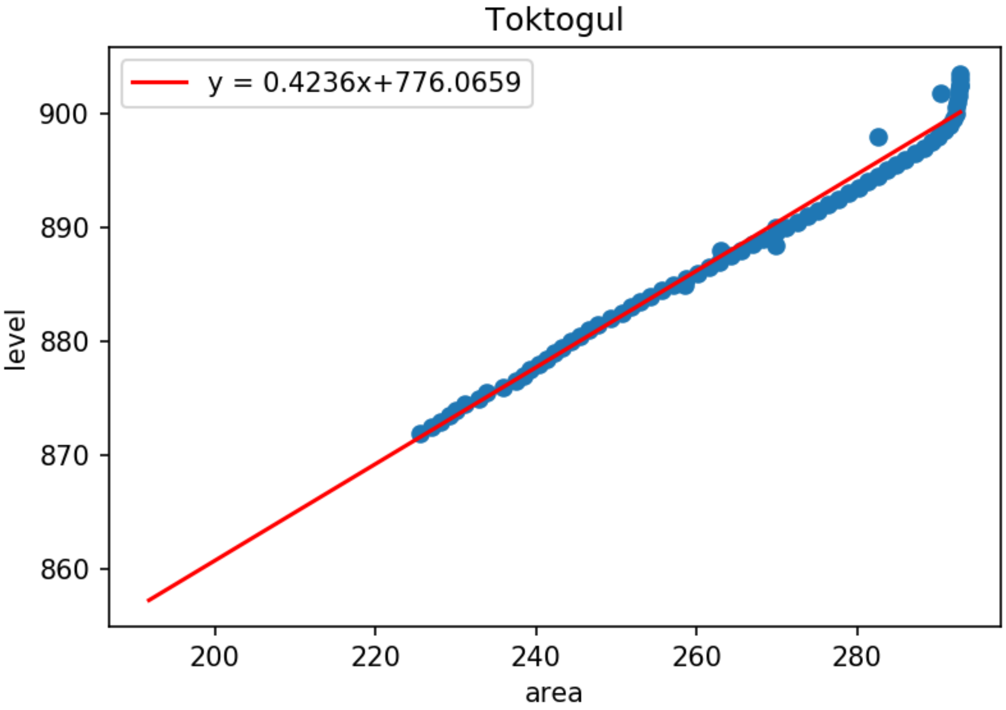

Figure 3.19: Hypsometry of Toktogul

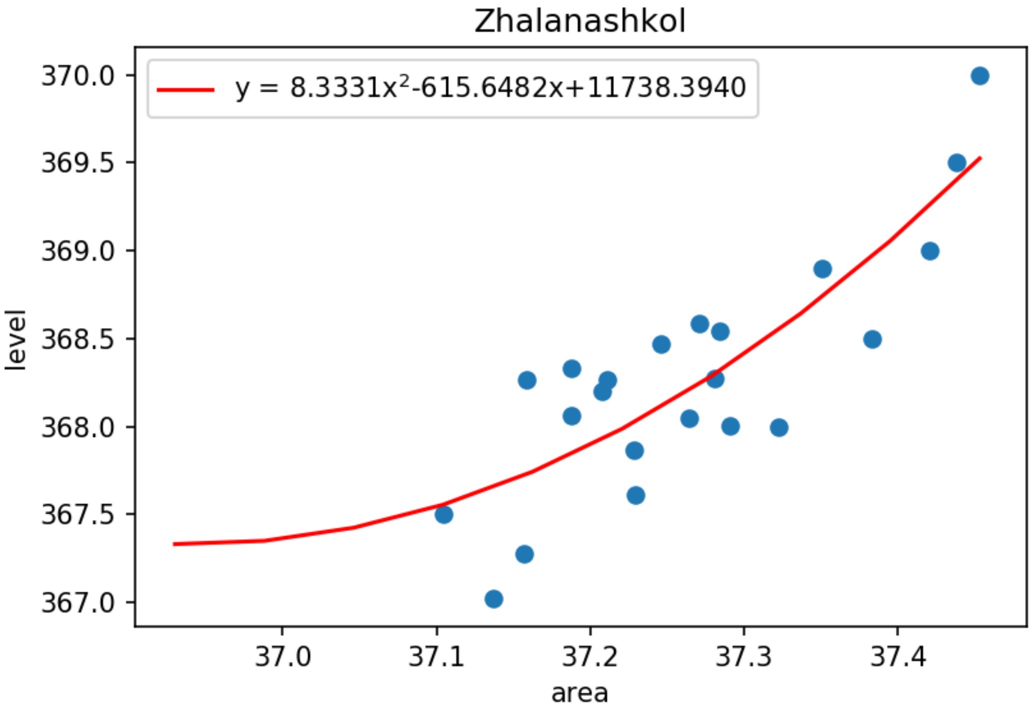

Figure 3.20: Hypsometry of Zhalanashkol

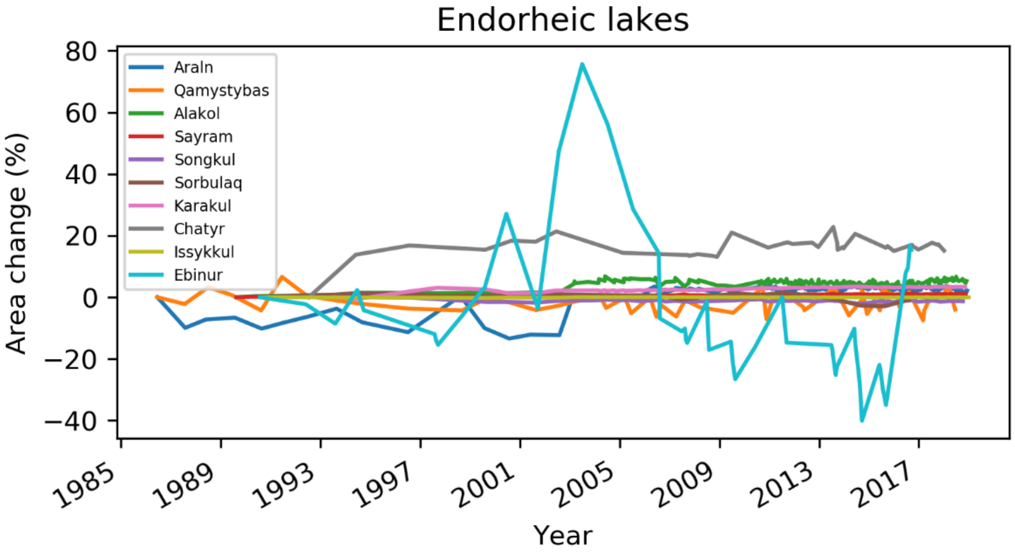

Figure 3.21: Area changes of endorheic lakes

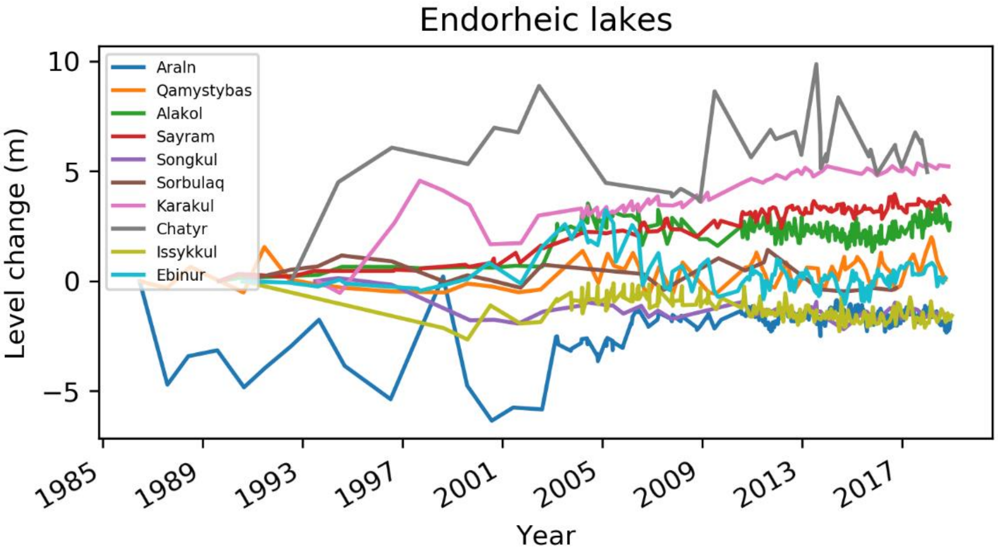

Figure 3.22: Level changes of endorheic lakes

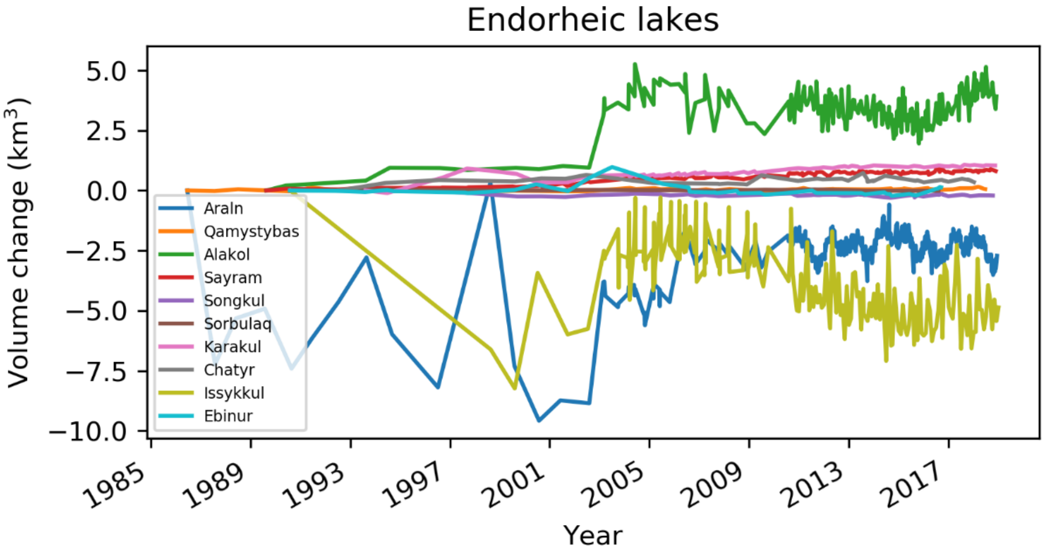

Figure 3.23: Volume changes of endorheic lakes

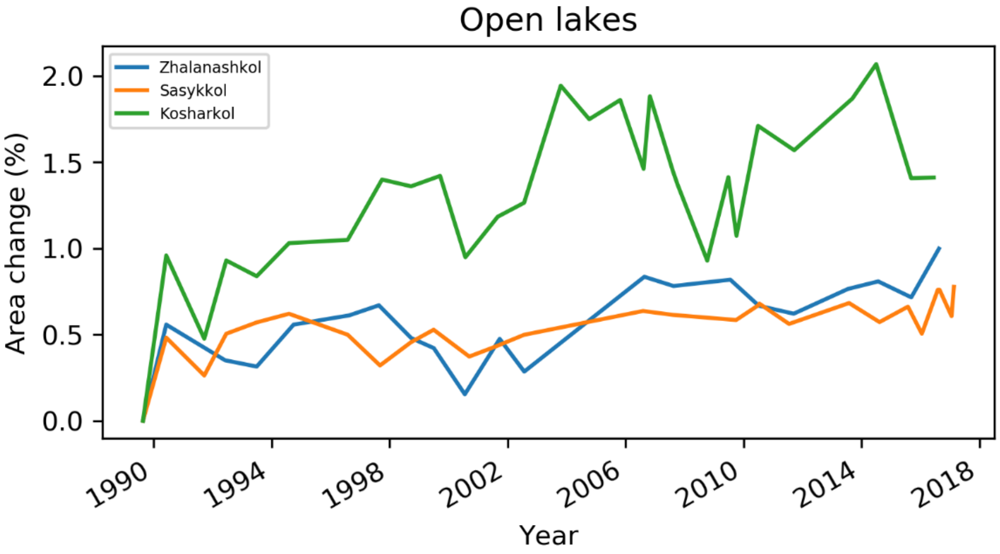

Figure 3.24: Area changes of open lakes

