

# Chapter 18

## Water Supply and Ancient Society in the Lake Balkhash Basin: Runoff Variability along the Historical Silk Road



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**Abstract** Expansion of agricultural practices from the Fertile Crescent to China during the mid and late Holocene are believed to have shaped the early network of Silk Road routes and possibly regulated the dynamics of trade and exchange in the urban oases along the Silk Road throughout its existence. While the impacts of climate change on the Silk Road are more or less documented for the medieval period, they remain poorly understood for early history of the Silk Road, especially in Central Asia. We analyze hydroclimatic proxies derived from fluvial stratigraphy, geochronology, and tree-ring records that acted on various time scales in the Lake Balkhash Basin to learn how changes in water supply could have influenced the early farmers in the Semirechye region of southern Kazakhstan. Our approach aims to identify short-term and long-term variability of regional runoff and to compare the hydrological data with cultural dynamics coupled with the archaeological settlement pattern and agricultural production. The reconstructed runoff variability underscore the contribution of winter precipitation driven by the interaction between the Arctic oscillation and the Siberian High-Pressure System, to Central Asian river discharge. We show that Saka people of the Iron Age employed extensive ravine agriculture on the alluvial fans of the Tian Shan piedmont, where floodwater farming peaked between 400 BC and 200 BC. The early Silk Road farmers on the alluvial fans favored periods of reduced flood flows, river stability and glacier retreat in the Tian

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Shan Mountains. Moreover, they were able to apply simple flow control structures to lead water across the fan surface. It is very unlikely that changes in water supply ever significantly constricted agricultural expansion in this region.

**Keywords** Central asia · Ili river · Water resources · Silk road archaeology  
Saka agriculture · Dendrochronology · Fluvial geomorphology · Siberian high

## 18.1 Introduction

Human-environmental interactions are extremely complex, and can be obscured not only by the dynamic complexity of the climate system but also by the diversity in societal response and human adaptation to changing landscape (Adger et al. 2013). Societal response to climate change greatly varies and relies in part on a particular level of cultural sophistication and economic development that can seldom be measured. The role of climate change on the landscape and water resources throughout the prehistory of Central Asia has been researched with multi-disciplinary approaches for a long time. Yet the progress in unveiling physical mechanisms linking socio-economical change to the environment and climate change has been limited (Koryakova and Epimakhov 2007; Kuzmina 2007; Giosan et al. 2012; Macklin and Lewin 2015). Along the historical Silk Road the timeframe of ancient trade and technological exchange between the west and the east is reaching back in time from the medieval period to the Bronze Age (4500 years ago) (Frank and Thompson 2005; Frachetti et al. 2017). However it is not evident how the landscape itself could have facilitated the early development and sustainability of historical Silk Road networks.

It is reasonable to suspect that understanding water resource availability would lead to a comprehensive model explaining surplus accumulation and population growth at particular nodes of the ancient trading networks in the arid lands of Central Asia. Here we describe an approach that synthesizes hydroclimatic variability modeled with fluvial geomorphology and dendrochronology to understand the fluctuations of water supply for agriculture in agropastoralist communities of Bronze Age and Iron Age occupying the Tian Shan piedmonts. We hypothesize that fertile alluvial fans could have engaged the ancient population in a pursuit of agriculture while the mobile pastoral economy of the time encouraged exchange with neighboring people.

In this chapter we outline two case studies in the Lake Balkhash Basin exploring variations of local and regional hydrology of the past. The first case study addresses long-term variability of runoff to link Holocene river dynamics, climate change and floodwater farming on the Talgar alluvial fan of Tian Shan piedmont (Macklin et al. 2015). The second deals with modeling short-term river discharge from tree rings and explores the atmospheric circulation drivers in the runoff fluctuations (Panyushkina et al. 2018). The technical details on methods and datasets used in this chapter could be found in aforementioned publications. Although, the second case study considers the last few centuries only, it identifies the key climatic drivers of hydrological variability that most likely regulated the fluctuation of regional water resources in

the ancient times. We note that the scarcity of archeological data and hydro-proxies greatly limits our understanding of the impacts of water supply on the ancient agricultural communities. This work is currently most comprehensive assemblage of measured and absolutely dated information approximating the changes of hydrological regime in the region. To familiarize the readers with the historical background of this Central Asian region we describe briefly the geography and ancient society of Lake Balkhash Basin. The discussion is mainly focused on social impacts of runoff fluctuations and adaptations of farming populations to hydrological changes.

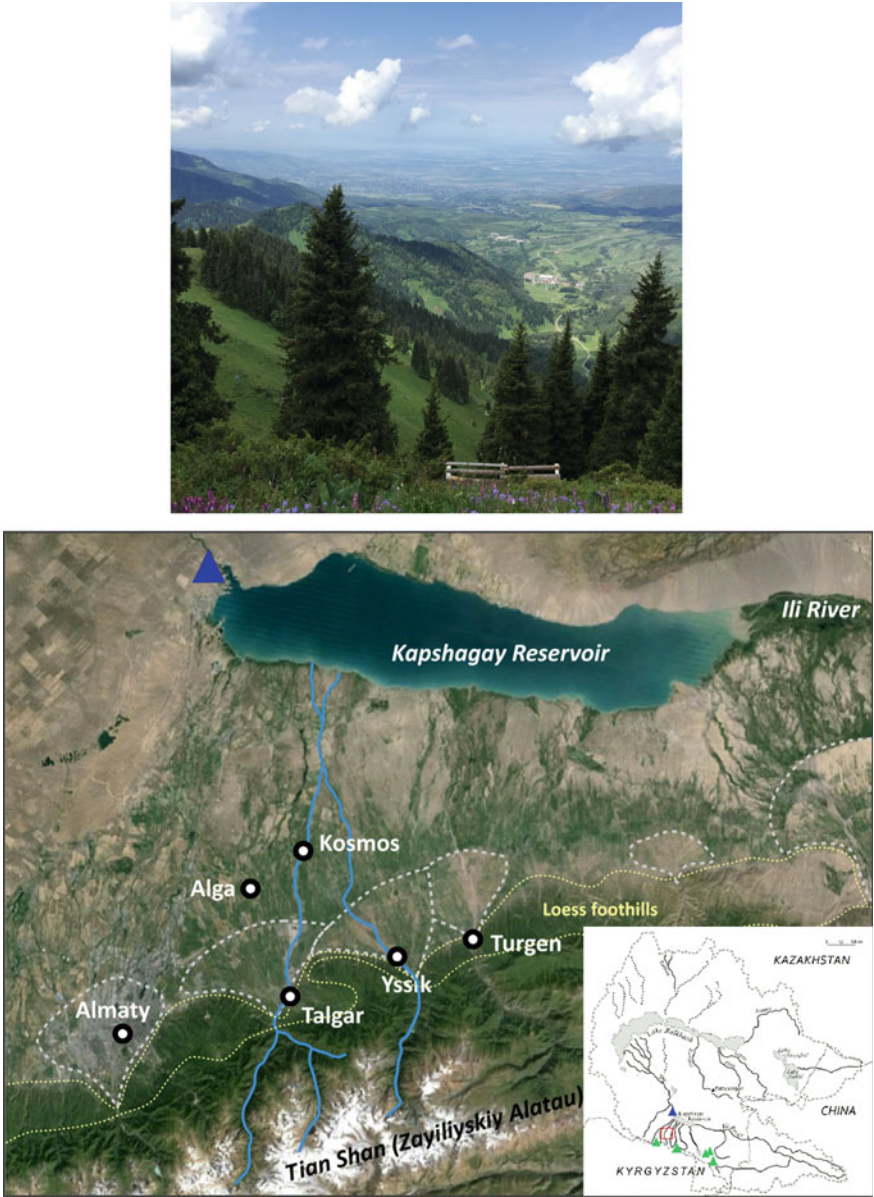
## 18.2 Ancient Society of the Lake Balkhash Basin

### 18.2.1 *Historical Region of Semirechye in the Lake Balkhash Basin*

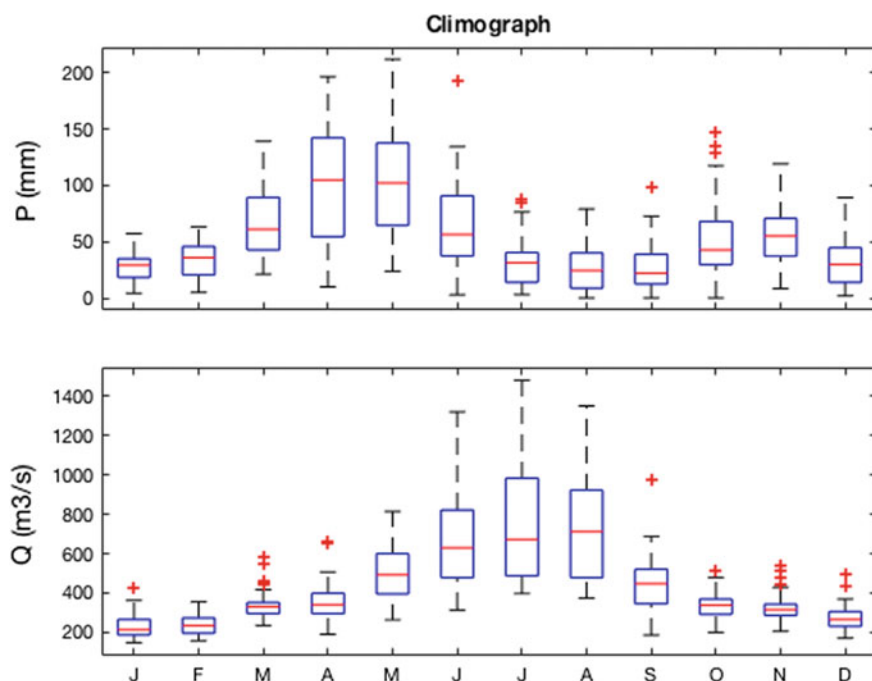
The study is located in the Semirechye (Land of Seven Rivers) of Central Asia also called Zhitasu by Kazakhs that geographically corresponds to the Lake Balkhash Basin (Fig. 18.1). This closed basin in Inner Eurasia is comparable in area (413,000 km<sup>2</sup>) to the neighboring Aral-Caspian and Tarim basins. Most regional rivers have headwaters in China and Kyrgyzstan, and flow from south to north through Kazakhstan. Annual runoff of the Lake Balkhash Basin is 0.26–0.36 km<sup>3</sup>/y (Mamatkanov et al. 2006; Kuzmichenok 2009).

Glacier and snow meltwater with high flows between May and September, and the highest peaks in July and August dominate the hydrological regime of the watershed (Fig. 18.2). While the glacier share of runoff is estimated to range from ca. 10 to 40%, there is large uncertainty in estimation of glacial area and glacier volume of the hundred small glaciers in the basin (Sorg et al. 2012; Farinotti et al. 2015).

The Ili River (length 1439 km, catchment area 140,000 km<sup>2</sup>), formed by the confluence of the Tekes and Kunges rivers in Xinjiang, China, is the largest river in the basin (Fig. 18.1 insert). The main tributaries of the Ili River that drain the Zailiyskiy Alatau Range, and the Tian Shan Mountains in Kazakhstan, are the Charyn, Keskelen, Talgar, Turgen and Chilik Rivers. The delta of the Ili River runs through the Sary Aka and Taukum Deserts, and forms vast areas of wetlands, sand dunes, and marshes before reaching the southeastern shoreline of Lake Balkhash. The tributary catchments contain nearly one hundred small glaciers, whose areas range from 4 to 26% of the area of the watershed, and which contribute from 17% (Keskelen River) to 56% (Talgar River) of the summer runoff (Vilesov and Uvarov 2001). The total area of these small glaciers is presently ca. 253 km<sup>2</sup> (Konovalov and Pimankina 2016). The average discharge of the Ili is about 480 m<sup>3</sup>/s per year. The highest discharge peak is in July ca. 770 m<sup>3</sup>/s and the lowest flow in January is ca. 230 m<sup>3</sup>/s (Fig. 18.2). The tributaries have multi-faceted alluvial fans (Fig. 18.1), 15–25 km wide and up to 20 km long, with multiple lobes decreasing in elevation from west to east (Akiyanova 1998).



**Fig. 18.1** Rolling foothill landscape on the northern slopes of the Tian Shan Mountains in southern Kazakhstan. Photo on the right is the Talgar alluvial fan viewed from the upper valley covered with spruce forest. Below is catchment of the Talgar-Yssyk Rivers (Scale: 5 km in 1 cm) and its position in the Lake Balkhash Basin (right insert). *Blue lines* are Talgar and Yssyk Rivers. *Circles* show locations of geomorphological ground survey and sediment sampling. *White dashed line* delineates alluvial fans at the foothills of Trans-Ili Range (former Zailiyskiy Alatau). The Kapchagay Reservoir and power station (*blue triangle*) built in 1969 are located on the Ili River. *Green triangles* of the insert map mark the tree-ring sites sampled for modeling the Ili River discharge. *Red rectangle* marks the Talgar-Yssyk catchment



**Fig. 18.2** Annual regime of precipitation and river flow in the study area. Top plot is monthly precipitation for the instrumental interval 1936–2014 at weather station Almaty ( $43^{\circ} 23' N$ ,  $76^{\circ} 93' E$ , 895 m asl) located in the Malaya Almatinka River Valley adjacent to the Talgar River catchment. The station represents precipitation variation in the Lake Balkhash Basin (Zhou et al. 2017). Bottom plot is monthly hydrograph of Ili River discharge as recorded at the U. Kapchagay gauge ( $44^{\circ} 13' N$ ,  $76^{\circ} 98' E$ , 428 m asl) for the instrumental period 1936–1985 (Fig. 18.1). Precipitation and discharge in individual months are displayed as box plots with a horizontal line at the median, a box over the interquartile range, and plus signs at values more than 1.5 times the interquartile range above or below the box. If there are no such outliers, the bracket marks the data extremes

Analysis of instrumental data covering the last 70 years indicates that runoff in this region has not changed significantly or has declined only slightly (1–2%) over the period 1940–2005 while regional temperature has a warming trend (Aizen et al. 1996; Konovalov and Pimankina 2016). The measured contribution of glacier melt has been decreasing, while snowmelt significantly increased over 1940–1991 (Konovalov and Pimankina 2016). Glacier mass-balance modeling estimates an 18–27% decrease in the glacier area across the Tian Shan since 1961 (Farinotti et al. 2015). Precipitation over the larger region of Central Asian drainages is decreasing (Lammers et al. 2001; Bothe et al. 2012). Ili River runoff has been permanently altered since 1970 by construction of the Kapchagay Dam and Reservoir (Fig. 18.1). The dam was completed in 1969 and the reservoir filled over the next 20 years.

## 18.2.2 *Socio-Cultural History of Semirechye During the Late Holocene*

The Bronze Age World System on the Eurasian steppe is often characterized as the precursor for the Silk Road (Christian 1994; Frank and Thompson 2005; Frachetti et al. 2017). The Bronze Age (BA) of the Semirechye was represented by a small population of Andronovo people (2500–1400 BC) in the upland valleys and foothills of the Dzhungarskiy Alatau and Zailiyskiy Alatau Ranges. The Andronovo people were primarily pastoralists, who negotiated trade in surplus livestock and metal goods along mountain corridors (Frachetti 2012). Later, during the Iron Age (800 BC–AD 200, IA), the foothill alluvial fans supported mixed farming and herding, but not yet mobile pastoralism (Akishev 1969; Chang et al. 2003). Archaeological data suggest multiple scenarios for the shift in economic strategies from transhumant pastoralism to settled agro-pastoralism that took place at the transition from the Late BA to IA (Chang et al. 2003; Frachetti 2012; Spengler et al. 2013; Chang 2018): (1) upland mountain valleys served refuges for mobile pastoralism that persisted despite a climate change to cooler and drier conditions in the first millennium BC; (2) groups of sedentary agro-pastoralists moved into fertile lowland regions and combined both mobile pastoralism and small-scale agriculture during the IA; and (3) throughout both BA and IA periods, the population facilitated upland transhumant pastoralism and lowland agro-pastoralism. The most recent archaeological framework in the Semirechye favors a diversified and highly intensified economy (scenario #3) that emerged by the Late BA, and during which the agricultural pursuits on the alluvial fans led to exchange of surplus grain throughout Central Asia (Spengler et al. 2017).

Historical evolution of the IA in the Semirechye climaxes into military confederacies of the Saka (Asian Scythians) and later Wusun, which had highly complex production from farming and herding to metalworking, and intensive trade with the neighboring agrarian kingdoms of Bactria and Parthia (DiCosmo 1999). Further adaptation of Late IA population to the warming medieval times served as the economic backbone for the social development of hierarchically arranged principalities in the region by c. AD 600 (Baipakov 2008).

The medieval history of the Semirechye involved several Turkic Khaganates<sup>1</sup> primarily occupied the Ili River basin and the Tian Shan foothills. At this time the culture and economy of urban oases reached their peak, being imbedded into the Silk Road networks. Farming and irrigation played an important role in the economic development of the region (Groshev 1985; Oberhänsli et al. 2007; Baipakov 2008). The last Khaganate, called the Kara Khanid (10th–11th century), introduced Islam, which blended organically into the well-developed urban environments of the Semirechye.

The conquest of the Kara Khanid by the Mongol Empire (after AD 1206) destroyed the urban centers, reduced the population and dramatically changed the social order in the region. The regional economy fell into stagnation, and agricultural production

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<sup>1</sup>Khaganate, alternatively spelled as Khanate, is a political entity of Central Asian tribes ruled by Khagan or Khan. This is an equivalent to tribal chiefdom, principality or kingdom.

halted while the mobility of pastoralists increased. Along with the crash in technological growth and cultural diffusion, the Silk Road network fragmented (Christian 1998). The Kazakh Khanate (AD 1465–1731) unified nomadic people ruled by multiple tribal alliances branched out from the Jochi Khan (the eldest son of Genghis Khan) clan. There are no historical data documenting the agricultural production in the Semirechye during this time. Winter camps of herders occupied the low reaches of rivers draining the area south of Balkhash Lake where freshwater springs were abundant (Krasnov 1887; Baipakov 2008). The fertile alluvial fans of the Tian Shan foothills served as the transit corridor between the lowland winter camps and summer camps in the upland meadows. The modern era started with Russian colonization of the Semirechye (Eastern Turkistan) after 1867. With colonization came revived farming and gardening practices, development of new irrigation lands, and westernization (including sedentarization) of the nomadic population.

### **18.3 Long-Term Variability of Runoff in the Semirechye Derived from Fluvial Geomorphology and Its Relation to Ancient Farming**

The case study by Macklin et al. (2015) demonstrated how changes in water supply could have impacted early farmers that occupied the Talgar alluvial fan in the Ili River Basin. Environmental proxies of runoff in Central Asia are limited and their temporal resolution is irregular, so instead, a long-term and absolutely dated fluvial chronology of a small catchment was used to investigate centennial and multi-centennial variability of water supply and its impact on the society. The long-term variability of runoff was approximated on the Talgar River catchment where a Kazakh-American archaeological team lead by Prof. Claudia Chang (Sweet Briar College, VA) conducted archaeological excavations and surveys over the past 25 years focusing on sedentary settlements (Chang 2018). Linking fluvial terracing to long-term changes in water and sediment supply, a chronology of Holocene major aggradation and incision episodes was established. These were dated with radiocarbon ( $^{14}\text{C}$ ) and Optically Stimulated Luminescence (OSL). The chronology was compared with other regional hydroclimatic records, and the river dynamics are linked to climate change. This allowed evaluating the impact of runoff variability on water supply for floodwater farming.

#### ***18.3.1 Settings of Fluvial Geomorphology Study on the Talgar Alluvial Fan***

The Talgar River (length c. 120 km, drainage area c. 440 km<sup>2</sup>) is located in the Ili River catchment and drains the Trans-Ili (former Zayliysky Alatau) Range (Fig. 18.1). Topographic maps prior the construction of the Kapchagai reservoir (1969) show the Talgar River splitting into a series of distributary channels that drained into an enclosed wetland, not connecting directly with the Ili river except possibly during

floods. Annual precipitation at the apex of the fan is 755 mm with spring (major) and autumn (minor) peaks, rising to 900 mm (Aubekeroev and Gorbunov 1999) at the higher elevation of the Mount Talgar (5020 m asl), the highest point in the Talgar catchment.

Field data on river terrace sedimentology, stratigraphy and geochronology were collected along a 35-km transect stretching from the apex of the Talgar fan downstream to the Talgar River confluence with the Yssyk River (Figs. 18.1 and 18.3). Geomorphological mapping was carried out using satellite imagery (Shuttle Radar Topography Mission: SRTM), topographic maps, and ground survey. OSL and  $^{14}\text{C}$  dating of fluvial units was undertaken at three 1-km long reaches: 1) apex of the fan centered on the medieval town of Talkhar ( $43^{\circ}16' \text{ N}$ ,  $77^{\circ}13' \text{ E}$ ), 2) Kosmos ( $43^{\circ}30' \text{ N}$ ,  $77^{\circ}15' \text{ E}$ ) and 3) Talgar-Yssyk confluence ( $43^{\circ}35' \text{ N}$ ,  $77^{\circ}17' \text{ E}$ ) (Fig. 18.1). The ages reported herein use (1) calibrated  $^{14}\text{C}$  years before present (AD 1950), which we denote as 'cal AD' and 'cal BC', and (2) annum unit with error or age range denoted with "ka" (thousands years ago) for OSL dates. In some cases, cross-referencing OSL and  $^{14}\text{C}$  dates with archaeological and historical periods results in denoting the calendar time with AD or BC datum.

### ***18.3.2 River Terraces, Stratigraphy and Geochronology in the Talgar Catchment***

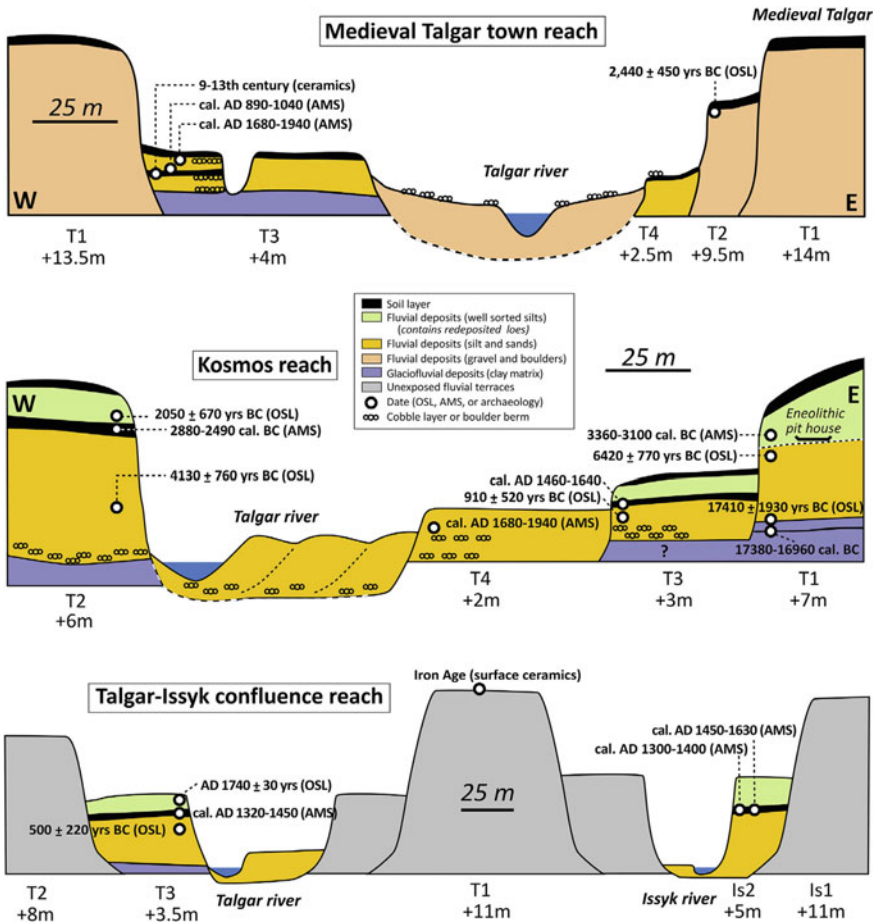
At the upper Talgar River valley, four terraces are found at c. 13.5 m (T1), 9.5 m (T2), 4 m (T3), and 2.5 m (T4) above the current river-bed (Fig. 18.4). The medieval town of Talgar (alternative spelling Talkhar), occupied from 9th to the 13th centuries AD, is located on the surface of T1 (Fig. 18.4). The buried soil contains 9–13th century AD ceramics as well as abundant bones and charcoal associated with the Kara Khanids (Figs. 18.3c and 18.5). The age of this soil is about cal AD 890–1040, which is consistent with the historical dating of Talgar. These deposits above that soil relate to a major period of flooding and channel aggradation that buried the medieval settlement around cal AD 1680–1940 (Macklin et al. 2015).