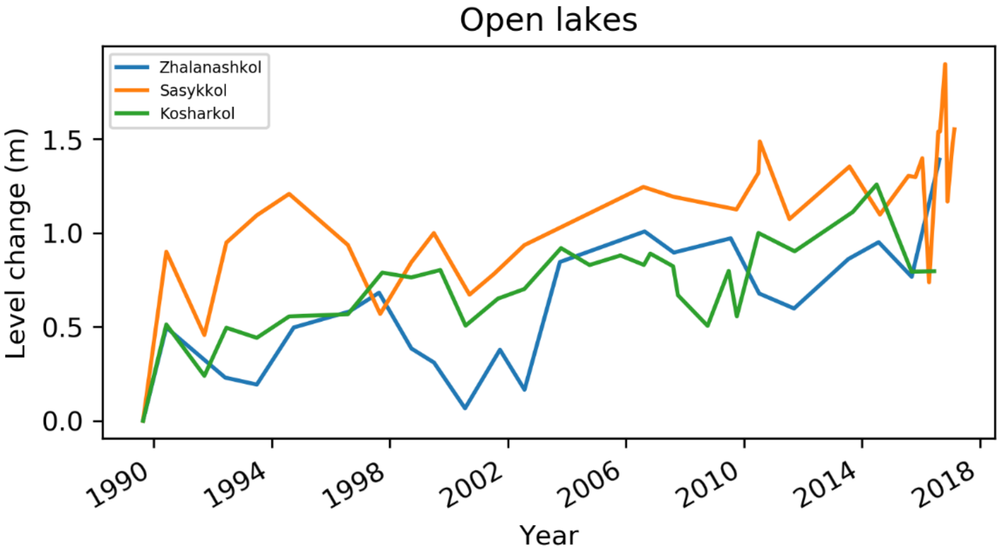

Figure 3.25: Level changes of open lakes

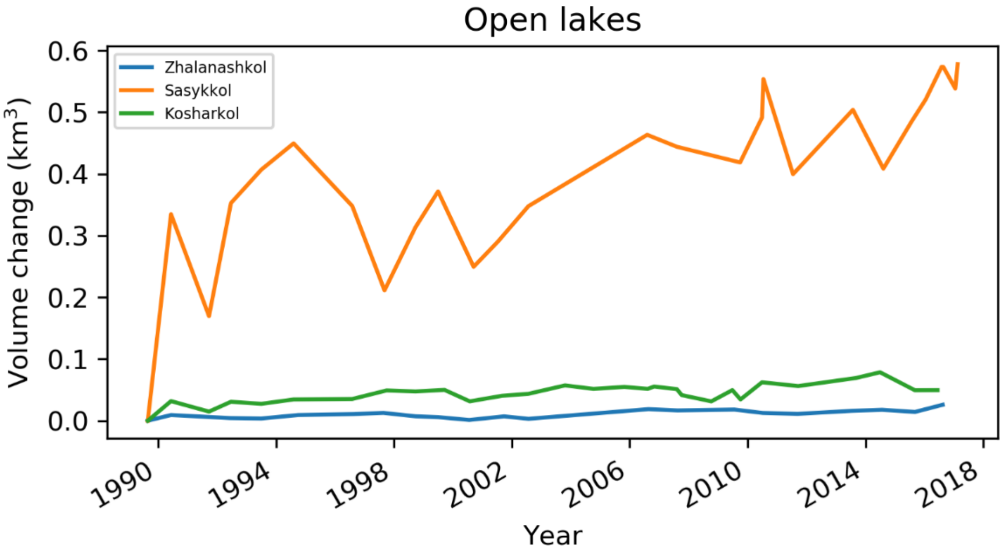

Figure 3.26: Volume changes of open lakes

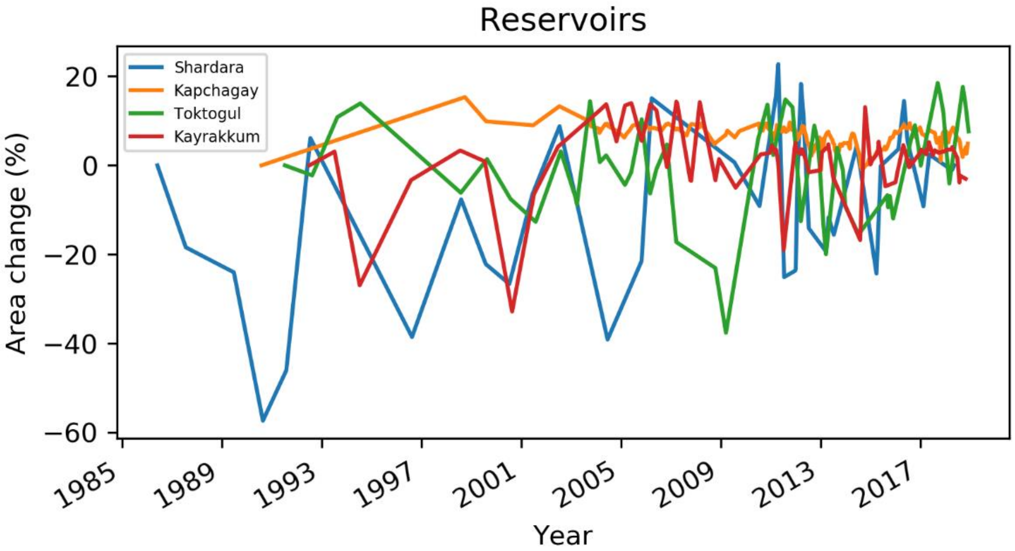

Figure 3.27: Area changes of reservoirs

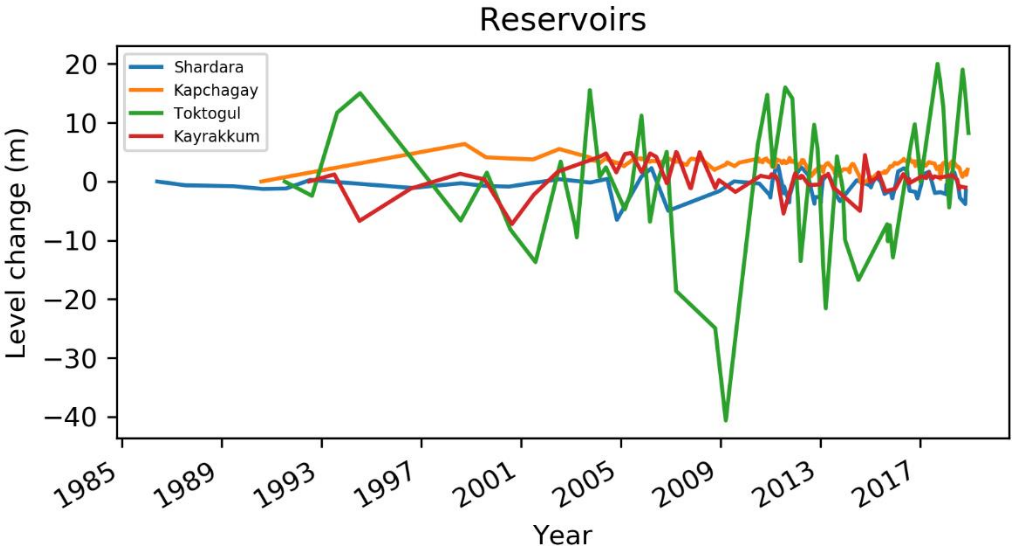

Figure 3.28: Level changes of reservoirs

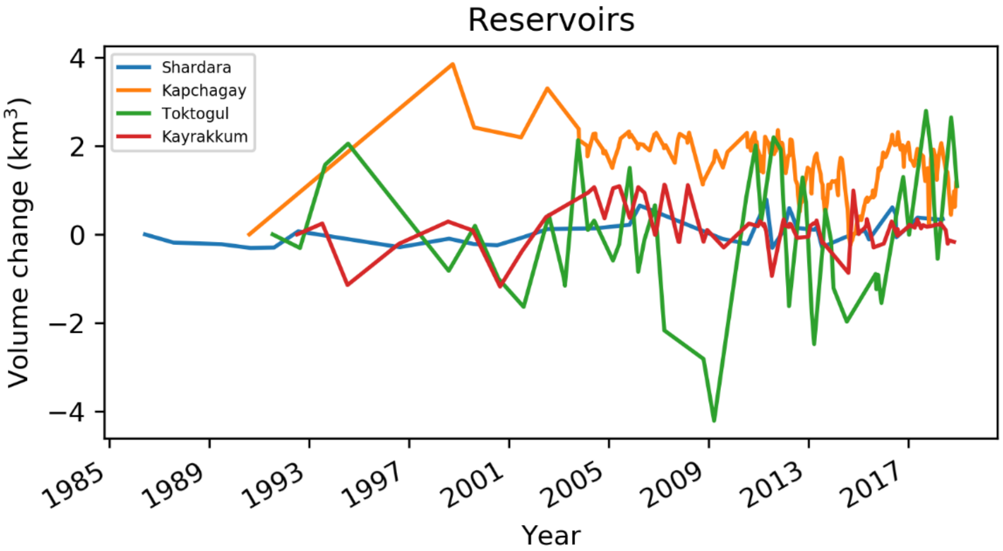

Figure 3.29: Volume changes of reservoirs

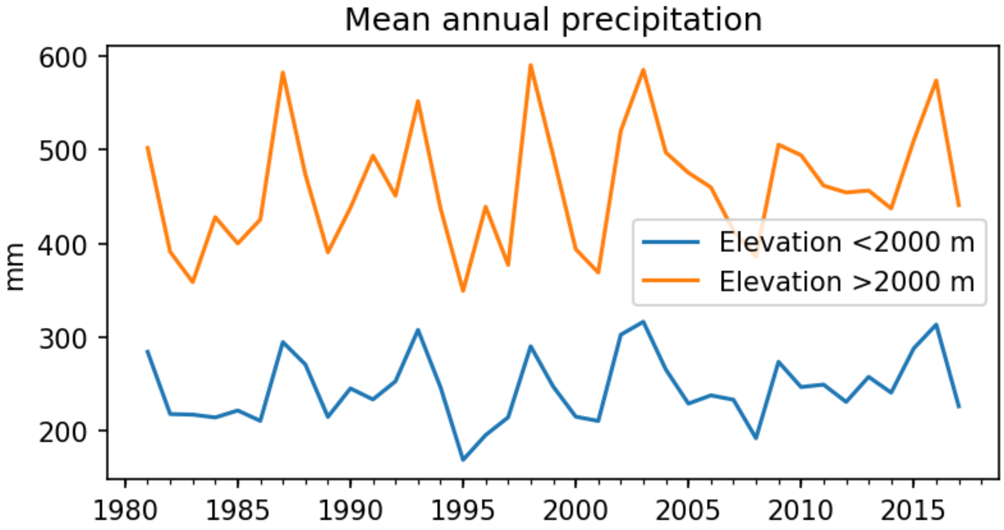

Figure 3.30: Precipitation trends at difference elevations (Harris et al., 2014)