Downstream reach Kosmos is located 30 km from the fan apex (Fig. 18.1), where the valley width is about 300 m (Fig. 18.3d). The present river runs in a 100 m wide meander channel belt, has a high-sinuosity channel and is confined within river terraces of Holocene age 2–7 m (Fig. 18.4). Four major terraces are evident at c. 7 m (T1), 6 m (T2), 3 m (T3), and 2 m (T4) m above the present river level and can be traced fragmentally for 15 km northwards towards the Kapchagay Reservoir and 10 km upstream. A well-developed soil was formed in the IA between 2880 and 2490 cal BC and c. 2440 ( $\pm 450$ ) BC (Fig. 18.4f). A second palaeosol is dated to cal AD 1460–1640. Confluence with the Yssyk River (Figs. 18.1 and 18.4) reckons three terraces (T1—11 m, T2—8 m, and T3—3.5 m), while the Yssyk River has only two major terraces (Y1—11 m and Y2—5 m). The ages of the buried soil at the Talgar-Yssyk confluence is dated to cal. AD 1320–1450 at T3 and from cal AD 1300–1400 to 1450–1630 at Y2 (Fig. 18.4).



**Fig. 18.3** Collection of field data on river terrace: **a** Typical box-shaped valley on the alluvial fan surface, with fine-grained deposits on the valley floor (**a'**). **b** Exposure of Terrace 1 in the fan apex reach. **c** Terrace 3 in the fan apex reach with a buried soil, ceramics, hearth, and flood units at the top of the section. **d** The Talgar River valley in the Kosmos reach. **e** Section of Terrace 1 in the Kosmos reach showing glaciofluvial deposits, cross-bedded fluvial sands, flat-bedded fluvial sands, and fluvially redeposited calcified aeolian silts. **f** Section of Terrace 2 Kosmos reach showing Holocene channel-fill deposits, and a well-developed paleosol capped by fine-grained fluvial sediments containing reworked loess. **g** Section of Terrace 4 in the Kosmos reach showing 19th century AD coarse grained flood units. **h** Incision in the alluvial fan surface caused by recent flow diversion of the Tseganka tributary

Morpho-stratigraphic relationships between Talgar fan and valley terraces, and dating estimates (Table 1, Macklin et al. 2015) provide the reconstruction of a chronology of river aggradation and down-cutting for the last c. 20,000 years



**Fig. 18.4** Sketch of river terrace stratigraphy, sedimentology and geochronology of Talgar-Yssyk catchment (tributary of Ili River) reconstructed for the last c. 20,000 years (reproduced from Macklin et al. 2015). Stratigraphic cross-profiles of the apex reach near medieval Talgar town, the Kosmos and Talgar-Issyk confluence reaches show the terrace sequences (T1...T4), terrace height and key dates. Direction of profiles is from the west (W) to the east (E)

(Fig. 18.4). The most recent T1 with evidence of human occupation records channel aggradation from c. 17,400 to 17,000 cal BC until c. 6420 BC ( $\pm 770$ ) BC, followed by a 3000 year long hiatus and then renewed overbank sedimentation after 3360–3100 cal BC (BA).

T3 is contemporaneous to Y2 in the Yssyk Valley. River entrenchment in the Talgar catchment (and formation of T2) began c. 2880–2490 cal BC with valley floor filling re-commencing sometime before c. 910 ( $\pm 520$ ) BC (Kosmos reach, Fig. 18.4) and continuing until c. 500 ( $\pm 220$ ) BC (Talgar-Yssyk confluence reach, Fig. 18.4). A well-developed buried soil within T3 and Y2 is dated to cal AD 890–1040 in the



**Fig. 18.5** Photo of the most recent terraces at upstream reach near the medieval town of Talgar (left) and downstream reach Kosmos (right). The buried soil dated to cal AD 890–1040 related to the terrace T3 contains 9–13th century AD ceramics as well as abundant bones and charcoal (right). The top deposits relate to a major period of flooding and channel aggradation that buried the medieval soil and the riparian trees during the Little Ice Age. In situ tree stump dated cal AD 1680–1940 is imbedded in the terrace T4 (left)

medieval Talgar town reach, cal AD 1460–1640 in the Kosmos reach, and cal AD 1320–1450 (T3) and cal AD 1300–1400 to 1450–1630 (Y2) in the Talgar and Yssyk confluence reach. These dates indicate a prolonged, 400–700-year-long episode of valley floor stability roughly between the late 9th and early 17th century AD with little overbank sedimentation in the Talgar and Yssyk rivers. A phase of channel sedimentation is evident at c. AD 720 ( $\pm 260$ ) within the Tseganka distributary of the Talgar fan (Fig. 18.3h), but is not recorded downstream in the Talgar river valley.

Valley floor sedimentation began again sometime during the late 17th century AD (T3 medieval Talgar town reach) with dated fluvial deposits at c. AD 1740 ( $\pm 30$ ), and continued into the 19th and possibly early 20th century. The date of cal AD 1680–1940 on the buried tree stump within T4 (Kosmos reach, Fig. 18.5) provides a *terminus post quem* for the last significant episode of channel aggradation in the Talgar valley.

### ***18.3.3 Talgar River Response to Holocene Hydroclimatic Variability in the Lake Balkhash Basin***

To explore the relationship between river dynamics in the Talgar catchment and climate change in the Holocene, the phases of river aggradation and incision are correlated with: (1) periods of glacier dynamics in the Tian Shan Mountains (Savoskul and Solomina 1996; Sorg et al. 2012; Takeuchi et al. 2014); (2) water level records in the Aral Sea (Krivonogov et al. 2010, 2014) and Lake Balkhash (Endo et al. 2012; Sala et al. 2015; Chiba et al. 2016); (3) regional episodes of soil development (Sun

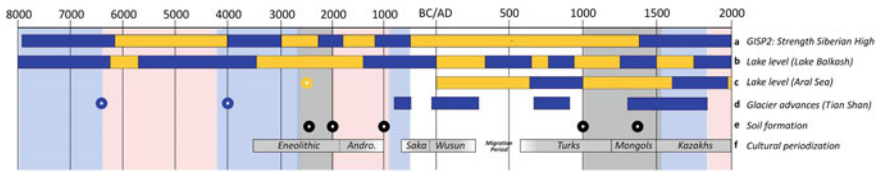
2002; Solomina and Alverson 2004; Blättermann et al. 2012); and (4) strength of the Siberian High Pressure System (SH) (Meeker and Mayewski 2002; Mayewski et al. 2004). Although there are quite a wide range of proxy climate records available for the Lake Balkhash Basin, only water levels in the Aral Sea and glacier advances in the Tian Shan span the entire Holocene and have centennial-scale time resolution.

We compare the river dynamics with a multi-millennium record of the SH index inferred by  $K^+$  fluctuations in the GISP2 ice core that represent long-term variability of seasonal atmospheric circulation in Asia (Meeker and Mayewski 2002; Mayewski et al. 2004). The primary source of moisture for runoff in the region is cold season precipitation and spring storms embedded in the mid-latitude westerlies, with some contributions from the higher latitudes (Lydolf 1977). The annual and seasonal distribution of runoff in Central Asia is impacted by modulations of the prevailing hemispheric circulation lead by climate change (Cohen et al. 2001; Jeong et al. 2011). In winter, Central Asia is under the influence of the SH, a cold-season anticyclone over Mongolia that forms in response to radiative cooling of the air above snow-covered Eurasia in October and remains until April (Lydolf 1977). During a strong SH the region west of and outside the SH source area (Mongolia) experiences high cyclonic activity, and fall and spring storms deliver excess precipitation. The variability of SH intensity and its teleconnections have been linked to large changes in patterns of snow in the fall, heavy snowfall events, severe cold-surge outbreaks and frequency of spring storms over Inner Eurasia (Panagiotopoulos et al. 2005; Jeong et al. 2011). Short-term variability of the SH index has been reconstructed with Eurasian tree-ring records for the last 400 years (D'Arrigo et al. 2005). This SH record links to recent climatic fluctuations and will be applied to the runoff variation in next section.

Figure 18.6 summarizes the response of Talgar runoff to climate change during the Holocene. Early Holocene river aggradation up to c. 6420 ( $\pm 770$ ) BC coincides with a high-stand in Lake Balkhash (Endo et al. 2012; Sala et al. 2015) and renewed glaciation in the Tian Shan mountains between c. 12,500 and 8000 (Takeuchi et al. 2014). The first major phase of Holocene channel entrenchment in Talgar River (c. 6420–4130 BC) likely onsets shortly after 6420 ( $\pm 770$ ) BC and has counterparts in falling water levels of Lake Balkhash, including an abrupt drop at 6200 cal BC (Sala et al. 2015), and significant glacier shrinkage at 6000 cal BC with very low rates of ice accumulation until 4220–3970 cal BC (Takeuchi et al. 2014). A major regression in the Aral Sea is also recorded between 5050–4650 cal BC (Krivonogov et al. 2014). Early-middle Holocene river incision in the Talgar valley appears to be a response to a warming climate and higher temperatures under a weaker SH between c. 6000 and 4000 cal BC (Fig. 18.6).

Renewed channel and floodplain aggradation occurred in the Talgar valley between 4130 ( $\pm 760$ ) and 2880–2490 cal BC coinciding with cooler conditions and glacier expansion in the Tian Shan (Takeuchi et al. 2014), a period of strong SH (Mayewski et al. 2004), and high water levels in the Aral Sea (Krivonogov et al. 2014) and Lake Balkhash (Endo et al. 2012; Sala et al. 2015; Chiba et al. 2016).

The second and most prominent phase of Holocene river down-cutting occurred in the Talgar catchment shortly after 2880–2490 cal BC and before 910 ( $\pm 520$ ) BC. Similar to the early-middle Holocene entrenchment phase, it coincided with a



**Fig. 18.6** Correlation of Holocene Talgar river entrenchment (*pink*), aggradation (*blue*) and soil formation (*grey*) with regional hydroclimatic proxies: **a** long-term variability of Siberian High (Mayewski et al. 2004), **b** fluctuation of Lake Balkhash and **c** Aral Sea levels (Krivonogov et al. 2010, 2014; Endo et al. 2012; Sala et al. 2015; Chiba et al. 2016), **d** Tian Shan glacial advances (Savoskul and Solomina 1996; Aubekeroov and Gorbunov 1999), **e** soil formation in Central Asia (Sun 2002; Solomina and Alverson 2004; Blättermann et al. 2012), and **f** cultural periodization (Andro. = Andronovo community complex of BA). Dated periods of floodwater farming on the Talgar fan in the Iron Age and medieval periods are shown *in black*. Phases are depicted with *bars* and shorter known episodes with a *dot*. *Yellow* and *blue* denote, respectively, strong and weak Siberian High, or low and high water levels in the lakes, or warm and cold intervals (**d**)

shift to a drier and probably warmer (weaker SH) climate. This is recorded by a pronounced dry interval between c. 3000 and 1950 cal BC in Lake Son Kol, Central Kyrgyzstan (Lauterbach et al. 2014), a regression in the Aral Sea between c. 2250 and 1250 cal BC (Krivonogov et al. 2014) and a major period of local and regional soil development (Sun 2002; Solomina and Alverson 2004; Blättermann et al. 2012).