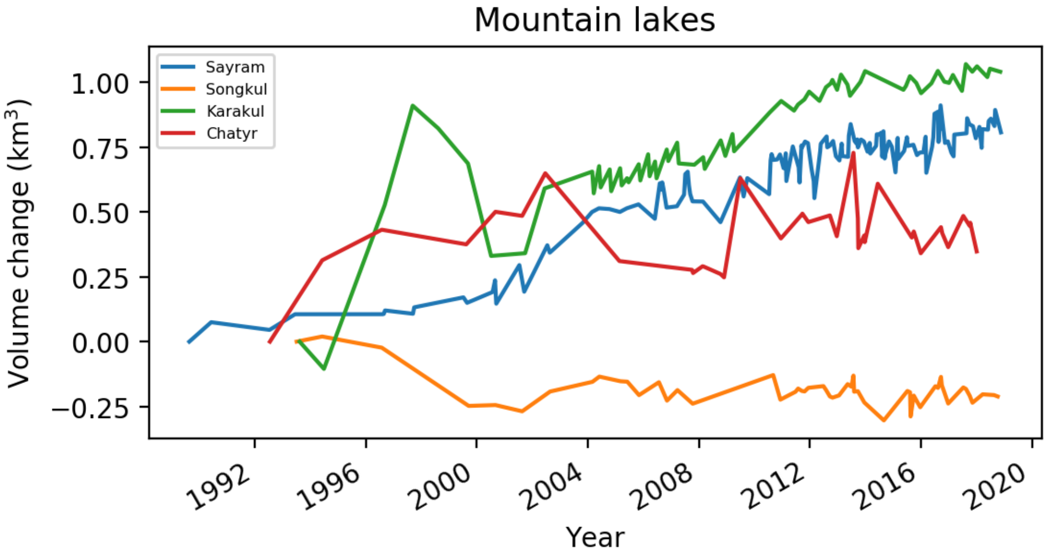

Figure 3.31: Volume change of mountain lakes at elevation above 2,000 m

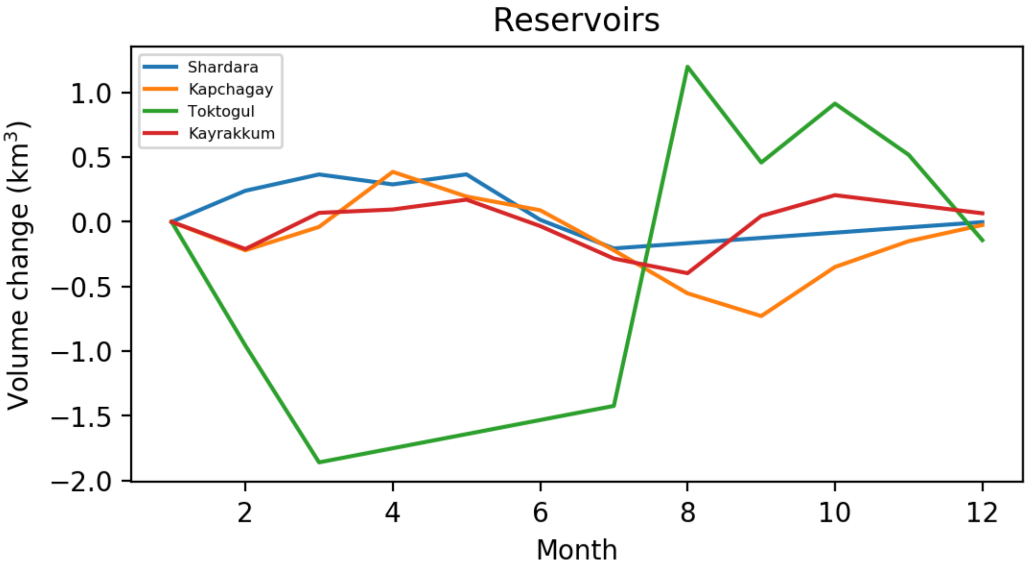

Figure 3.32: Seasonal volume change of reservoirs

Table 3.1: Lake characteristics

Lake name	County	Type	Elevation
Alakol	Kazakhstan	Endorheic	347
Aral Sea north	Kazakhstan	Endorheic	39
Chatyr	Kyrgyzstan	Endorheic	3,526
Ebinur	China	Endorheic	194
Issykkul	Kyrgyzstan	Endorheic	1,601
Kapchagay	Kazakhstan	Reservoir	475
Karakul	Tajikistan	Endorheic	3,915
Kayrakkum	Tajikistan	Reservoir	345
Kosharkol	Kazakhstan	Open	348
Qamystybas	Kazakhstan	Endorheic	55
Sasykkol	Kazakhstan	Open	348
Sayram	China	Endorheic	2,072
Shardara	Kazakhstan	Reservoir	248
Songkul	Kyrgyzstan	Endorheic	3,011
Sorbulaq	Kazakhstan	Endorheic	618
Toktogul	Kyrgyzstan	Reservoir	871
Zhalanashkol	Kazakhstan	Open	366

Table 3.2: Lake hypsometry derived from digital elevation model and range of area and water level

Lake name	Equation	Area range (km^2)	Level range (m)
Alakol	$H = 2.3065 \times 10^{-5} \times A^2 - 0.1182 \times A + 497.2126$	[2873.49, 3009.72]	[348.45, 350.64]
Aral Sea north	$H = 0.0146 \times A + 4.2809$	[2802.82, 3393.62]	[39.40, 42.21]
Chatyr	$H = 0.0070 \times A^2 - 1.6881 \times A + 3623.0605$	[130.42, 160.17]	[3528.88, 3532.14]
Ebinur	$H = 2.4450 \times 10^{-6} A^2 + 0.0027 \times A + 192.6407$	[324.37, 950.84]	[191.35, 195.49]
Issykkul	$H = 0.0033 \times A^2 - 41.1033 \times A + 128558.3667$	[6202.14, 6218.08]	[1602.93, 1605.12]
Kapchagay	$H = 0.0372 \times A + 432.8686$	[1116.7, 1291.32]	[473.67, 478.20]
Karakul	$H = 0.0090 \times A^2 - 6.8183 \times A + 5199.2527$	[390.42, 409.71]	[3916.01, 3918.49]
Kayrakkum	$H = 0.0003 \times A^2 - 0.1472 \times A + 354.5827$	[267.52, 415.12]	[340.18, 346.43]
Kosharkol	$H = 0.0435 \times A^2 - 10.3606 \times A + 966.3586$	[123.43, 125.99]	[350.10, 350.87]
Qamystybas	$H = 0.0045 \times A^2 - 1.2755 \times A + 146.0976$	[144.80, 162.55]	[55.33, 57.88]
Sasykkol	$H = 0.0105 \times A^2 - 15.3671 \times A + 5969.7212$	[741.74, 747.37]	[348.28, 350.72]
Sayram	$H = 0.0451 \times A^2 - 40.8125 \times A + 11307.3392$	[458.00, 463.01]	[2073.36, 2075.75]
Shardara	$H = 8.7239 \times 10^{-6} \times A^2 - 0.0043 \times A + 249.2169$	[266.51, 680.37]	[241.88, 251.09]
Songkul	$H = 0.0281 \times A^2 - 15.2606 \times A + 5083.3997$	[274.80, 281.20]	[3012.64, 3013.49]
Sorbulaq	$H = 0.4485 \times A^2 - 54.4686 \times A + 2275.2113$	[59.93, 62.84]	[617.49, 618.73]
Toktogul	$H = 0.4236 \times A + 776.0659$	[215.44, 292.75]	[843.45, 904.08]
Zhalanashkol	$H = 8.3331 \times A^2 - 615.6482 \times A + 11738.3940$	[36.98, 37.35]	[366.19, 369.89]

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Agreement (1993) Agreement between the Republic of Kazakhstan, the Kyrgyz Republic, the Republic of Tajikistan, Turkmenistan, and the Republic of Uzbekistan on joint actions for addressing the problems of the Aral Sea and its Coastal Area, improving the environment, and ensuring the social and economic development of the Aral Sea region, Kzyl-Orda (signed 26 March 1993)

Agreement (1996) Agreement between the Republic of Uzbekistan and Turkmenistan on cooperation in water management issues, Chardjev, Turkmenistan (signed 16 January 1996)

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CHAPTER 4

CHANGES IN AGRICULTURE EXTENT ACROSS CENTRAL ASIA IN THE PAST 20 YEARS OBSERVED FROM REMOTE SENSING

4.1 Introduction

Central Asia is an arid region with over 100 million population. The common definition includes the former Soviet Central Asian republics (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan), northeastern Iran, Afghanistan, northern and central Pakistan, northern India, western China and Mongolia (Dani et al., 1992). Population density is highest along the foothills of Tianshan and Pamir mountains in the former Soviet Central Asian republics and parts of Xinjiang, China (Pesaresi et al., 2013). Agriculture plays a significant role in the economy Central Asia, accounting for 5.0% to 27.4% of GDP in Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (FAO, 2016) with 20% to 50% of the labor force working in the agriculture sector (Qushimov et al., 2007). Due to its aridity, between 75% and 100% of agriculture land in Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan is irrigated (Frenken, 2013). About 90% of Central Asia receives less than 400 mm of precipitation per year while the Tianshan and Pamir mountains can receive over 1,000 mm due to orographic effects (Bolch, 2007; Williams, 2008; Mueller et al., 2014). As a result, about 50% to 90% of available water resources in the region originates from the mountains (Viviroli and Weigartner, 2004).

During the Soviet era when Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan were part of the Soviet Central Asian republics, each country specialized in certain crop types. Kazakhstan specialized in grain production, Kyrgyzstan in alfalfa and maize while Tajikistan, Turkmenistan and Uzbekistan focused on cotton (Suleimenov 2014). Extensive irrigation canals and drainage systems were developed in the region that extended well into the deserts and irrigated agriculture experienced steady expansion during this time (Micklin, 2014). Soil salinization has become a serious issue as a result of heavy irrigation and irrigation efficiency declined as more water is required to flush the salt out from the soil prior to planting crops (Pankova et al. 1996; Micklin, 2000).

After the collapse of the Soviet Union in 1991, these countries adopted their own agricultural strategies to achieve food security. Uzbekistan became the country having the largest irrigated area (4.28 million ha) as well as the largest share of irrigation water withdrawal (53.0%) in the Aral Sea basin in 1995 (World Bank, 1998). The expansion rate of irrigated area greatly decreased since 1995 and irrigated area became stable since 2000. Associated with changes in irrigation area are changes in the type of crops being planted. Uzbekistan, which was the largest cotton producer at the Soviet Union time, shrank its area of cotton plantation by 19% (Index 2012a) while tripling its area of wheat plantation during the first five years after the collapse of the Soviet Union (Index 2012b). During 1995-2011, Uzbekistan further reduced its cotton area by 10% while increasing its wheat area by 8%. Turkmenistan, which was the second largest cotton producer, shrank its cotton area by 28% during 1990-1995 (Index, 2012c) while sextupling its wheat area (Index, 2012d) and again doubling the 1995 wheat area by 2011. These changes are driven by the need to strengthen the countries' food bases (Micklin 2014). Kazakhstan and Uzbekistan being the largest rice producers, also dropped their rice plantation area by 23% between 1990-1995 and 72% between 1990-2001 respectively (Index, 2012e; Index, 2012f). Legume crops such as dry peas, dry beans and chickpeas were also introduced (Suleimenov, 2014).

In western China, agriculture has been developed since the 1950s and has been rapidly expanding (Sun and Gao 2010). The widespread irrigation combined with inefficient water management strategies has led to severe desertification and ecological deterioration in Ebinur lake basin in Xinjiang (Zhang et al., 2015). In efforts to restore ecological stability in Ebinur basin, Ebinur lake wetland nature reserve was established in the late 1990s (Bai, 2007). Highly efficient drip irrigation was also introduced around the late 1990s (Xu et al., 2003).

In light of the importance of agriculture to the local economy as well as the impact of agriculture on water resources, it is crucial to understand the development of agriculture in Central Asia in the modern era. It is especially important to understand agriculture changes in the former Soviet Central Asian republics as they have undergone drastic re-organizations of agriculture land since independence in 1991 (Hamidov et al., 2016). The goal of this study is to 1) examine changes in agriculture extent in the most populated lake/river basins in Central Asia; 2) compare and contrast patterns shown in different basins and countries and 3) discuss the implication of those changes on water resources in the region.

4.2 Study area

Figure 4.1 shows the study area which includes the most fertile and populated regions in Central Asia. The study area includes nine lake or river basins namely: Alakol, Amu Darya, Ebinur, Ili, Issykkul, Sayram, Sarykamish, Songkul, Syr Darya. Countries that share the basins include Afghanistan, China, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Table 4.1 shows basic characteristics of the countries that share these basins. Kazakhstan has the largest share of all basins accounting for 670,005 km^2 (38%) followed by Uzbekistan accounting for 380,042 km^2 (22%). All other countries share a similar area ranging between 121,435 km^2 and 166,081 km^2. The largest basin by area is Amu Darya at 793,131 km^2 (45%) and is shared by all countries except China. The most notable agriculture regions in the area is the Fergana valley which is in the Syr Darya river basin and shared by Kyrgyzstan, Tajikistan and Uzbekistan.

4.3 Data and methods

We collected the 16-day MODIS Vegetation Indices product at 250 m resolution (MOD13Q1) from 2000 to 2017 and used the Normalized Difference Vegetation Index (NDVI) data set to derive agriculture extent in our study area. This period was chosen because it takes some time for the re-organization of agriculture to take settle after the former Soviet Central Asia republics gained independence (Hamidov et al., 2016). A total of 2,055 images were collected to cover the entire spatial and temporal extents. To map the extent of agriculture in the region, we used a simple thresholding technique based on the annual mean NDVI as in Rembold and Maselli (2006) with additional criteria based on the terrain. Three criteria were used to determine whether a pixel is considered to be agricultural or not. 1) Its annual mean NDVI value is between 0.25 and 0.45; 2) its elevation is below 2,000 m and 3) its slope is less than 5%. This set of criteria effectively identifies agriculture lands from the surrounding barren lands while also removes forested regions in the high mountains. The results were then partitioned into basins and countries for further analysis.

We removed misclassifications through manual inspection using Google Earth high resolution imagery to remove misclassifications of wetlands and grasslands. We also collected the agricultural cropland area product for Central Asia from the Global Food Security Support Analysis Data (GFSAD30) Cropland Extent 30 m for nominal year 2015 (Phalke et al., 2017; Telunguntla et al., 2017). This product was derived using Landsat data collected between 2013 and 2015. Accuracy of our classification for 2015 was validated against this product to assess the reliability of our results.

4.4 Results

Figure 4.2 shows the maximum agriculture extent from 2000 to 2017 with the extent in all years combined. Most agriculture land occurs near water sources such as the foothills of the

Tianshan mountains, along river channels and river deltas near the river terminus. Significant amount of agriculture has also expanded into the desert area in Kazakhstan, Uzbekistan and Turkmenistan.

Figures 4.3 – 4.9 show the area changes of agriculture land by country. All countries except for China, Turkmenistan and Kazakhstan had an overall stable area from 2000 to 2017 with some interannual variability. The average agriculture area in these basins of Afghanistan, China, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan are 4,289, 17,812, 41,202, 5,335, 8,051, 6,535 and 55,384 km^2 respectively with the majority being in Kazakhstan and Uzbekistan. Over the 18 years, agriculture area in China and Turkmenistan had an increasing trend of 478 and 174 km^2/yr respectively while Kazakhstan had a slight decreasing trend of 728 km^2/yr. China has shown a steady expansion of agriculture area, while all other countries shared similar patterns of interannual variability. For example, Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan all had a sharp decline of agriculture area in 2001, 2008, 2011 and 2014 and remarkable growth in 2003, 2009, 2010, 2015 and 2016.

Figures 4.10 – 4.16 show the area changes of agriculture land by basin. The average agriculture area in Alakol, Amu Darya, Ebinur, Ili, Issykkul, Sarykamish and Syr Darya are 4,875, 52,655, 6,062, 26,374, 2,055, 4,030 and 45,310 km^2 respectively with the majority being in Amu Darya, Ili and Syr Darya. Over the 18 years, four out of seven basins had an increasing trend in agriculture area while two of them had a decreasing trend and one basin remained relatively stable. Agriculture area in Alakol, Ebinur, Sarykamish and Syr Darya increased by 141, 266, 164 and 279 km^2/yr respectively while Amu Darya, Ili and Issykkul slightly decreased by 258, 104 and 1 km^2/yr respectively. Ebinur showed significant growth while all other basins shared similar patterns of interannual variability as well. For example, they all had lower agriculture area in 2001, 2008, 2011 and 2014 and larger area in 2003, 2009, 2010 and 2016, which is similar to patterns seen when grouped by countries.

4.5 Discussion

4.5.1 Accuracy assessment

The overall accuracy of our binary classification (agriculture or non-agriculture) is 91.5%. The user accuracy for agriculture area is 75.1% while the producer accuracy is 50.3%. Figure 4.17 shows a map of the accuracy assessment. We also compared the reference data to Google Earth imagery in 2015 and we found a general over-estimation especially in Alakol and Ili basin which in part explains the low producer accuracy.

4.5.2 Cause of agriculture area changes

The percentage of agriculture area that is irrigated in Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan ranges between 75% and 100% (Frenken, 2013). Thus, agriculture is highly dependent upon available water in the region. Figure 4.18 shows mean annual precipitation in the entire study area derived from the Climate Research Unit data set (Harris et al., 2014). Mean annual precipitation is low in 2001, 2008 and 2017 while high in 2003, 2009 and 2016. This is similar to agriculture patterns in Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan and all basins except Ebinur.

Table 4.2 shows the correlation between agriculture area and mean annual precipitation in each country and basin. The correlation between agriculture area and precipitation in Afghanistan, Tajikistan and Uzbekistan and in Amu Darya, Ili and Syr Darya basins are all above 0.7. This suggests that available irrigation water in these countries and basins are highly dependent upon precipitation from the same year. In the Ebinur basin (98% area is in China), where agriculture has expanded continuously regardless of annual precipitation, other water sources are available for irrigation. Groundwater is likely the source that is used for irrigation. In fact, in a field survey conducted in the summer of 2018 we found widespread groundwater pumps in the agriculture fields in Ebinur basin. Drip irrigation is also widely adopted in Ebinur basin (Su, 2014). This is a much more efficient irrigation technique compared to furrow irrigation that is generally used in the other countries (Micklin, 2007).

In the former Soviet Central Asian republics (i.e. Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan), groundwater infrastructures are largely underdeveloped (Rakhmatullaev et al., 2010). Groundwater withdrawal accounts for 4.0% - 19.6% in the former Soviet Central Asian republics (FAO, 2016) Most of the groundwater extraction in the Amu Darya basin still uses equipment developed during the Soviet period (Rakhmatullaev et al., 2010) and it is not economically profitable in Uzbekistan due to the extraction cost (Borisov, 1990). Also, the canals transferring water deep into desert regions for irrigation suffers from large evaporation and exfiltration (Micklin 2007).

Therefore, due to irrigation inefficiency, precipitation likely limits the number of crops that can be cultivated each year in all countries except China. Agriculture area changes in those countries is likely reflecting the changes in mean annual precipitation. In China, irrigation water is not limited by annual precipitation as water is also extracted from groundwater aquifers. As a result, agriculture has been expanding continuously in China and especially in the Ebinur basin.

4.5.3 Connection with lake changes

Since irrigation account for over 90% of water withdrawal in five out of seven countries in the area (FAO, 2016), it has great impacts on the amount of water that flows into lakes. Historically, between the 1950s and 1980s when agriculture development in Soviet Central Asia was the fastest, we observed the catastrophic decline of the Aral Sea from what used to be the fourth largest lake in the world in the 1960s to roughly one sixth of its original area at present. This is commonly known as the as Aral Sea disaster and its cause is widely attributed to irrigation extraction of water from Amu Darya and Syr Darya which feed the lake (Micklin, 2007; Kosti͡anoĭet al., 2010; Cretaux et al., 2013).

Since the 1980s, the majority of lakes in the region have remained stable with some decline (See Chapter 3). Lakes located in the remote high-elevation mountain regions are generally expanding throughout the period due to the increased melting of snow and glaciers in a warming climate. This suggests that more water is being generated from the mountains. Nevertheless, due to the development of agriculture in the lowland regions, lakes at low elevations have not seen similar expansions like mountain lakes. In basins with relatively stable agriculture extent between 2000 and 2017 lakes have remained stable as well. For example, Aral Sea north and Qamystybas are both stable between 2000 and 2017. They both lie in the Syr Darya basin whose agriculture area have only seen a slight increase. This indicates possible influence of agriculture irrigation on lake volume. Some interesting exceptions are Alakol, Sassykol and Zhalanashkol lakes which have all expanded between 2000 and 2017 while the agriculture extent in their basin has also slightly expanded. Ebinur Lake as discussed in Chapter 2 has declined between 2000 and 2017 while agriculture has expanded continuously. Modeling results show that the natural climate conditions would be also responsible for the decline of Ebinur Lake.

4.6 Conclusion

Irrigated agriculture plays a significant role in the economy in Central Asia and has great influence on water resources in the region. Here, we used satellite imagery to examine the changes of agriculture area in various countries and basins in Central Asia from 2000 to 2017. We derived annual agriculture extent from a MODIS NDVI product and assessed the accuracy using Google

Earth imagery and Global Food Security Support Analysis Data (GFSAD30) Cropland Extent data. We analyzed the patterns of agriculture development and discussed its relationship with lake and water resource changes.

First, we found that agriculture area remained relatively stable in Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan. There is a high correlation between agriculture area with the annual rainfall of that year. Given the older and less efficient irrigation infrastructure used in the former Soviet Central Asian republics, the amount of available surface water generated from precipitation likely limits the development agriculture in these countries.

Second, rapid expansion of agriculture was found in China and to a lesser degree in Turkmenistan. Agriculture expansion in China was contributed mostly by the development in Ebinur basin. The use of groundwater for irrigation is widespread in Ebinur basin but not in counties in the former Soviet Central Asian republics. This additional source compensating surface water and more efficient irrigation techniques may have allowed the continuous expansion of cultivated land in China.

Third, the link between agriculture development and lake changes between 2000 and 2017 is relatively weak. There is little correlation between lake changes and agriculture area and in some cases the climate variability has a more dominant influence of lake changes. Future work aided by better data availability and quality is required to fully assess the independent contribution of climate and human factors on water resources in this region.