New river aggradation took place in the Talgar valley between 910 ( $\pm$  520) and 500 ( $\pm$  220) BC with valley floor refilling sometime earlier. This aggradation phase coincides with a strong SH, glacier advances in the Tian Shan Mountains and high water levels in the Aral Sea (Fig. 18.6). With the exception of a sedimentation episode in the Tseganka distributary on the Talgar fan at c. AD 720 ( $\pm$  260), which coincided with brief high-stands of the Aral Sea cal AD 500–600 and cal AD 850–950 as well as glacier re-advance in the Tian Shan, the period between c. 500 BC and c. AD 1740 was one of reduced geomorphic activity in the Talgar catchment. It coincided with a weakening of the SH between the second half of the 1<sup>st</sup> millennium BC and the end of the 14th century AD, as well as with major regressions in the Aral Sea between 150 cal BC–cal AD 600–650 and again between cal AD 850–950 and 1600–1700 (Krivonogov et al. 2010, 2014). Extensive floodplain soil development between cal AD 1300–1640 indicates significantly reduced flooding and relatively dry conditions. It also coincides with a major regression of the Aral Sea documented in the late medieval period (Yang et al. 2014; Krivonogov et al. 2010, 2014). The last phase of river aggradation in the Talgar catchment is dated to c. AD 1740 ( $\pm$  30), and may have continued until the early 20th century. It matches high-water levels in the Aral Sea until a drop to modern levels since AD 1960 and a stronger SH.

Overall, Holocene river dynamics in the Talgar catchment have been controlled by fluctuations in regional hydroclimate and by glaciation in the Tian Shan Mountains. Phases of Late Pleistocene and Holocene channel aggradation and floodplain sedimentation in the Talgar River at c. 17,400–6420, 4130–2880 and 910–500 cal BC, and between the mid-18th and early 20th centuries correspond with periods

of cooler and wetter climate as reflected by high-water levels in the Aral Sea and Lake Balkhash, glacier advances in the Tian Shan and a stronger SH (Fig. 18.6). River entrenchment between these dates, and soil development between c. 2880 and 2490 cal BC and cal AD 1300–1640, correlate with low-water levels in the Aral Sea and Lake Balkhash, and glacier retreat associated with a warmer and drier climate.

### ***18.3.4 Influence of Holocene Hydrological Regimes on Floodwater Farming in the Semirechye***

The earliest Late Eneolithic/Early BA site in the Talgar valley is a pit house dated to c. 3360–3100 cal BC within T1 in the Kosmos reach (Fig. 18.4). Occupation coincides with river aggradation and cooler conditions, as recorded by a strong SH and high water-levels in the Aral Sea (Fig. 18.6). On the basis of a single house no wider archaeological inferences can be drawn other than that similar age settlements may be concealed below alluvium elsewhere at the fan. The preservation of this house, and its position on an upstanding floodplain surface reflect a period of relatively rapid but low energy sedimentation.

Dated mid BA or Andronovo sites are recorded in the upland headwaters of the Talgar (Panyushkina et al. 2010), but no sites of this age have so far been identified on the Talgar fan (Fig. 18.1). The Andronovo period c. 1800–1550 cal BC was a time of channel incision and occurred under regionally dry and warm climatic conditions as shown by a major regression in the Aral Sea and a weaker SH (Fig. 18.6).

IA settlement and floodwater farming on the Talgar fan and along the Talgar River are <sup>14</sup>C dated at three settlements to between 760 cal BC and cal AD 10 with nearly 62% of the dates on archaeological charcoal falling in the period of 400–200 cal BC (Chang 2008). This period of intense floodwater farming, the most significant before the modern period, immediately follows a major phase of aggradation along the Talgar River at c. 910–500 BC that coincides precisely with a strong SH, glacier advances in the Tian Shan Mountains and high water levels of the Aral Sea (Fig. 18.6).

This period of late extensive IA settlement and floodwater farming occurs during a period of stable channel bed levels in the Talgar River, a weakening SH at 500 cal BC and a major regression in the Aral Sea at c. 150 cal BC (Fig. 18.6). The apogee of IA agriculture on the Talgar fan is also bracketed between two major glacier advances in the Tian Shan Mountains that ended at c. 500 cal BC and began again around 50 cal BC. Taken together these records indicate a period of warm climate in the late IA with reduced river flow from c. 150 cal BC as evidenced by a fall of the Aral Sea water level. Nevertheless, given the elevation of the Tian Shan Mountains, late spring and early summer glacier and snow melt floods, would have still produced adequate water for irrigation on the Talgar fan, as can be seen today with glacier shrinkage under a warming climate.

## 18.4 Short-Term Variability of Runoff from Tree Rings

The linkage between short-term climatic variability, mainly forced by the SH, and Central Asian runoff can be explored at high precision with annually resolved tree-ring proxy of river flow in recent past. The decadal and annual variability reflects the scale of runoff fluctuation that might have affected past farming communities, in addition to long-term variability as reflected in river dynamics, by changes in water supply from one year to another. Networks of tree-ring records for the Semirechye have been developed in the Tian Shan Mountains since the early 1970s, but record lengths are limited to the last 600 years (Borscheva 1988; Panyushkina et al. 2010; Chen et al. 2016). Below we focus on a recent study of tree-ring reconstruction of Ili River discharge for the interval 1779–2015 (Panyushkina et al. 2018), and use it to address the potential impact of short-term variability of runoff on water supply on economic development in the region on the time scale of last few centuries - with a discussion of potential impacts of similar variability on prehistoric people.

### 18.4.1 Climatic Signals in Annual Variation of Spruce Tree-Ring Widths

*Picea schrenkiana* (Fisch. and C.A. Mey.), or Schrenk's spruce, is a widely distributed conifer specie in the mountain forests of Central Asia, which tree rings form a suitable climatic proxy for the hydroclimatic modeling in the Lake Balkhash Basin. The tree-ring studies suggest that spruce growth in the Tian Shan Mountains is limited by both temperature and precipitation (Borscheva 1988; Wang et al. 2005; Solomina and Maksimova 2010). Trees growing under moisture stress at low and high elevations, and under temperature stress at the upper tree-line are found within the elevation range 1700–2750 m asl. Cold-season temperature and summer drought generally limit the growth of winter-dormant conifers. Radial growth rate is high in March–May and declines in summer following the July–August dry period (Wang et al. 2005). A warm spring and early snowmelt favor an early onset of the growth season and a high rate of tree-ring growth (Kozhevnikova 1982; Wang et al. 2005). High precipitation in the previous fall and winter recharges soil moisture, which along with snowmelt can help trees cope with summer drought, but deep snowpack can also negatively impact growth by shortening the growing season (Kozhevnikova 1982; Borscheva 1988).

The moisture signal in annual rings of Schrenk's spruce has been discussed in relation with previous fall-winter precipitation, and has been successfully used in reconstruction of precipitation, Palmer Drought Severity Index (PDSI), water balance and streamflow (Yuan et al. 2007; Solomina and Maksimova 2010; Konovalov and Maksimova 2012; Chen et al. 2015, 2016; Zhang et al. 2017a, b). In recent years, a tree-ring team lead by Dr. Feng Chen has produced an array of tree-ring reconstructions from the Lake Balkhash watershed describing in detail the

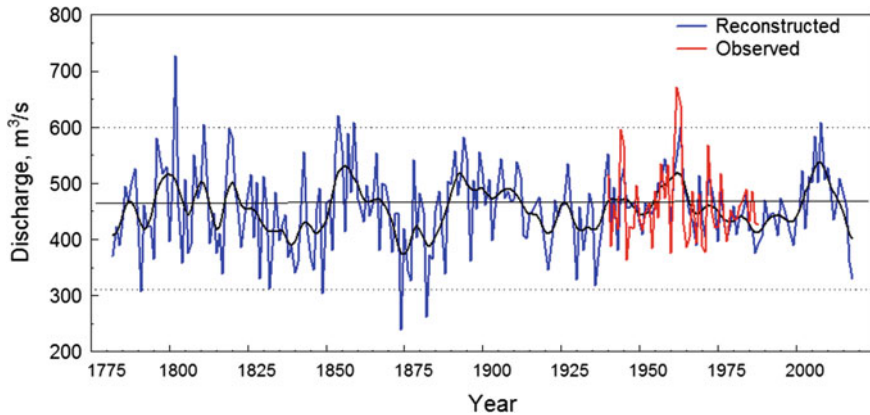
spatial-temporal pattern of moisture variability of the last 200–300 years (Chen et al. 2017a; Zhang et al. 2017b).

Air temperature over the last few centuries has surged upward, in agreement with the transition from the Little Ice Age to the modern warming. Warming has been noticeably faster in winter and spring than in summer. Reconstructed decadal variability of moisture can differ greatly between the tree-ring studies depending on the season of reconstruction and location. For example, precipitation reconstructed for the previous July to current April shows low variance for extended periods of time since 1560 and identifies decadal droughts centered at 1660s, 1710s, 1770s, 1900s, and 1980s (Chen et al. 2017a, b). Reconstructed January–May PDSI highlights nine multi-decadal droughts since 1580 (Cheng et al. 2014). Reconstructed July–June precipitation since 1474 points out eight different intervals of multidecadal drought with on average a frequency of one-two dry periods per century (Zhang et al. 2013). Even though the growing number of tree-ring studies leads to better synchrony of the modeled hydrological patterns across Central Asia in general an interpretation of water supply impact on past agricultural production taken place at a small catchment would be critically dependent on specific runoff reconstruction closely related to the locality of archaeological data.

#### ***18.4.2 High-Frequency Variability of Ili River Discharge Derived from Tree Rings***

Figure 18.7 shows the tree-ring reconstruction of Ili River annual discharge for the last 235 years published by Panyushkina et al. (2018). This publication presents the details of spruce tree-ring chronologies and the reconstructing model. Here we discuss only the decadal and interannual variability of tree-ring reconstructed discharge of the Ili River for the recent centuries. The record has relatively frequent periods of low flow lasting 25–30 years, and shorter periods of high flow lasting 10–15 years. Flow was low in 1825–1850, 1865–1885, 1916–1938 and 1975–2000; flow was generally high in 1793–1809, 1850–1857, 1886–1909, 1952–1962 and 2001–2013 (Fig. 18.7). Thirteen runoff events outside the  $\pm 2\sigma$  interval around the mean (316–594 m<sup>3</sup>/s) are found in reconstructed record. Individual years of extremely low flow are 1871, 1879, 1846, 1788, 1829 and 1933; years of extremely high flow are 1799, 1851, 2005, 1856, 1808, 1960 and 1816. The driest year is 1871, with a discharge (239 m<sup>3</sup>/s) only half the historical average (460 m<sup>3</sup>/s). The wettest year is 1799, with a discharge of 728 m<sup>3</sup>/s (+58% of historical average).

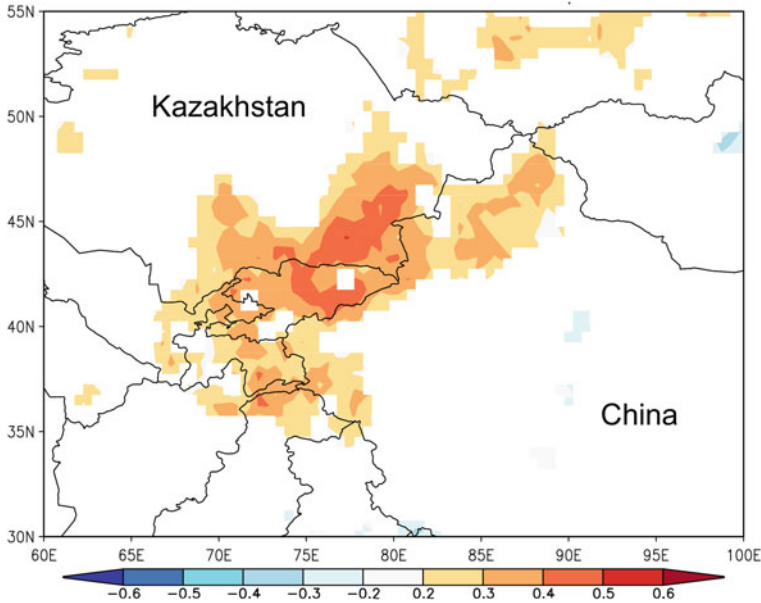
The spatial correlation field of gridded self-calibrated Palmer Drought Severity Index (scPDSI) with reconstructed Ili River discharge suggests that dry and wet hydrological conditions are similar across the entire Lake Balkhash Basin and Lake Issyk Kul Basin (Fig. 18.8). Great similarity of runoff anomalies and trends in these two adjacent basins has also been demonstrated with meteorological and hydrological data (Aizen et al. 1997). Decadal variability of reconstructed Ili discharge agrees



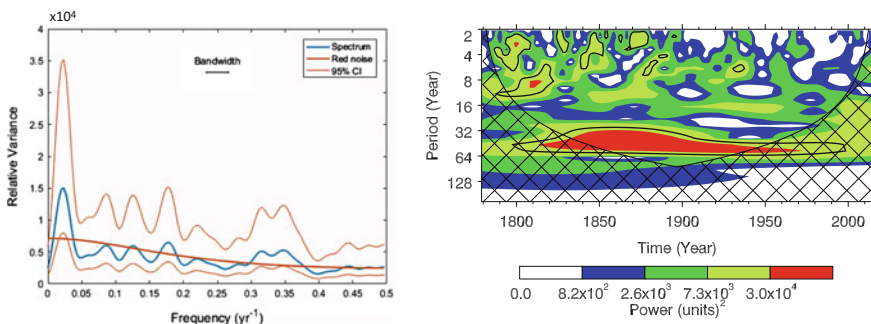
**Fig. 18.7** Short-term variability of Ili River flow. Tree-ring reconstruction of the Ili River discharge for October–September water year shown in blue is from 1779 to 2015 (reproduced from Panyushkina et al. 2018). Red line is instrumental discharge at the U. Kapchagay gauge (Fig. 18.1). Black line emphasizes the decadal variations estimated with 10-year Tukey filter. Horizontal grey line is at  $460 \text{ m}^3/\text{s}$  calibration-period mean (1937–1985). Grey dashed lines at  $+2\sigma$  ( $594 \text{ m}^3/\text{s}$ ) and  $-2\sigma$  ( $316 \text{ m}^3/\text{s}$ ) delineate discharge extremes for the last 235 years

fairly well with tree-ring reconstructed discharge for the Aksu, Kurshab, and Black Irtys Rivers, and with the water balance of the Lake Balkhash, Lake Issik Kul and Tarim Basins (Fang et al. 2010; Konovalov and Maksimova 2012; Chen et al. 2015, 2017b; Zhang et al. 2016). PDSI and precipitation reconstructions from spruce tree rings in southern Kazakhstan and the broader Pamyir-Tian Shan region are consistently coherent on the decadal scale (Li et al. 2006; Fang et al. 2010; Zhang et al. 2017a, 2017b).

Spectral analysis of the runoff reconstruction reveals a significant ( $\alpha = 0.05$ ) peak at 42.7 years, and other peaks near 11.6, 8.0, 5.7, and 2.9 years (Fig. 18.9). The spectral peaks show some agreement with reported frequency bands in significant modes of variability of atmospheric circulation indices, such as the SH index, East Asian Winter Monsoon (EAWM), and El Niño–Southern Oscillation (ENSO) (Wu and Wang 2002; Jhun and Lee 2004; D’Arrigo et al. 2005). The 42.7-year rhythm is also evident in the smoothed time plot (Fig. 18.9), which shows a prominent low-frequency fluctuation with most recent peaks in the 1950s and early 2000s. Wavelet analysis shows this low-frequency feature most prominent in the late-1800s, and indeed the time plot shows a major low near 1870 flanked by major peaks near 1850 and 1895 (Fig. 18.9). Variance is relatively low over 1975–2000, a period when flow stabilizes considerably below the historical average. This reduced-variance interval is a prominent feature not only of Ili River discharge but also of other reconstructed and instrumental runoff records for internal drainages in Inner Eurasia (Aizen et al. 1997; Yuan et al. 2007; Zhang et al. 2016; Chen et al. 2016, 2017b; Chen and Yu 2017). Interestingly, flow recovers after that segment and is marked by high-amplitude



**Fig. 18.8** Geographical coverage of runoff represented by the Ili River discharge. Map shows pattern of spatial correlation between reconstructed October-September discharge of the Ili River and gridded October-September scPDSI field (CRU 3.24) for interval 1901–2014 ( $p_{\text{field}} < 0.5$ ). *Rectangle* marks the location of tree-ring sites in Semirechye (reproduced from Panyushkina et al. 2018)



**Fig. 18.9** Runoff periodicity in the Lake Balkhash Basin inferred from tree rings (reproduced from Panyushkina et al. 2018). Left plot is smoothed-periodogram spectrum of reconstructed October-September discharge of the Ili River, 1779–2015. Significant spectral peak relative to red noise is at 42.7 years. CI- confidence level. Right plot is the wavelet power spectrum (Morlet 6.0/6) of the reconstructed series. *Contour levels* are chosen so that 75, 50, 25, and 5% of the wavelet power is above each level, respectively. The *cross-hatched region* is the cone of influence, where zero padding has reduced the variance. *Black contour* is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum

swings, in which the smoothed curve reaches a peak in the early 2000s and a low at the end of the record more extreme than any since the late 1800s (Fig. 18.7).

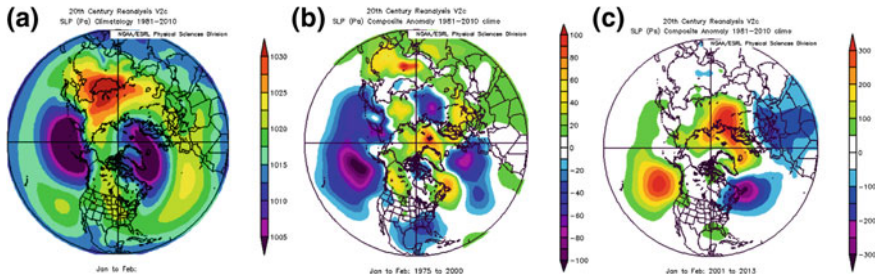
### ***18.4.3 Linking Ili River Discharge to Climate Change***

The physical mechanisms behind runoff changes in Central Asia are not yet well understood. Temperature appears less important as a forcing factor than previously thought (Lammers et al. 2001). Changes in Central Asian instrumental runoff have been reported to be consistent with the decline of snowpack since 1940 (Aizen et al. 1997). Greater snowpack over broader Eurasia results in positive anomalies of instrumental runoff for the largest Siberian Rivers with headwaters in Central Asia (Shiklomanov et al. 2013). The Ili River discharge reconstruction underscores the importance of winter precipitation above summer drought.

Surface pressure over the Ili River basin is positively correlated with surface pressure over the broader geographical region of the seasonally strong SH during the October-February season of snow accumulation (Panyushkina et al. 2018). Anomalous strength and positioning of the SH likely moderates snow delivery to the Ili Basin through steering of storms and winter moisture delivery. Spring moisture as well is important to the river flow (Fig. 18.2), and its conveyance would also be influenced by anomalies in westerly flow (Cohen et al. 2014). This suggests that the SH should contribute to the interannual variability of runoff. A test of this hypothesis with cross-wavelet analysis of tree-ring reconstructed river discharge and SH index (D'Arrigo et al. 2005) fails however, to indicate consistent coherency through time at any band of wavelengths (Panyushkina et al. 2018). Significant coherency is found only at high frequencies (e.g., periods less than 4 years) and then only for some isolated times in the 19th and 20th centuries. Furthermore, where coherency is significant, the phase is opposite; meaning high flow is linked to weak SH. In-phase coherence does appear only near wavelength 30–40 for one episode around the late 1900s.

The link between SH intensity and interannual runoff variability in the Lake Balkhash Basin appears to be complex and may be entangled with Arctic forcing of north-south linkages of atmospheric circulation features in Inner Eurasia (Cohen et al. 2001, 2014). A reconstruction of the latitudinal position of the North Atlantic jet in August from the European tree-ring network explained an exceptional number of extreme weather events like floods and heatwaves in the mid latitudes over the recent decades (Trouet et al. 2018). The finding of an increase in variability of meridional sways of the polar jet could be similarly important for the region considered in this study. Since Arctic thermodynamic amplification can reinforce regional geopotential height patterns, we assume that the late 20th century Arctic warming impacts the hydroclimatic extremes and interannual climatic variability in the study region.

December extremes in the Arctic Oscillation (AO) have been more variable in the past decade than at any other time since the mid-20th century (Overland and Wang 2016; Francis et al. 2017). Generally, large positive values of the AO indicate



**Fig. 18.10** Composite maps of the 20th Century Reanalysis data of January-February surface pressure for **a** normal condition for interval 1981–2010, **b** anomaly low-flow interval of 1975–2000, and **c** anomaly high-flow interval of 2001–2013 reconstructed Ili River discharge (reproduced from Panyushkina et al. 2018)

zonal flow and large negative values suggest increased meridional circulation that brings cold air advection into the mid latitude inland (Thompson and Wallace 1998). Comparison of reconstructed runoff variations with 500 hPa geopotential height and surface pressure anomalies over Eurasia, and with primary teleconnection modes of Eurasia upper air circulation indicates that the natural runoff variability (extremes, decadal trends and spectral properties) are linked to the interaction of Arctic air circulation with the SH intensity and negative phase of North Atlantic Oscillation (NAO). The Ili River discharge correlates negatively with the spring Polar/Eurasian Pattern index ( $-0.32$ ,  $p < 0.05$ ) and with winter AO ( $-0.34$ ,  $p < 0.05$ ). Our estimated associations are consistent with a weaker circumpolar vortex during the increased flows. The development of the strong SH has been associated with an enhanced East Asian winter monsoon (Jhun and Lee 2004; Panagiotopoulos et al. 2005), which suggests an even more complex relationship of runoff to the atmospheric teleconnections during the warming trends.

In some intervals, the teleconnections of SH surge the impact on the runoff. The annual discharge correlates significantly and negatively with December-February SH index for 1950–2014 ( $-0.32$ ,  $p < 0.05$ ), and the correlation is driven by few extreme years. The SH is normally centered over Mongolia, to the east of the study area (Fig. 18.10a). A shorter period of generally low recent flows (1975–2000) coincided with a weakening of the SH and a shift of the high pressure southward to the Tibet Plateau. (Figure 18.10b). A subsequent decadal period of generally high Ili River discharge (2001–2013) coincided with increased SH intensity and a shift in the position of the winter surface high toward Western Siberia (Fig. 18.10c).

Clearly, these recent and short time associations are consistent with a positive correlation between the runoff and strength of the SH. In recent decades, therefore, different mechanisms of SH influence on Ili River flow may operate at high frequencies less than 1 year. The resolution of the reconstruction does not allow examination of summer and winter discharge independently or finer periodicity. A side of this ambiguity, snow cover has profound implications for runoff variability in the Lake Balkhash Basin, which is directed by the interaction of SH and AO.

#### ***18.4.4 Social Impact of Short-term Runoff Fluctuations in Semirechye During Recent Times***

The tree-ring reconstructed discharge of the Ili River represents runoff variability over Semirechye and more broadly over the internal drainages of the Pamir-Tian Shan Mountain system, which includes bordering southern Kazakhstan, Kirgystan, eastern Uzbekistan and China (Fig. 18.8). The historical conquest of Semirechye by the Russian Empire took place between 1847 and 1864. Our data on flow extremes and anomalies suggests that hydrological conditions are unlikely to have a major role in the response of Kazakh population to the military campaign. The Russian troops had been building forts and gradually advancing from the southeastern part of Lake Balkhash Basin westward, finding very minor resistance from the Kazakh nomadic herders in this part of Central Asia. Siberian Cossacks and farmers from the Tomsk Governorate were the first colonists who started agricultural production in the Semirechye. However, the arrival of new settlers coincides with the 1886–1909 wet interval (Fig. 18.7), the farming population significantly increased the area of apple and apricot orchards, gardens, grape estates and wheat fields through irrigation with aryks. By 1909, Verniy (Almaty) uyezd (administrative district of the Russian Empire comparable to the Soviet raion or U.S. county) comprised 23 towns with a population of 277,569 people (Lukhtanov 2014). Russian and Uyghur immigrants arriving from China involved in agricultural production made up 40% of the total population. This illustrates successful adaptation of agriculturalists coming from both wetter and dryer environments (north and south) to farming on the Semirechye alluvial fans in relatively short interval.

During the Soviet period (1918–1990) the government heavily subsidized water allocation and irrigation in the region. Key studies based on instrumental data indicate that runoff in this region has remained unchanged or has declined only slightly (1–2%) over the period 1940–2005 (Aizen et al. 1996; Konovalov and Pimankina 2016). Both low variance of natural discharge during that time and Soviet water management directed by five-year plans of highly politicized economic development that were ineffective (Propastin 2012) but could have muted the social impact of climate stress on the water supply and agriculture production. The situation has changed radically since the Soviet Union collapsed in 1991. Newly independent republics of Central Asia have abolished the high number of USSR water management institutions and abandoned funding, and domestic disputes on the water supply have turned into international conflicts. In modern time, water supply shortfalls in conjunction with rapid economic development and population growth have become a tangible problem for Central Asian countries situated across the internal drainage systems (Bernauer and Siegfried 2008). Weak environmental policies and political tensions over water withdrawals increasingly impact Asian geopolitics and create new international conflict zones (Abdolvand et al. 2015).