Figure 4.1: Study area

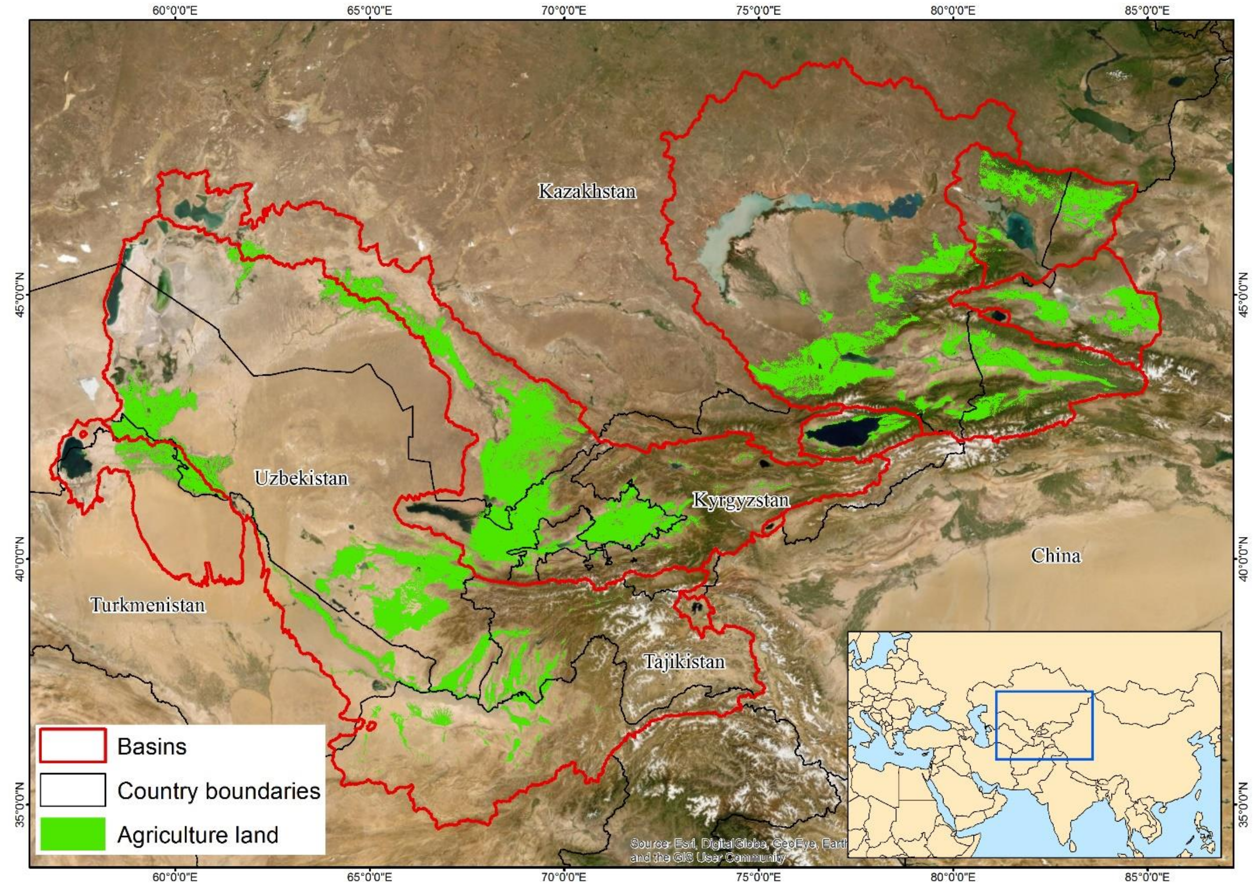

Figure 4.2: Maximum agriculture extent between 2000 and 2017

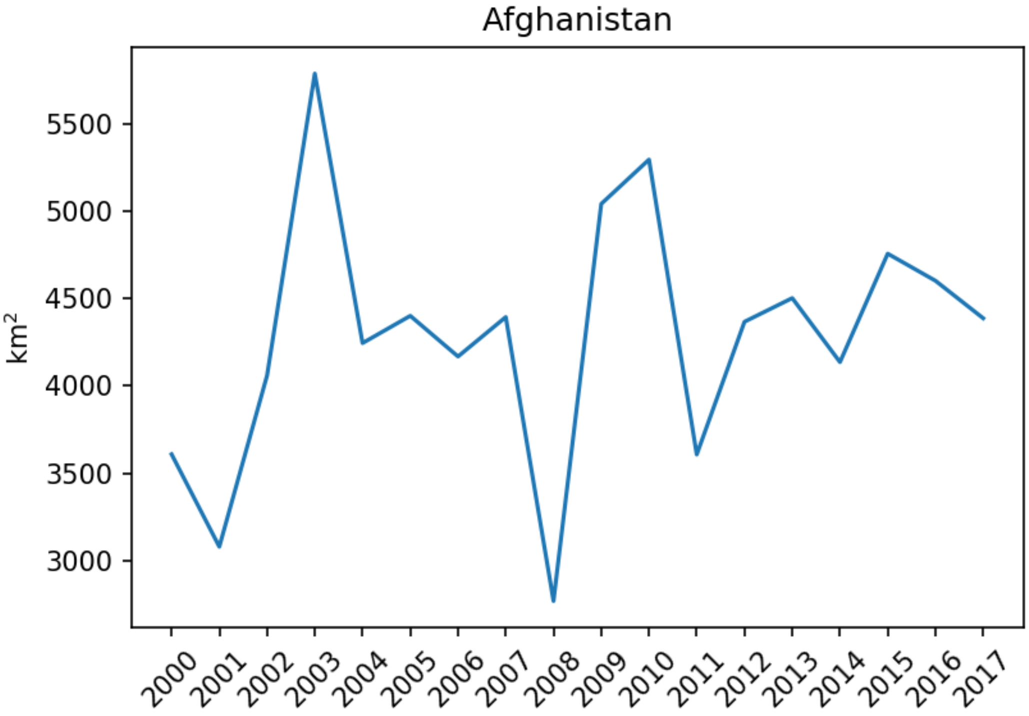

Figure 4.3: Annual agriculture area in Afghanistan

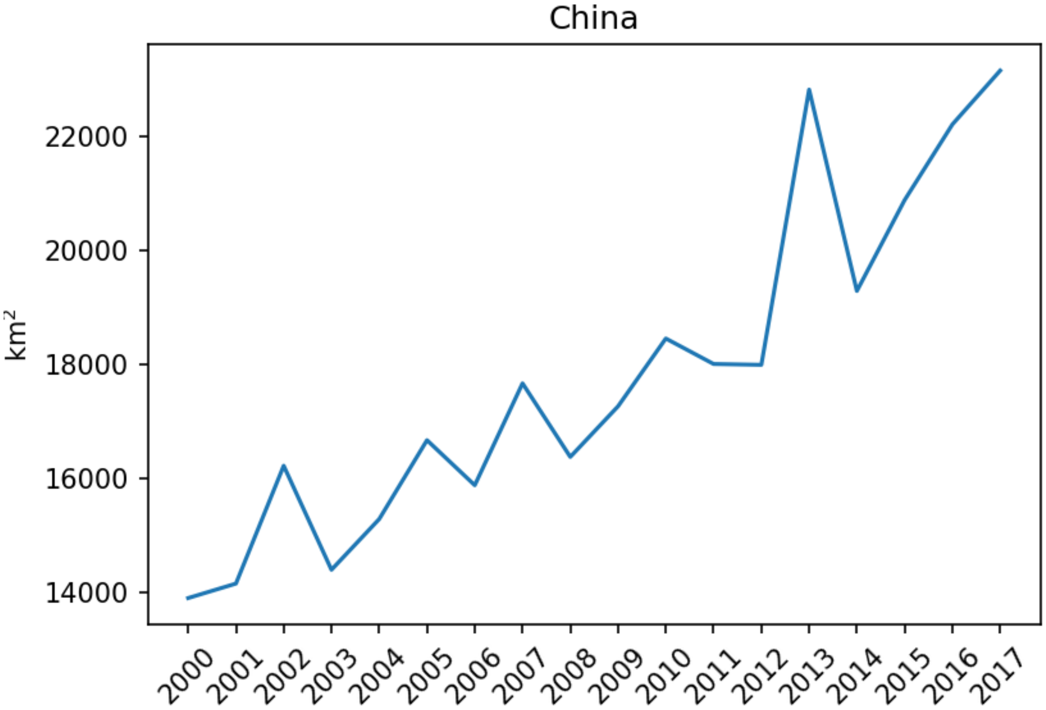

Figure 4.4: Annual agriculture area in China

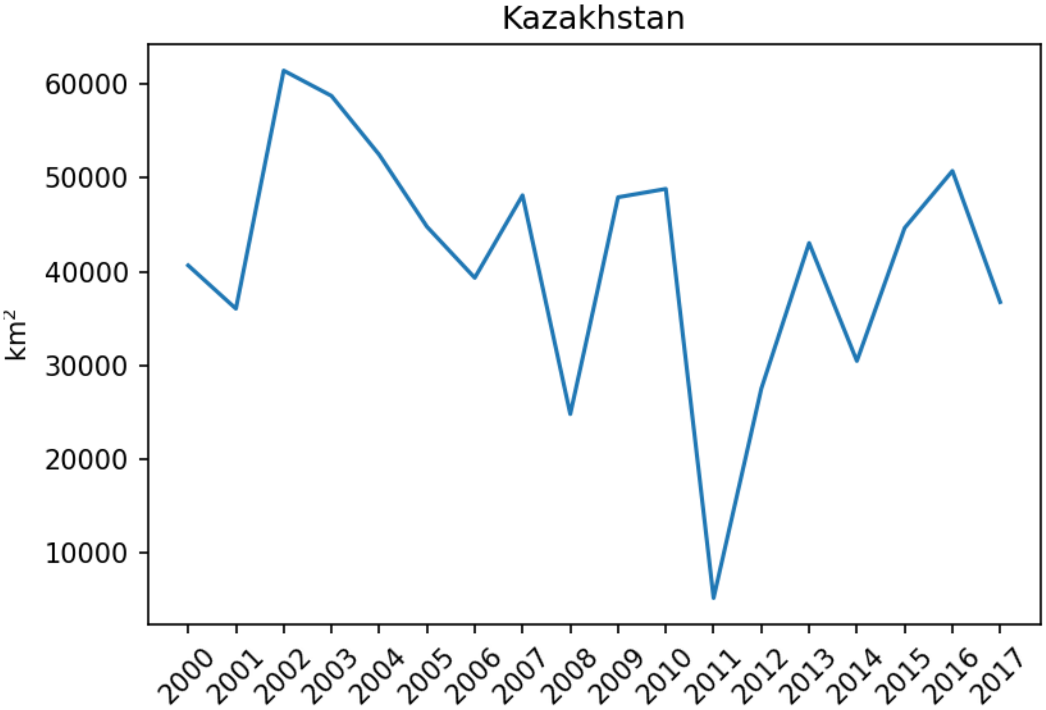

Figure 4.5: Annual agriculture area in Kazakhstan

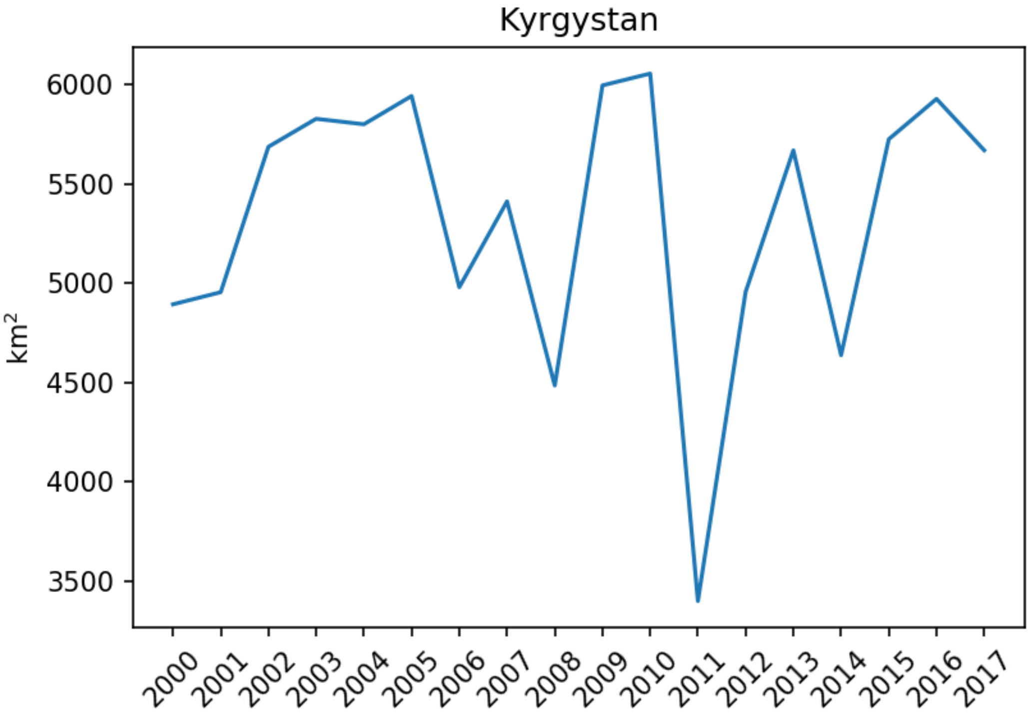

Figure 4.6: Annual agriculture area in Kyrgyzstan

Figure 4.7: Annual agriculture area in Tajikistan

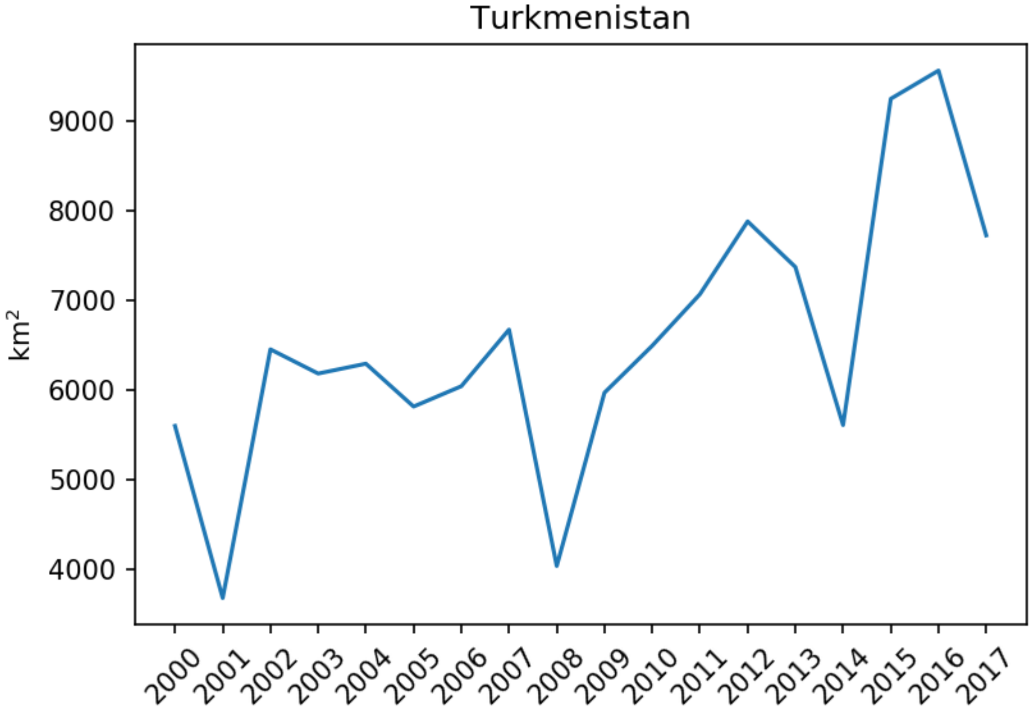

Figure 4.8: Annual agriculture area in Turkmenistan

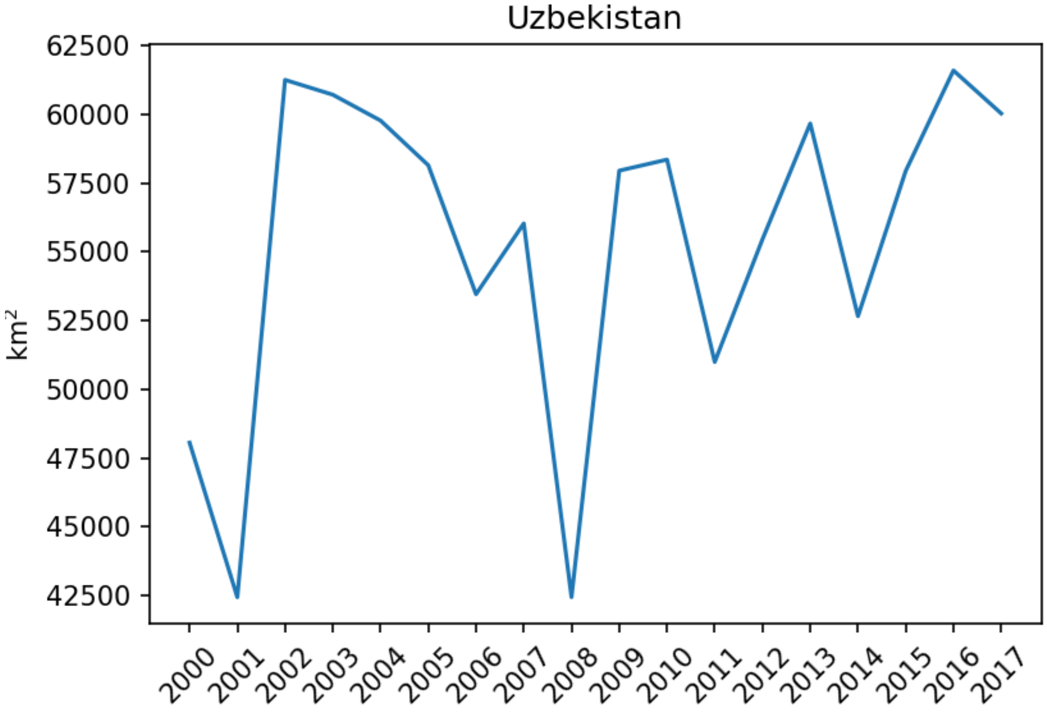

Figure 4.9: Annual agriculture area in Uzbekistan

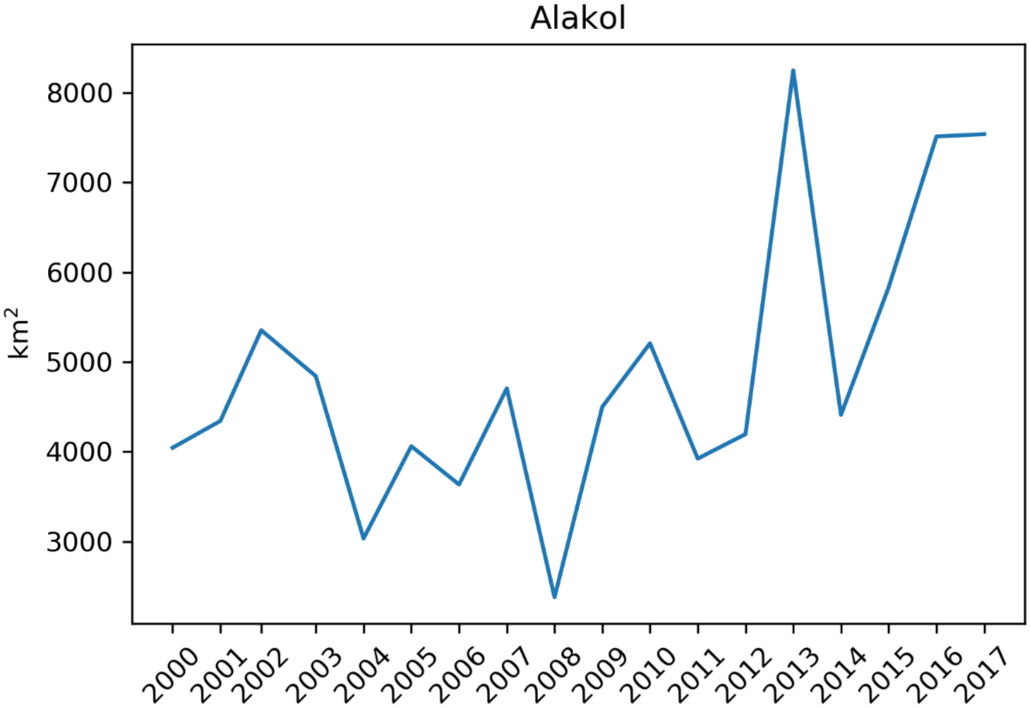

Figure 4.10: Annual agriculture area in Alakol basin

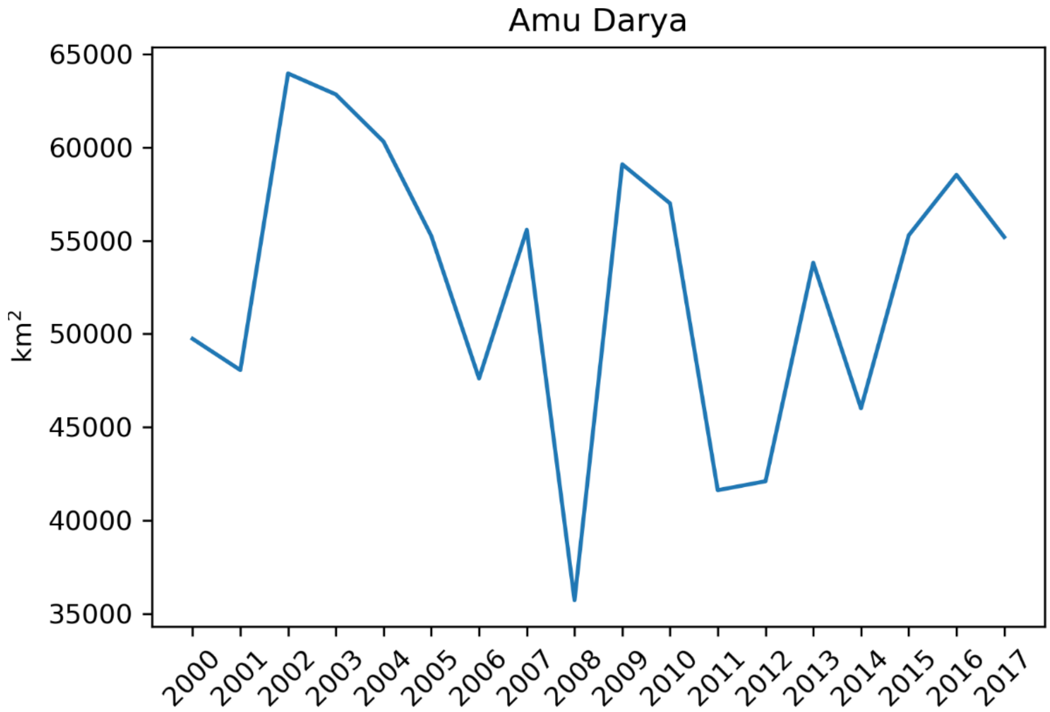

Figure 4.11: Annual agriculture area in Amu Darya basin

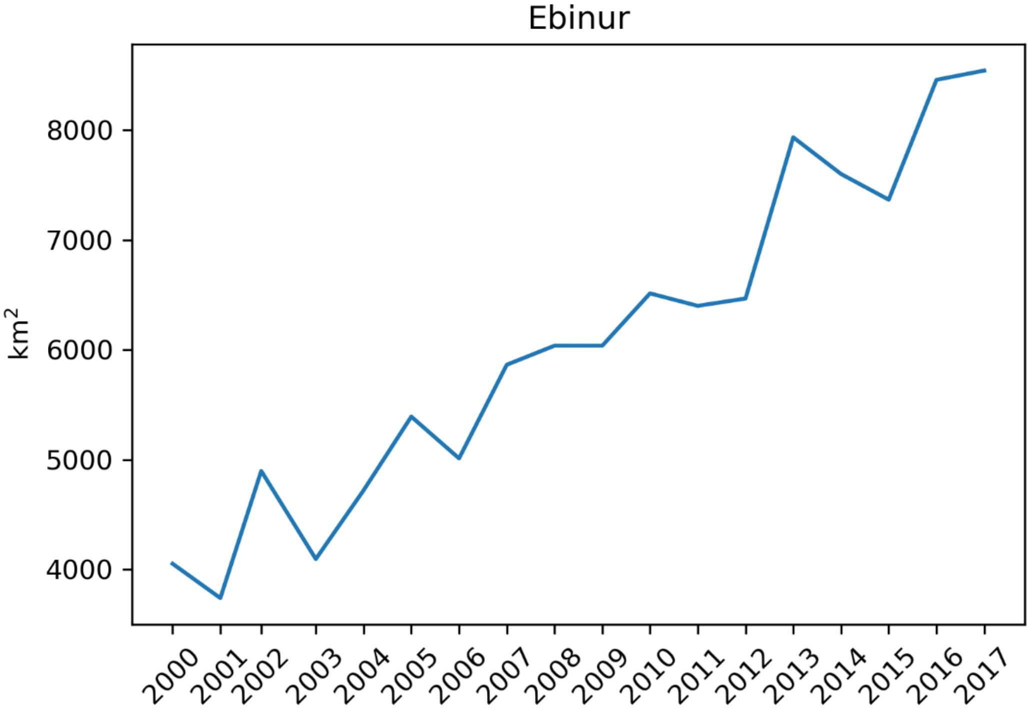

Figure 4.12: Annual agriculture area in Ebinur basin

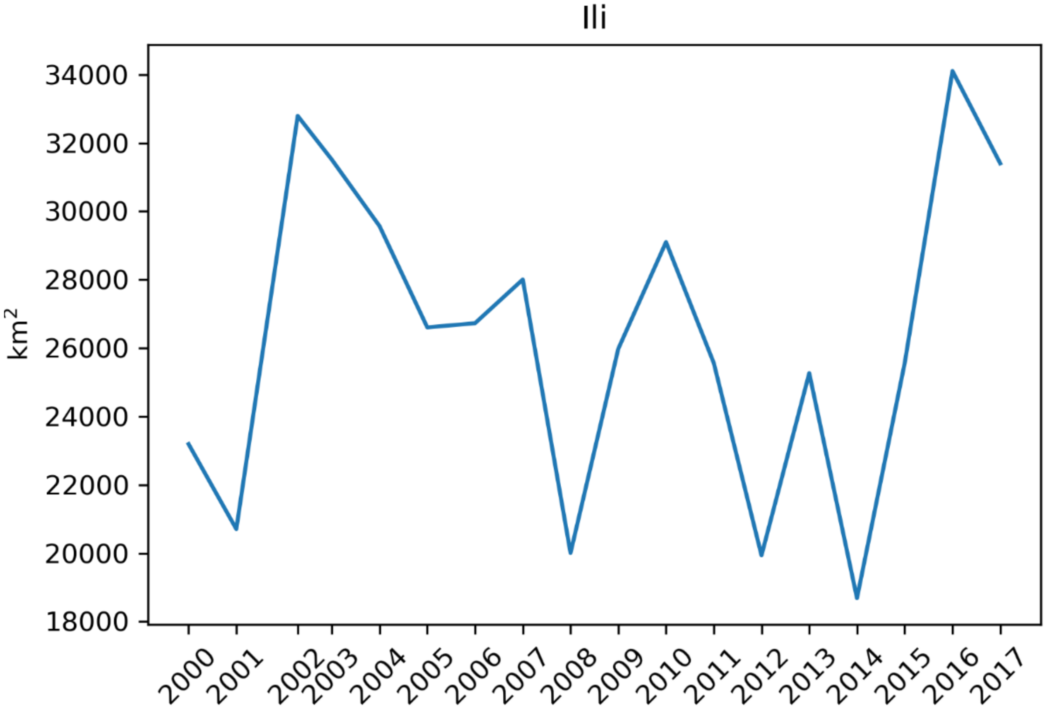

Figure 4.13: Annual agriculture area in Ili basin

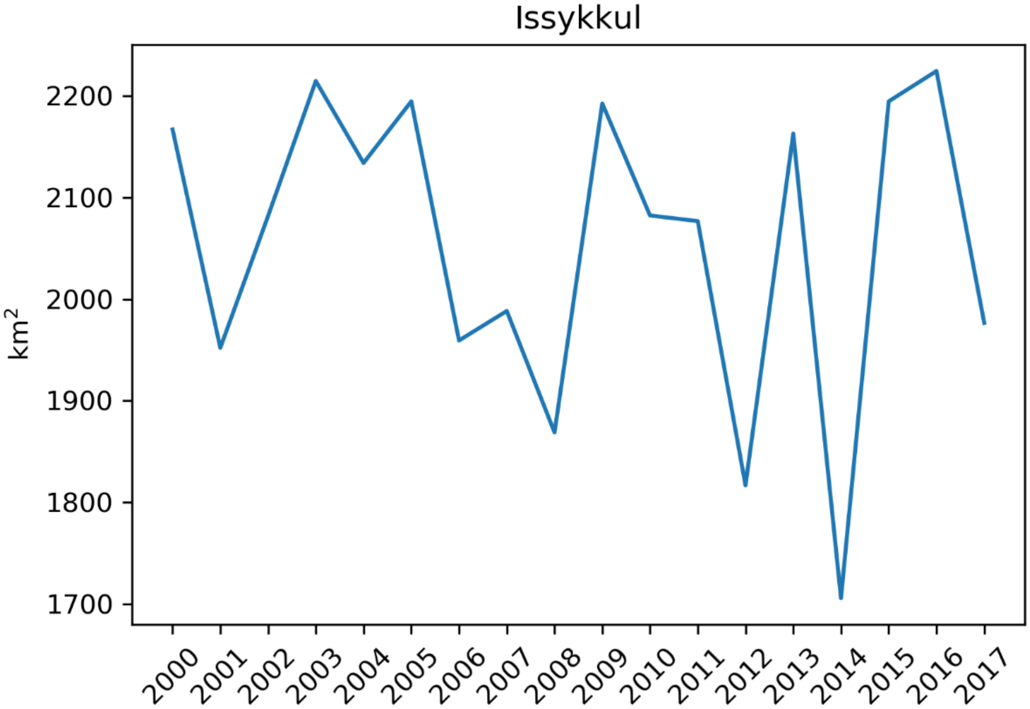

Figure 4.14: Annual agriculture area in Issykkul basin

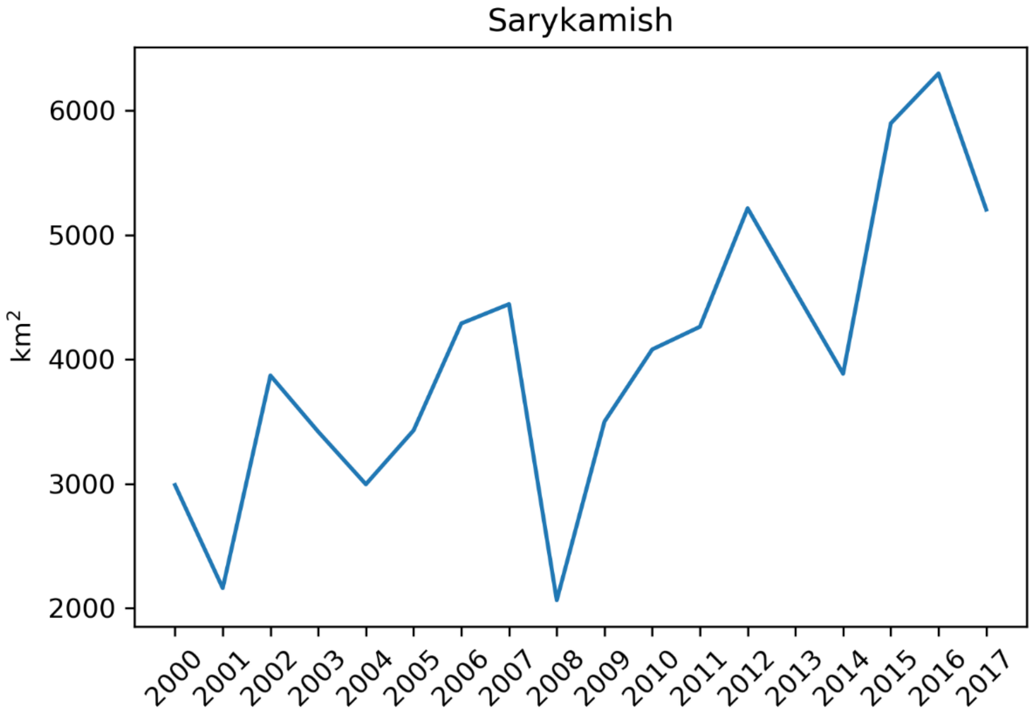

Figure 4.15: Annual agriculture area in Sarykamish basin

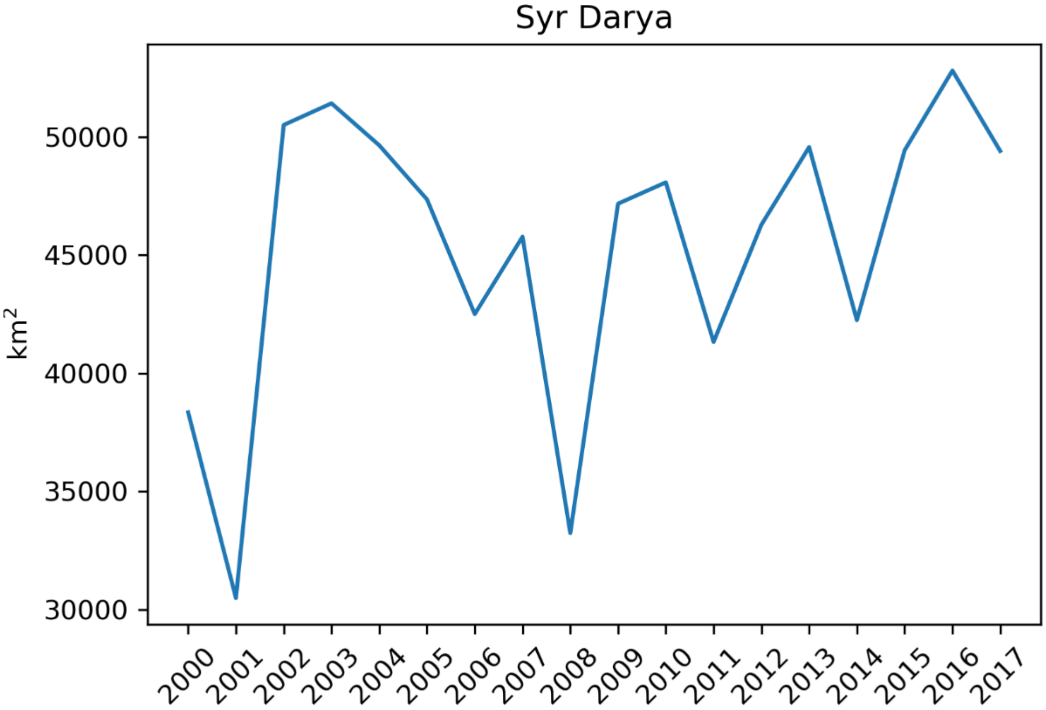

Figure 4.16: Annual agriculture area in Syr Darya basin

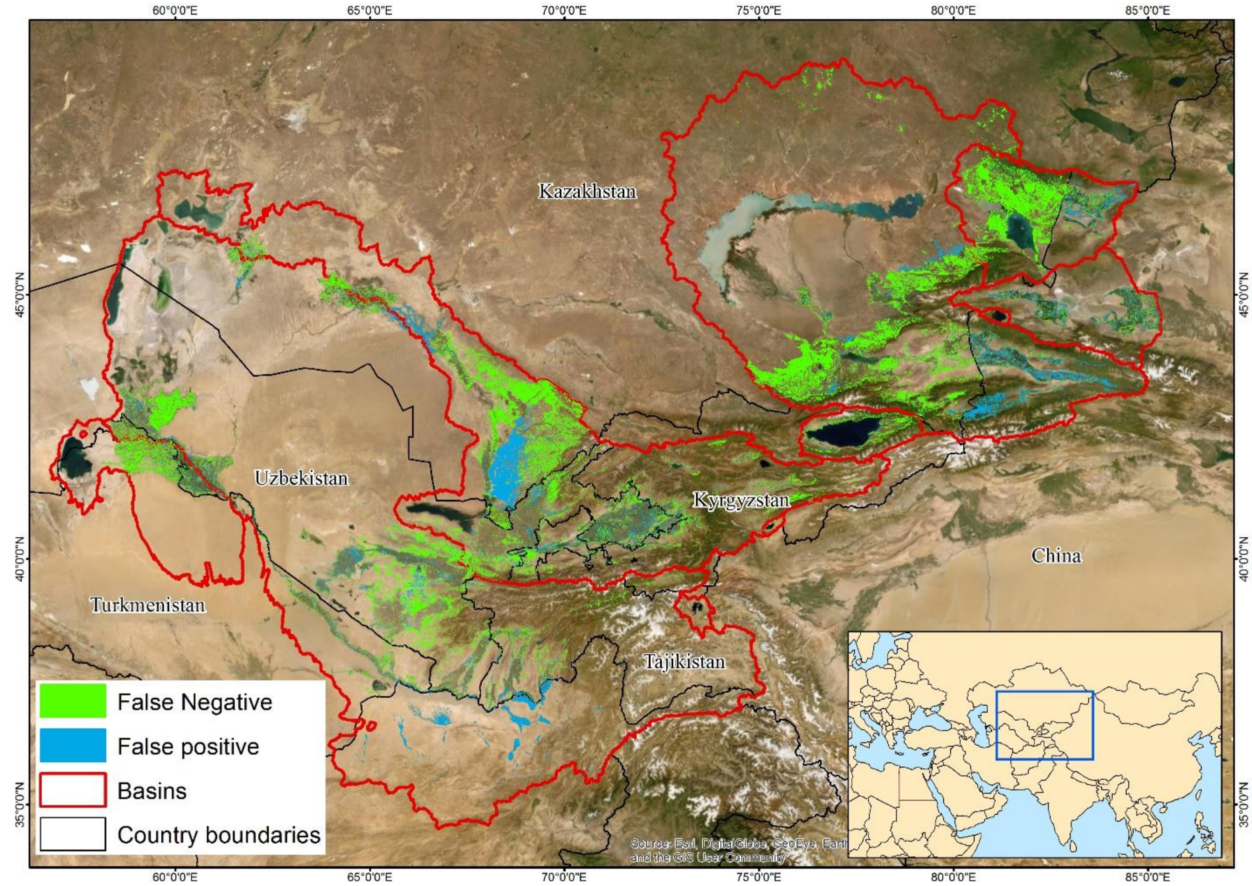

Figure 4.17: Agriculture classification accuracy assessment for 2015

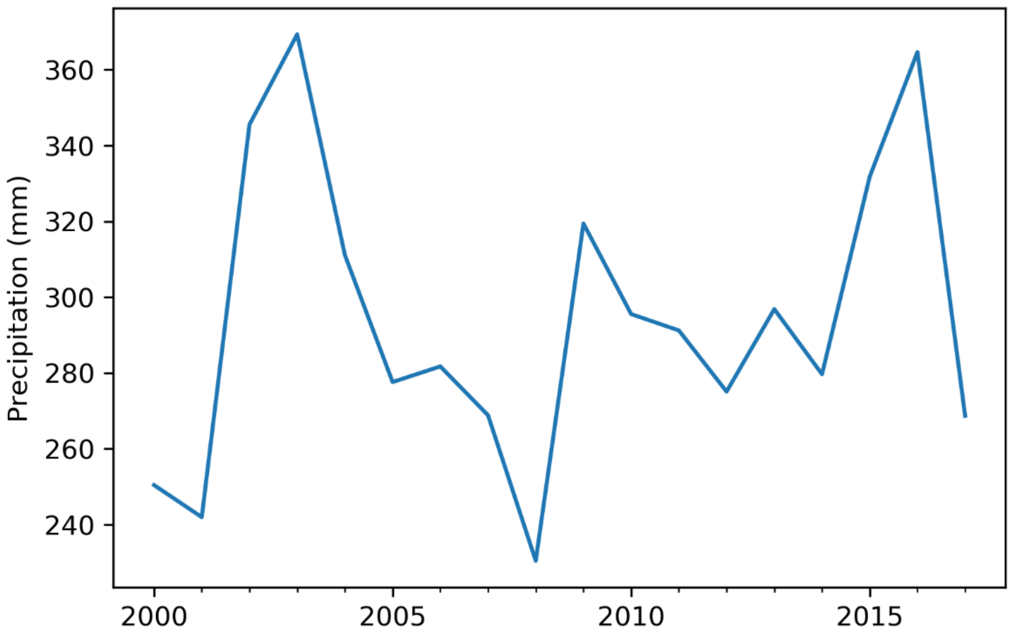

Figure 4.18: Mean annual precipitation in the study area

Table 4.1: Characteristics of countries within the study area

Country	Basin	Area (km^3)
Afghanistan	Amu Darya	166,081.7
China	Alakol	20,243.9
	Ebinur	50,922.5
	Ili	56,895.8
	Sayram	1,331.5
Kazakhstan	Alakol	43,586.8
	Amu Darya	128,732.3
	Ebinur	891.4
	Ili	357,385.2
	Syr Darya	139,409.7
Kyrgystan	Amu Darya	7,728.6
	Ili	717.8
	Issykkul	21,925.8
	Songkul	1,079.0
	Syr Darya	111,333.7
Tajikistan	Amu Darya	124,101.6
	Karakul	4,454.1
	Syr Darya	12,883.7
Turkmenistan	Amu Darya	57,774.8
	Sarykamish	63,661.1
Uzbekistan	Amu Darya	308,613.3
	Sarykamish	8,679.0
	Syr Darya	62,750.3

Table 4.2: Correlation between agriculture area and mean annual precipitation in countries and basins

Country	Correlation	Basin	Correlation
Afghanistan	0.71	Alakol	0.41
China	0.20	Amu Darya	0.73
Kazakhstan	0.59	Ebinur	0.14
Kyrgyzstan	0.51	Ili	0.70
Tajikistan	0.70	Issykkul	0.59
Turkmenistan	0.58	Sarykamish	0.47
Uzbekistan	0.77	Syr Darya	0.79

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CHAPTER 5

SUMMARIES