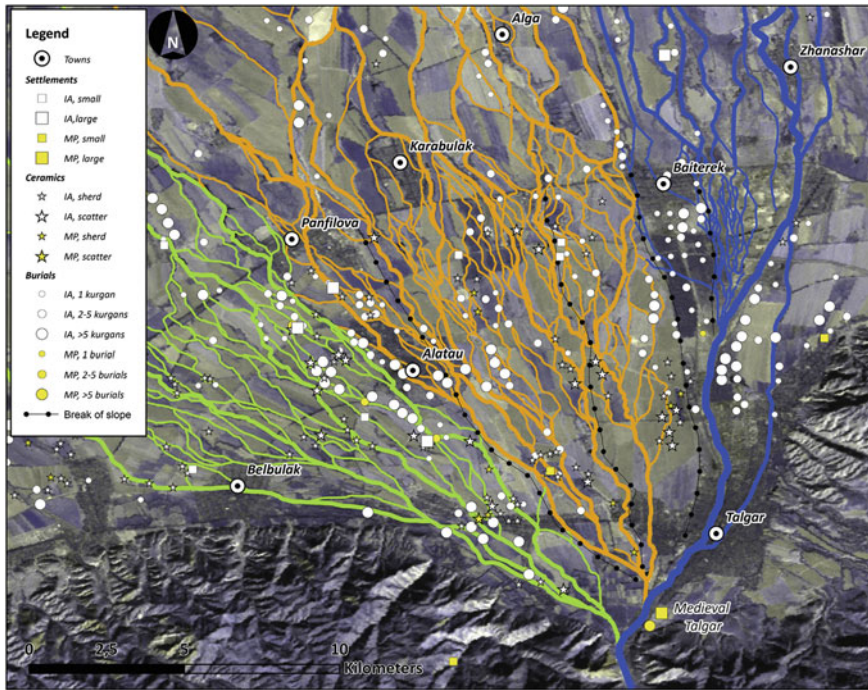
Water allocation on the Syr Darya River is the most serious issue in the region. A total of 75% of Syr Darya runoff originates in Kyrgyzstan (Naryn River), then flows through arid and riparian Uzbekistan, Tajikistan and Kazakhstan. Uzbekistan is the

major hydrocarbon and irrigation user that formerly controlled the electric power production on the Syr Darya. Around 90% of the Syr Darya annual flow is regulated by reservoirs that are used for irrigated agriculture (Bernauer and Siegfried 2008). The fragile balance was broken when Kyrgyzstan changed the operation mode of the Toktogul reservoir from irrigation to electric power production, and started construction of new power stations. Thus, Uzbekistan and Kazakhstan located downstream, face the most severe water security risks whereas upstream Kyrgyzstan is in almost total physical control of the catchment's runoff.

The Ili River catchment has been the second hotspot of water conflicts in the region since 1999 (Propastin 2012). The mean annual runoff of Balkhash Lake Basin is about 27.8 km<sup>3</sup>, 41% (or 11.7 km<sup>3</sup>) of which originates in China. Unparalleled economic boom and development in Xinjiang Province, China, challenges the international balance in water allocation and creates uncertainty in the water supply of Kazakhstan. The irrigation area of the Ili River catchment in Kazakhstan (346,000 ha for the Akdala area in the Ili River Delta in 2000) is continually declining, while the Chinese government develops 15 water reservoirs on the Ili River's upstream tributaries (Tekes, Kashe and Kunes) to extend the irrigated area by 450,000 ha. This will increase the annual water consumption of Ili water by Xinjiang Province by 5 km<sup>3</sup>/y. Under various scenarios, the forecasted discharge of the Ili River could be reduced from 15 km<sup>3</sup>/y to 6–10 km<sup>3</sup>/y (Propastin 2012). This would impair the water supply for the Akdala irrigated land and for the largest power station in the region at the Kapchagay reservoir, which has already experienced severe water shortages in the recent decade similar to those of the low flow interval since 2003 (Figs. 18.1 and 18.7). The tree-ring reconstructed discharge shows the changes in spatial–temporal domains of runoff variability before the last 60–70 years of instrumental observations, and provides a historical background of natural runoff variability for modeling the socioeconomic response to water stress. The sharp decline of the Ili River flow after 2003 is comparable to the onset of pronounced drought 1865–1885 (Fig. 18.7), however the social implications of water supply impact on the society are not alike. In modern times, a prolonged climatically-driven period of drought greatly enhanced the water stress in the region as a larger volume of water has been allocated in China due to high rate of economic and population growth, and putting more stress on the remaining flow in the Ili River basin.

## 18.5 Linking Runoff Variations and Agriculture Along the Historic Silk Road in the Semirechye

The geomorphological reconstruction provides evidence for how the IA population (Saka) used the water of the Talgar River for farming. With limited evidence for early farming in the Bronze and Iron Ages but more detail for the Late IA we can conclude that floodwater farming on the Talgar fan reached its height in the Late IA (400 BC to AD 1); high population density attested from more than 70 settlement sites and



**Fig. 18.11** Distribution of archaeological sites on the Talgar alluvial fan (reproduced from Macklin et al. 2015). The positions of archeological sites are compiled from a GIS database assembled by C. Chang and colleagues as part of the Kazakh-American Talgar Archaeological Project. The GIS database categorizes different types of archaeological sites (settlements, cemeteries, and ceramic scatters) using age and morphology of surveyed artifacts, which are plotted on the SRTM satellite imagery (Chang 2018). IA sites are indicated in *white* and medieval sites (MP) in *yellow*. Settlement size was inferred from surface finds (small) and excavations (large). Distributaries of the Talgar River are shown using different colors: Taldy Bulak (*green*), Tseganka (*orange*), and the main Talgar River (*blue*). Breaks of slope separating alluvial fan facets are marked by *black dashes and dots* (after Akiyanova 1998)

700 burial mounds (Fig. 18.11). It is unlikely that the Talgar fan is a single isolated episode of agriculture in the Semirechye, yet supportive archaeological research is largely missing from other parts of Semirechye.

### 18.5.1 Ancient Agriculture in the Semirechye

The Semirechye is the southeast margin of the Eurasian steppe that extends along the northern piedmont of the Tian Shan Mountains where the northern routes of the ancient Silk Road came together before crossing the Tian Shan Mountains and entering northwest China. The foothills, alluvial fans and rivers of the Tian Shan constitute

near ideal environments for floodwater farming (Lewis 1966), with spring-summer floods generated by melting glaciers and snow providing a reliable source of water for irrigation. Floodwater farming is still practiced today in southern Kazakhstan and there is good evidence that in the medieval and prehistoric periods it was an important locus for irrigation agriculture (Groshev 1985; Itina and Yablonskiy 1997).

Eurasian archaeology holds a long-standing debate concerning the development of farming systems in the Eurasian steppes. Traditionally Central Asia, including the Semirechye region, is referred as a pastoral realm during the BA-IA with a shift ca. 800 BC toward a highly mobile pastoralism, followed by medieval nomadism (Christian 1994; Kuzmina 2007; Spengler et al. 2017). As early as 1990s the debates on the mobility development in Eurasia have been pointing to climate change. Christian (1998) describes a mixed farming-herding strategy during the BA (c. 2500–1100 cal BC) under warm and wet conditions with a shift to a horse riding pastoral economy in the Early IA (c. 800 cal BC) coinciding with a cold and dry climate, and deforestation.

However, recently a large body of archaeological evidence from environmentally specialized studies challenges the traditional nomad-centered system in the ancient economy model of Central Asia (Chang 2012; Macklin et al. 2015; Spengler 2015; Frachetti et al. 2017). Archaeobotanical studies at the Talgar alluvial fan strongly suggest that the IA farmers cultivated free-threshing wheat and hulled barley (long-season grain crops), broomcorn, foxtail millet, grapes and apples (Rosen et al. 2000, Spengler et al. 2017). Spengler et al. (2014) demonstrate that a similar assemblage of crops was grown across Central Asia from the Tian Shan to Himalaya during the second millennium BC (BA), and argue (Spengler et al. 2017) that hulled-large-grained forms replaced by the first millennium BC the compact-naked forms of barley dominated in the BA. This revolutionizes our understanding of the spread of ancient farming in Central Asia, and breaks the traditional dogma on the Central Asian economy during the BA-IA. It is clear that in Central Asia regional agriculture and sedentary communities existed since the Late BA.

### ***18.5.2 Agricultural Water Management on the Talgar Alluvial Fan During the Iron Age***

Figure 18.11 shows the density of archaeological sites across the Talgar alluvial fan (Macklin et al. 2015). The most-studied Iron Age settlements on the Talgar fan lies along the Taldy Bulak and Tseganka distributary stream networks (green lines) located in the middle reaches of these systems, 5–10 km downstream of the fan apex (Figs. 18.1 and 18.11). Largest settlements, burial sites, and concentrations of surface finds, are preferentially located along a series of distributaries, many of which must have been engineered in order to enable water diversion onto adjacent terraces.

It appears that the key to floodwater farming during the Late IA, similar to modern irrigation, was the control and management of water flow from the Tseganka and

Taldy Bulak channel systems. For the current Taldy Bulak, stream water is still diverted by a simple stretch dam and lateral outlet at the apex of the alluvial fan. The force of flow from the main river ‘pushes’ water into a low-gradient distributary channel, which allows bringing the flow up onto the higher terrace at downstream locations. IA farmers could also have very well used this simple technique. Notably, the levels of the Talgar River bed during the Early IA were c. 2 m higher than now, such decreasing the difference in gradient between action river channel and engineered distributary. The study of fine alluvial sediments infilling the floor of the Tseganka channel (Macklin et al. 2015 and Fig. 18.3a’) show that flow was not high enough to naturally maintain these distributaries as perennial or seasonal channels. Hence, water supply was depending on engineered channel networks and sufficient discharge to make the upstream bifurcation function.

The bifurcation node of the Taldy Bulak system is roughly 1 km upstream and 5 m above the level where the Tseganka channel leaves the present day Talgar River. IA farmers must therefore have constructed flow control structures to lead water across the fan surface. Careful management of these systems would have been required to ensure that water flow down the Tseganka and Taldy Bulak channels was not too large to cause channel incision, making it difficult and eventually impossible to direct flow into smaller irrigation canals that would have fed fields on the higher fan surface. Indeed, in the Soviet period this is exactly what happened through the inadvertent leakage of flow from concrete irrigation canals. Figure 18.3h shows an example of the Tseganka channel, which locally incised 6 m into fine-grained loess-derived sediments after artificial redirection of flow. Large floods in these distributary systems have always been a significant hazard to floodwater farming because of the highly erodible nature of their channel banks and regional substrate.

### ***18.5.3 Hydrology of the Tian Shan Piedmont and Water Supply for Ancient Farming***

In Semirechye, and probably in Tarim Basin, the southern Tian Shan and Pamir piedmont, high river flow and the maximum *potential* for water resources to support floodwater farming in both prehistoric and historical times have been associated with cold and wet conditions and glacier expansion (Sect. 5.1). However, the development of extensive Late IA settlement and rapid growth of population in the Talgar area, supported at least in part by floodwater farming, occurred during a phase of relatively warm and dry climate associated with a period of channel stability. This would suggest that hydroclimate and hydrology, at least locally, were not a constraint to the establishment of IA farming on the Talgar fan, nor were they the only factors in its demise. The key to the success of the Late IA (and medieval) agriculturists appears instead to have been a period of moderate main channel river flows confined within a Late Pleistocene age alluvial fan that as a consequence of having small, partially

entrenched distributary channels was naturally configured to facilitate floodwater farming.

We, therefore, do not need to evoke hydroclimate change as the proximate cause for this relatively short-lived (c. 400 years) period of Late IA floodwater farming in the Talgar region. Instead we should develop explanatory models that emphasize the skill of these IA societies in choosing and exploiting particular river environments and hydromorphic regimes that facilitated successful and long-lived farming practices (Macklin and Lewin 2015).

Nevertheless, considering the large Ili, Syr Darya, and Amu Darya dryland rivers downstream of, and fed by, the Tian Shan and Pamir piedmont, conjecture might suggest that wet Holocene neoglacial periods with higher river flow would have been more conducive to floodplain irrigation agriculturists. This may explain the great expansion of irrigation in the region during the first half of the 1st millennium BC as originally noted by Lewis (1966) nearly 50 years ago. New research on Holocene river dynamics, underpinned by robust geochronologies is urgently required on Central Asia's main rivers—the Syr Darya, and Amu Darya—in order to evaluate long-term society-river environment interactions.

## 18.6 Conclusions

We demonstrated a novel approach integrating fluvial geomorphology and tree-ring studies to explore the relationship between natural variability of runoff and its impact on ancient society. The approach links diverse spatial scales (small river catchments and regional watersheds) and temporal scales (centennial, decadal and inter-annual) of proxies for hydrological variability to explore the relationship between economy and settlement pattern of ancient societies, and climate change. The relative contribution of each method is skewed in this study because the tree-ring records do not overlap the emphasis of archaeological data. Nevertheless, the tree-rings provide valuable insight into a potential mechanism linking variability of recent and past runoff in Central Asia to large-scale atmospheric circulation. The interaction between a warming or cooling Arctic and intensity of the Siberian High surface-pressure system could be a key to unlock that mechanism. The tree-ring reconstructed hydrological extremes provide new information on the length and frequency of droughts and wet episodes in the endorheric basins of Central Asia that may be applied to help decipher strong socioeconomic impacts identified in the post-history of Silk Road.

The new proposed model for use of water by the IA farmers brings into the light many scattered archaeological shreds of evidence related to plant cultivation on the alluvial fans of Pamir-Tian Shan piedmont. We did not anticipate synthesizing these shreds of evidence, yet the reconstruction of river dynamics in the Tian Shan piedmont prompts us to challenge the dogmatic concept of Central Asian nomads prevalent in Inner Eurasian archaeology till now. Previously unknown correspondence of agricultural expansion c. 400–200 BC with a period of reduced flood flows, river stability and glacier retreat in the Tian Shan Mountains explains the strategy

of Late IA agriculturists for exploitation of moderate flows within an alluvial fan environment to facilitate transfer of water through a series of partially entrenched distributary channels. Holocene climate change was therefore not a proximate cause for the development and demise of this relatively short-lived (c. 400 years) period of IA farming.

River dynamics in the Tian Shan piedmont are, however, strongly coupled with regional hydroclimatic fluctuations, and they have likely acted locally as ‘push’ and ‘pull’ factors for riparian agriculturists in both upstream and downstream directions. Future geoarchaeological research in the region needs to expand downstream from the Tian Shan piedmont into the Ili, Syr Darya, and Amu Darya rivers, as it is likely that these exotic and dryland systems will have human-river environmental dependencies comparable to those of ancient river civilizations in Mesopotamia and the Indus Valley (Giosan et al. 2012; Macklin and Lewin 2015).

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## References

- Abdolvand, B., Mez, L., Winter, K., Mirsaedi-Globner, S., Schütt, B., Rost, K. T., et al. (2015). The dimension of water in Central Asia: Security concerns and the long road of capacity building. *Environmental Earth Science*, 73(2), 897–912.
- Adger, W. N., Barnett, J., Brown, K., Marshall, N., & O’Brien, K. (2013). Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, 3, 112–117. <https://doi.org/10.1038/nclimate1666>.
- Aizen, V. B., Aizen, E. M., & Melack, J. M. (1996). Precipitation, melt and runoff in the northern Tien Shan. *Journal of Hydrology*, 186, 229–251.
- Aizen, V. B., Aizen, A. M., Melack, J. M., & Dozier, J. (1997). Climatic and hydrologic changes in the Tien Shan, Central Asia. *Journal of American Meteorological Society*, 10, 1393–1404.
- Akishev, K. A. (1969). Zimovki poseleniya I zhilsha drevnih Usunei (Winter settlement and dwelling of the ancient Wusun). *Izvestia Akademii Nauk KazSSR*, 1, 29–47.
- Akiyanova, F. J. (1998). *Geomorphological map of Talgar River fluvial fan. Scale 1:25000*. Almaty: KAZ Institute of Geography.
- Aubekerov, B., & Gorbunov, A. (1999). Quaternary permafrost and mountain glaciation in Kazakhstan. *Permafrost and Periglacial Processes*, 10, 65–80.
- Baipakov, K. M. (2008). Gorod i step’ v drevnosti: Osledost’ i zemledelniye i Sakov i Usunei Zhetisu (City and steppe in ancient times: Settlement and farming of the Saka and Wusun in Semirechye). *Izvestia of National Academy of Science, Republic of Kazakhstan*, 1(254), 3–25.
- Bernauer, T., & Siegfried, T. (2008). Compliance and performance in International water agreements: The case of the Naryn/Syr Darya basin. *Global Governance*, 14, 479–501.
- Blättermann, M., Frechen, M., Gass, A., Hoelzmann, P., Parzinger, H., & Schütt, B. (2012). Late Holocene landscape reconstruction in the Land of Seven Rivers, Kazakhstan. *Quaternary International*, 251, 42–51.
- Borscheva, N. M. (1988). Limiting factors of Schrenk’s spruce radial growth. In: *Ecological studies in Northern Kirgizstan* (pp. 15–22). Frunze: Tian Shan Mountain Research Station Press.

- Bothe, O., Fraedrich, K., & Zhu, X. (2012). Precipitation climate of Central Asia and the large-scale atmospheric circulation. *Theoretical and Applied Climatology*, 108(3–4), 345–354.
- Chang, C. (2008). Mobility and sedentism of the Iron Age agropastoralists of southeast Kazakhstan. In H. Barnard & W. Wendrich (Eds.), *The archaeology of mobility* (pp. 329–342). Los Angeles: Cotsen Institute of Archaeology, University of California.
- Chang, C. (2012). Lines of power: Equality or hierarchy among the Iron Age Agro-pastoralists of Southeastern Kazakhstan. In C. W. Hartley, G. B. Yazicioglu, & A. T. Smith (Eds.), *The archaeology of power and politics in Eurasia: Regimes and revolutions* (pp. 122–142). Cambridge: Cambridge University Press.
- Chang, C. (2018). *Rethinking prehistoric Central Asia. Shepherds, farmers, and nomads*. Abingdon & New York: Routledge, 978-1-138-73708-2.
- Chang, C., Benecke, N., Grigoriev, F. P., Rosen, A. M., & Tourtellotte, P. A. (2003). Eurasian Iron Age settlements and chronology in Southeastern Kazakhstan. *Antiquity*, 77(196), 298–312.
- Chen, F., He, Q., Bakytbek, E., Yu, S., & Zhang, R. (2017a). Reconstruction of along streamflow record using tree rings in the upper Kurshab River (Pamir-Alai Mountains) and its application to water resources management. *International Journal of Water Resources and Development*, 33(2), 976–986.
- Chen, F., He, Q., Ermenbaev, B., Yu, S.-L., & Zhang, R. (2015). Climatic signals in tree rings of *Juniperus turkestanica* in the Gulcha River Basin (Kyrgyzstan) reveals the recent wetting trend of high Asia. *Dendrobiology*, 74, 33–40.
- Chen, F., & Yu, S. (2017). Tree-ring indicators of rainfall and streamflow for the Ili-Balkhash Basin, Central Asia since CE 1560. *Paleogeography, Paleoclimatology, Paleoecology*, 482(15), 48–56.
- Chen, F., Yuan, Y., Davi, N., & Zhang, T. (2016). Upper Irtysh River flow since AD 1500 as reconstructed by tree rings, reveals the hydroclimatic signal of inner Asia. *Climate Change*, 139, <https://doi.org/10.1007/s10584-016-1814-y>.
- Chen, F., Yuan, Y., & Yu, S. (2017b). Tree-ring indicators of rainfall and streamflow for the Ili-Balkhash Basin, Central Asia since CE 1560. *Paleogeography, Paleoclimatology, Paleoecology*, 482(15), 48–56.
- Cheng, F., Yuan, Y.-J., Chen, F.-H., Wei, W.-S., Yu, S.-L., Chen, X.-J., et al. (2014). A 426-year drought history for Western Tian Shan, Central Asia, inferred from tree rings and linkages to the North Atlantic and Indo-West Pacific Oceans. *The Holocene*, 23(98), 1095–1104. <https://doi.org/10.1177/0959683613483614>.
- Chiba, T., Endo, K., Sugai, T., Haraguchi, T., Kondo, R., & Kubota, J. (2016). Reconstruction of Lake Balkhash levels and precipitation/evaporation changes during the last 2000 years from fossil diatom assemblages. *Quaternary International*, 397, 330–341. <https://doi.org/10.1016/j.quaint.2015.08.009>.
- Christian, D. (1994). Inner Eurasia as a unit of World History. *Journal of World History*, 5(2), 173–211.
- Christian, D. (1998). History of Russia, Central Asia and Mongolia, Volume 1. *Inner Eurasia from Prehistory to the Mongol Empire*. Oxford: Blackwell.
- Cohen, J., Saito, K., & Entekhabi, D. (2001). The role of the Siberian High in Northern Hemisphere climate variability. *Geophysical Research Letters*, 28, 299–302.
- Cohen, J., Screen, A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., & Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, 7, 627–637. <https://doi.org/10.1038/ngeo2234>.
- D'Arrigo, R., Jacoby, G. J., Wilson, R., & Panagiotopoulos, F. (2005). A reconstructed Siberian High index since A.D. 1599 from Eurasian and North American tree rings. *Geophysical Research Letters*, 32, L05705.
- Di Cosmo, N. (1999). State formation and periodization in Inner Asian history. *Journal of World History*, 10(1), 1–40.