Water is a crucial resource in arid Central Asia and is heavily influenced by climate change and human activities. Lakes, especially endorheic lakes, are particularly sensitive to climatic and human impacts. Thus, lakes were used as proxy indicators of climate and anthropogenic change in Central Asia. After a thorough literature examination of past changes in climate, agriculture, and lakes in Central Asia the following questions were proposed and addressed in this dissertation:

1. How have lakes changed in the past 30 years in Central Asia?
2. What are the climatic impacts (precipitation and temperature) on water storage in lakes in Central Asia?
3. How has human activities (irrigation and water management) affected water storage in lakes in Central Asia?

In Chapter 2, a methodological framework was identified and applied to a pilot study area that includes the Ebinur and Sayram lake basins in Xinjiang, China. These lakes were chosen because they are located in proximity yet affected in different degrees by human activities. Ebinur Lake is located in an agriculture valley whose cultivated area expanded consistently over the study period while Sayram Lake is located in the mountains with little human activities. Optical remote sensing (Landsat and MODIS) was used to estimate the area of both lakes and satellite altimetry was used to estimate the water level of those lakes. Area and water level estimates were combined to derive observed volume changes. Hydrologic modeling was used to estimate hypothetical volume changes under no human influence. Optical remote sensing was also used to map annual extent of agriculture land to assess the impact of agriculture on lake changes. It was found that Sayram lake expanded steadily since the 1970s. Its area increased by 2%, level by 1.5 m, and its volume by 0.5 km^3 between 1977 and 2016. Ebinur lake showed large interannual variabilities since the 1980s. Its area increased dramatically by 45%, and volume by 0.2 km^3 between 1999 and 2003. The area then decreased by 25%, level by 2.5 m and volume by 0.2 km^3 between 2003 and 2016. Its volume increased again by 0.2 km^3 between 2016 and 2018. The modeled volumes had similar trends as the observed changes though the model showed much greater seasonal variability. Though it seems that the changes in both Sayram and Ebinur lakes are likely to be controlled by climate factors, they have distinct mechanisms. Changes of Sayram Lake are merely climate-driven as human activities are rather low, while Ebinur Lake is regulated by both the climate and human activities in the basin. Though agriculture expanded consistently between 2000 and 2017, Ebinur lake did not seem to be affected. The expansion of agriculture however may not have led to an increase in water consumption as more efficient irrigation technologies such as drip irrigation were introduced in the basin since late 1990s, compensating the agriculture expansion effect.

In Chapter 3, seventeen major lakes across the most populated regions of Central Asia were examined from 1980s to 2016 using a similar methodology as developed in Chapter 2. The lakes were categorized into three groups by type: endorheic, open and reservoirs and two groups by elevation: above and below 2,000 m. It was found that seven out of ten endorheic lakes showed increase in area between 1.0 – 15.4% while the three lakes decreased by 0.04 – 4%. Six out of ten lakes showed increase in water level between 0.05 – 5.2 m while four lakes showed decline between 0.3 – 1.9 m. The same six lakes showed increase in volume between 0.13 and 3.91 km^3 and the rest four lakes showed decline between 0.01 – 4.87 km^3. All three open lakes showed increase in area between 0.8 – 1.4%, level between 0.8 – 1.6 m and volume between

0.03 – 0.58 km^3. All four reservoirs showed increase in area between 0.02 – 8.4%. Three reservoirs showed increase in volume between 0.35 – 1.17 km^3 while one declined by 0.17 km^3. All reservoirs showed significant seasonal variability in two patterns. One reservoir located in the mountain region, whose major function is to generate hydropower, showed increasing volume during summer and declined during fall and winter. Three reservoirs located in the lowland region, whose major function is to provide irrigation water, showed increasing volume during winter and spring and declined during summer. Three out of four high elevation lakes showed consistent increase in volume. Results suggest that high elevation lakes were consistently expanding due to the increased melting of snow and glaciers under a warming climate. Lowland lakes showed variable changes possibly linked to agriculture developments in their vicinity. Reservoirs showed different seasonal patterns due to their function.

In Chapter 4, agriculture extent in the same area as Chapter 3 was examined from 2000 to 2017. The areas were examined by basins as well as by countries. It was found that all countries except for China, Turkmenistan and Kazakhstan had an overall stable area from 2000 to 2017. They also show similar interannual variabilities. China and Turkmenistan showed increasing area at 478 and 174 km^2/yr respectively while Kazakhstan showed decreasing trend of 728 km^2/yr. Four out of seven basins showed increasing trend while two showed decreasing trend and one remained stable. Two out of four basins that showed increasing trend have significant portions that lie within China while one lie within Turkmenistan. There is a strong correlation (> 0.7) between the agriculture extent