- Endo, K., Sugai, T., Haraguchi, T., Chiba, T., Kondo, R., Nakao, Y., Nakayama, Y., Suzuki, S., Silimizu, I., Sato, A., Montani, I., Yamasaki, I., Matsuoka, H., Yoslinaga, Y., Miyata, K., Minami, Y., Komori, J., Hara, Y., Nakamura, A., Kubo, N., Sohma, I., Deom, J.-M., Sala, R., Nigmatova, S. A., & Aubekerov, B. Z. (2012). Lake level change and environmental evolution during the last 8000 years mainly based on Balkhash Lake cores in Central Eurasia. In *Workshop Proceedings Towards a Sustainable Society in Central Asia: An Historical Perspective on the Future* (pp. 77–92). Kyoto-RIHN.
- Fang, K., Davi, N., Gou, X., Chen, F., Cook, E. R., Li, J., et al. (2010). Spatial drought reconstructions for central High Asia based on tree rings. *Climate Dynamics*, 35(6), 941–951.
- Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Molg, T., Bolch, T., et al. (2015). Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nature Geoscience*, 8, 716–722. <https://doi.org/10.1038/ngeo2513>.
- Frachetti, M. D. (2012). Multiregional emergence of mobile pastoralism and nonuniform institutional complexity across Eurasia. *Current Anthropology*, 53(1), 2–38.
- Frachetti, M. D., Smith, C. E., Traub, C. M., & Williams, T. (2017). Nomadic ecology shaped the highland geography of Asia's silk roads. *Nature*, 543(7644), 193–198.
- Francis, J. A., Vavrus, S. J., & Cohen, J. (2017). Amplified Arctic warming and mid-latitude weather: new perspectives on emerging connections. *WIREs Climate Change*, 8(5). <https://doi.org/10.1002/wcc.474>.
- Frank, A. G., & Thompson, W. R. (2005). Afro-Eurasian Bronze Age economic expansion and contraction revisited. *Journal of World History*, 16(2), 115–172.
- Giosan, L., Clift, P. D., Macklin, M. G., Fuller, D. Q., Constantinescu, S., Durcan, J. A., et al. (2012). Fluvial landscapes of the Harappan civilization. *PNAS*, 109(26), E1688–E1694.
- Groshev, V. A. (1985). *Irrigation of the Southern Kazakhstan in the Medieval times (Irrigatsia yujnogo Kazakhstana v srednie veka)*. Kazakh SSR, Almaty: Nauka.
- Itina, M. A., & Yablonskiy, L. T. (1997). *Saka of the Low Syr Darya (Saki nijney Syr-Daryi)*. Moscow: Rosspen.
- Jeong, J.-H., Ou, T., Linderholm, H. W., Kim, B.-M., Kim, S.-J., Kug, J.-S., et al. (2011). Recent recovery of the Siberian High intensity. *Journal of Geophysical Research*, 116, D23102.
- Jhun, J.-G., & Lee, E.-J. (2004). A new East Asian winter monsoon index and associated characteristics of the winter monsoon. *Journal of Climate*, 17, 711–726.
- Konovalov, V. G., & Maksimova, O. E. (2012). Reconstruction and forecast of water balance in the Naryn River from tree rings. *Ice and Snow*, 3(119), 87–98.
- Konovalov, V. G., & Pimankina, N. V. (2016). Spatial-temporal variability of water balance components in the north of Zailiisky Alatau Range. *Ice and Snow*, 56(4), 453–471.
- Koryakova, L. N., & Epimakhov, A. V. (2007). *The Urals and Western Siberia in the Bronze and Iron Ages*. (408 p.), Cambridge, U.K.: Cambridge University Press.
- Kozhevnikova, N. D. (1982). *Biology and ecology of Tien-Shan Spruce*. Frunze: ILIM.
- Krasnov, A. N. (1887). Essay on the life of the Kyrgyz in Semirechye. *Newsletters of the Imperial Russian Geographical Society*, XXIII. S. Petersburg.
- Krivanogov, S. K., Burr, G. S., Kuzmin, Y. V., Gusskov, S. A., Kurmanbaev, R. K., Kenschinbay, T. I., et al. (2014). The fluctuating Aral Sea: A multidisciplinary-based history of the last two thousand years. *Gondwana Research*, 26, 284–300.
- Krivanogov, S. K., Kuzmin, Y. V., Burr, G. S., Gusskov, S. A., Khazin, L. B., Zhakov, E. Y., et al. (2010). Environmental changes of the Aral Sea (Central Asia) in the Holocene: Major trends. *Radiocarbon*, 52(2–3), 555–568.
- Kuzmichenok, V. (2009). Monitoring of water, snow and glacial resources of Kyrgyzstan. *Assessment of Snow, Glacier and Water Resources in Asia*, 8, 84–99.
- Kuzmina, E. E. (2007). *The prehistory of the Silk Road*. V.H. Mair (Ed.). Philadelphia: University of Pennsylvania Press.
- Lammers, R. B., Shiklomanov, A. I., Vorosmarty, C. J., Fekete, B. M., & Peterson, B. J. (2001). Assessment of contemporary Arctic river runoff based on observational discharge records. *Journal of Geophysical Research*, 106(D4), 3321–3334.

- Lauterbach, S., Witt, R., Plessen, B., Dulski, P., Prasad, S., Mingram, J., et al. (2014). Climatic imprint of the mid-latitude Westerlies in the Central Tian Shan of Kyrgyzstan and teleconnections to North Atlantic climate variability during the last 6000 years. *The Holocene*, 24(8), 970–984.
- Lewis, R. A. (1966). Early irrigation in West Turkestan. *Annals of the Association of American Geographers*, 56(3), 467–491.
- Li, J., Gou, X., Cook, E. R., & Chen, F. (2006). Tree-ring based drought reconstruction for the central Tien Shan area in northwest China. *Geophysical Research Letters*, 33(7). doi: <https://doi.org/10.1029/2006gl025803>.
- Lukhtanov, A. (2014). *Verniy city and Semirechye Oblast* (Gorod Verniy I Semirechenskaya Oblast). (380 p.), Almaty.
- Lydolf, P. E. (1977). *Climates of the Soviet Union*. Oxford: Elsevier.
- Macklin, M. G., & Lewin, J. (2015). The rivers of civilization. *Quaternary Science Reviews*, 114, 228–244. <https://doi.org/10.1016/j.quascirev.2015.02.044>.
- Macklin, M. G., Panyushkina, I. P., Toonen, W. H. J., Chang, C., Tourtellotte, P. A., Duller, G. A., et al. (2015). The influence of Late Pleistocene geomorphological inheritance and Holocene hydromorphic regimes on floodwater farming in the Talgar catchment, Southeast Kazakhstan, Central Asia. *Quaternary Science Reviews*, 129, 85–95.
- Mamatkanov, D. M., Bazhanova, L. V., & Romanovsky, V. V. (2006). *Water resources of Kyrgyzstan*. Bishkek: NASK, Water Problems and Hydropower.
- Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., et al. (2004). Holocene climate variability. *Quaternary Research*, 62, 243–255.
- Meeker, L. D., & Mayewski, P. A. (2002). A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene*, 12, 257–266.
- Oberhänsli, H., Boroffka, N., & Sorrel, P. (2007). Climate variability during the past 2,000 years and past economic and irrigation activities in the Aral Sea basin. *Irrigation and Drainage Systems*, 21(3–4), 167–183.
- Overland, J. E., & Wang, M. (2016). Recent extreme Arctic temperatures are due to a split Polar vortex. *Journal of Climate*, <https://doi.org/10.1175/jcli-d-16-0320.1>.
- Panagiotopoulos, F., Shahgedanova, M., Hannachi, A., & Stephenson, D. (2005). Observed trends and teleconnections of the Siberian High. *Journal of Climate*, 18, 1411–1422.
- Panyushkina, I. P., Chang, C., Clemens, A., & Bykov, N. (2010). First tree-ring chronology from Andronovo archaeological timbers of Bronze Age in Central Asia. *Dendrochronologia*, 28(1), 13–21.
- Panyushkina, I. P., Meko, D. M., Macklin, M. G., Toonen, W. H. J., Mukhamedev, M. M., Konovalov, V. G., Ashikbaev, N. Z., & Sagitov, A. O. (2018). Runoff variations in Lake Balkhash Basin, Central Asia, 1779 to 2015, inferred from tree rings. *Climate Dynamics*. <https://doi.org/10.1007/s00382-018-4072-z>.
- Propastin, P. (2012). Problems of water resources management in the drainage basin of Lake Balkhash with respect to political development. In Leal Filho, W. (Ed.), *Increasing consumption of water resources in China in book climate change and the sustainable use of water resources* (pp. 449–461). Berlin: Springer.
- Rosen, A. M., Chang, C., & Grigoriev, F. P. (2000). Paleoenvironments and economy of the Iron Age Saka-Wusun agro-pastoralists in southeastern Kazakhstan. *Antiquity*, 74, 611–623.
- Sala, R., Deom, J. M., Nigmatova, S., Endo, K., & Kubota, J. (2015). Soviet, recent and future studies of the Balkhash Lake level. In *Izvestiya NAN RK (Proceedings of the National Academy of Sciences of the Republic of Kazakhstan, Geological series)*.
- Savoskul, O. S., & Solomina, O. N. (1996). Late Holocene glacier variations in the frontal and inner ranges of the Tien Shan, central Asia. *The Holocene*, 6(1), 25–35.
- Shiklomanov, A., Lammers, R. B., Lettenmaier, D. P., Polischuk, Y. M., Savichev, O. G., Smith L. C., & Chernokulsky, A. V. (2013). Hydrological changes: historical analysis, contemporary status, and future projections. In P.Y. Groisman & G. Gutman (Eds.) *Regional environmental changes in siberia and their global consequences* (pp. 111–154). Springer, Environmental Science and Engineering.

- Solomina, O., & Alverson, K. (2004). High latitude Eurasian paleoenvironments: Introduction and synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 209, 1–18.
- Solomina, O. N., & Maksimova, O. E. (2010). Dendroclimatic studies in the Tian Shan Mountains as the source of climate variability. *Proceedings Russian Academy of Sciences, Geographical Series*, 6, 54–66.
- Sorg, A., Bolch, T., Stoffel, M., Solomina, O., & Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*. <https://doi.org/10.1038/nclimate1592>.
- Spengler, R. N., III. (2015). Agriculture in the central asian bronze age. *Journal of World Prehistory*, 28(3), 215–253.
- Spengler, R. N., III, Chang, C., & Tourtellotte, P. A. (2013). Agricultural production in the Central Asian mountains; Tuzusai, Kazakhstan (450-150 BC). *Journal of Field Archaeology*, 38(1), 68–85.
- Spengler, R. N., III, Frachetti, M. D., Doumani, P. N., Rouse, L. M., Cerasetti, B., Bullion, E., et al. (2014). Early agriculture and crop transmission among Bronze Age mobile pastoralists of Central Eurasia. *Proceedings of the Royal Society B: Biological Sciences*, 281, 20133382.
- Spengler, R. N., III, Miller, N. F., Neef, R., Tourtellotte, P. A., & Chang, C. (2017). Linking agriculture and exchange to social developments of the Central Asian Iron Age. *Journal of Anthropological Archaeology*, 48, 295–308.
- Sun, J. (2002). Source regions and formation of the loess sediments in the High Mountain Regions of Northwestern China. *Quaternary Research*, 58, 341–351.
- Takeuchi, N., Fujita, K., Aizen, V. B., Narama, C., Yokoyama, Y., Okamoto, S., et al. (2014). The disappearance of glaciers in the Tien Shan Mountains in Central Asia at the end of Pleistocene. *Quaternary Science Reviews*, 103, 26–33.
- Thompson, D. W. J., & Wallace, J. M. (1998). The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, 25(9): 1297–1300, <https://doi.org/10.1029/98GL00950>.
- Trouet, V., Babst, F., & Meko, M. (2018). Recent enhanced high-summer North Atlantic Jet variability emerges from three-century context. *Nature Communications*, 9(180). <https://doi.org/10.1038/s41467-017-02699-3>.
- Vilesov, E. N., & Uvarov, V. N. (2001). *Evolution of Glaciation in the Zailiyskiy Alatau during the 20th Century (In Russian)*. Almaty: Kazakh State University.
- Wang, T., Ren, H., & Ma, K. (2005). Climatic signals in tree ring of *Picea schrenkiana* along an altitudinal gradient in the central Tian-Shan Mountains, Northwestern China. *Trees*, 19, 735–741.
- Wu, B., & Wang, J. (2002). Winter Arctic Oscillation, Siberian High and east Asian winter monsoon. *Geophysical Research Letters*, 29(19), 1897. <https://doi.org/10.1029/2002gl015373>.
- Yang, B., Qin, C., Wang, J., He, M., Melvin, T. M., Osborn, T. J., & Briffa, K. B. (2014). A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau, *PNAS*. <https://doi.org/10.1073/pnas.1319238111>.
- Yuan, Y., Shao, X., Wei, W., Yu, S., Gong, Y., & Trouet, V. (2007). The potential to reconstruct Manasi River streamflow in the Northern Tien Shan Mountains (NW China). *Tree-Ring Research*, 63(2), 81–93.
- Zhang, R., Shang, H., Yu, S., He, Q., Yuan, Y., Bolatov, K., & Mambetov, B. T. (2017b). Tree-ring-based precipitation reconstruction in southern Kazakhstan, reveals drought variability since A.D. 1770. *International Journal of Climatology*, 37(2), 741–750.
- Zhang, R., Yuan, Y., Gou, X., Yang, Q., Wei, W., Yu, S., et al. (2016). Streamflow variability for the Aksu River on the southern slopes of the Tian Shan inferred from tree ring records. *Quaternary Research*, 85(3), 371–379. <https://doi.org/10.1016/j.yqres.2016.03.001>.
- Zhang, T.-W., Yuan, Y.-J., Liu, Y., Wei, W.-S., Yu, W.-S., Chen, F., et al. (2013). A tree-ring based precipitation reconstruction for the Baluntai region on the southern slope of the central Tien Shan Mountains, China, since A.D. 1464. *Quaternary International*, 284, 55–62. <https://doi.org/10.1016/j.quaint.2012.03.037>.

- Zhang, R., Zhang, T., Kelgenbayaev, N., Qing, H., Maisupova, B., Mambetov, B., et al. (2017a). A 189-year tree-ring record of drought for the Dzungarian Alatau, arid Central Asia. *Journal of Asian Earth Science*, 148, 305–314. <https://doi.org/10.1016/j.jseaes.2017.05.003>.
- Zhou, H., Aizen, E., & Aizen, V. (2017). Constructing a long-term monthly climate data set in central Asia. *International Journal of Climatology*, <https://doi.org/10.1002/joc.5259>.

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