and annual precipitation in Afghanistan, Tajikistan, and Uzbekistan while the correlation in Kazakhstan, Kyrgyzstan and Turkmenistan ranged between 0.51 – 0.59. China had the lowest correlation of 0.2. This suggests that agriculture in the former Soviet Central Asia republics countries are highly dependent on the amount of surface water available due to less efficient irrigation infrastructure. China, having widely adopted drip irrigation, consistently expanded their agriculture extent. The development of agriculture is linked in a limited degree with lake changes. For example, in high mountain basins with no agriculture such as Karakul, Sayram and Songkul, lakes have expanded consistently. In basins with relatively stable agriculture such as Syr Darya, Aral Sea north, Qamystybas and lakes were also relatively stable. However, the expansion of agriculture in Alakol and Ebinur basins did not seems to affect changes in Alakol, Sassykol, Zhalanashkol and Ebinur lakes. This suggests that the climate is a more dominant factor influencing water availability in these basins.

This dissertation has examined changes in climate, agriculture, and lakes across Central Asia. Chapter 2 provides a methodological framework to assess changes in lakes and agriculture in an arid but data sparse environment while Chapter 3 and 4 uses this framework to assess such changes across Central Asia. This dissertation presented observational evidence on 1) the expansion of mountain lakes due to the melting glaciers and snow; 2) the relative stability of lowland lakes as influenced by agriculture activities; and 3) the different seasonal patterns of reservoir changes due to their major function. However, the influence of climate and human factors on water resources in Central Asia is still entangled. Quantitative attribution of lake change to climate and anthropogenic factors is still lacking. Hydrologic modeling of lake natural changes is limited by the lack of and/or the poor quality of forcing data. In situ precipitation and runoff measurements are lacking especially in mountain regions in the former Soviet Central Asia republics. Many station data, which are essential input and calibration data to hydrologic modeling, ended after the Soviet era due to the lack of station maintenance. Combining precipitation outputs from regional climate models and limited in situ measurements is a promising route to create precipitation forcing. Nevertheless, it still requires ancillary data such as that from remote sensing to constrain model outputs. Future work aided by better data availability and quality is required to fully assess the independent contribution of climate and human factors on water resources in this region.