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Focus Article

Modern impacts on an ancient landscape, the piedmont plain in southwest Turkmenistan

Jonas Berking,[1]* Brian Beckers,[1] Tony Reimann,[2] Susan Pollock[3] and Reinhard Bernbeck[3]

The piedmont plain in southwestern Turkmenistan has experienced a millennia-long settlement history despite prevailing arid climates. One of the prerequisites for the various agricultural efforts was irrigation. Most of the water used for irrigation measures came from the adjacent Kopet Dag mountain chain. This situation changed with the introduction of the Karakum canal in the middle of the 20th century. The present study evaluates the rich irrigation history of the piedmont plain by investigating two small catchments that drain the eastern ranges of the Kopet Dag. Within their catchments, geomorphological and hydrological analyses were conducted. We present several Optically Stimulated Luminescence and 14-C dating results that add to the understanding of the landscape history from the Pleistocene until modern ages. Moreover, modern climatological and hydrological data were analyzed that show a remarkable drop in runoff from the Kopet Dag since the 1960s.

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INTRODUCTION

The piedmont plain in southwest Turkmenistan is an arid and nowadays remote area. However, numerous settlement remains in the shape of small mounds (locally called *depes*) indicate that the area flourished in history and prehistory. For subsistence, these settlements relied on agriculture, raising of animals, and hunting, the first being only possible through irrigation measures. The area is among the earliest ones in Central Asia where agricultural activities, and hence irrigation, took place.[1–3]

As in many arid environments, agricultural success was mainly controlled by the highly variable spatial and temporal availability of water. Despite these challenges, vast drylands have been culturally highly dynamic areas in which the inhabitants have developed multiple ways to cope with these uncertainties.[4,5] The art of managing drylands and mitigating their risks is of significant interest to many studies and applications.[6–9]

The special character of the area in focus is its very long and quasi-continuous settlement history coupled with its irrigation strategies. Moreover, it is a good example of the numerous central Asian riverine or oasis landscapes which have been nuclei of human settlement activities throughout history.[10] This changed during the last century when the Soviet regime built the Karakum Canal in the region, which detaches regional irrigation measures

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*Correspondence to: jonas.berking@fu-berlin.de

[1] Department of Earth Sciences, Physical Geography, Freie Universität Berlin, Berlin, Germany

[2] Netherlands Centre for Luminescence Dating, Soil Geography and Landscape group, Wageningen University, Wageningen, The Netherlands

[3] Institute for Ancient Near Eastern Archaeology, Freie Universität Berlin, Berlin, Germany

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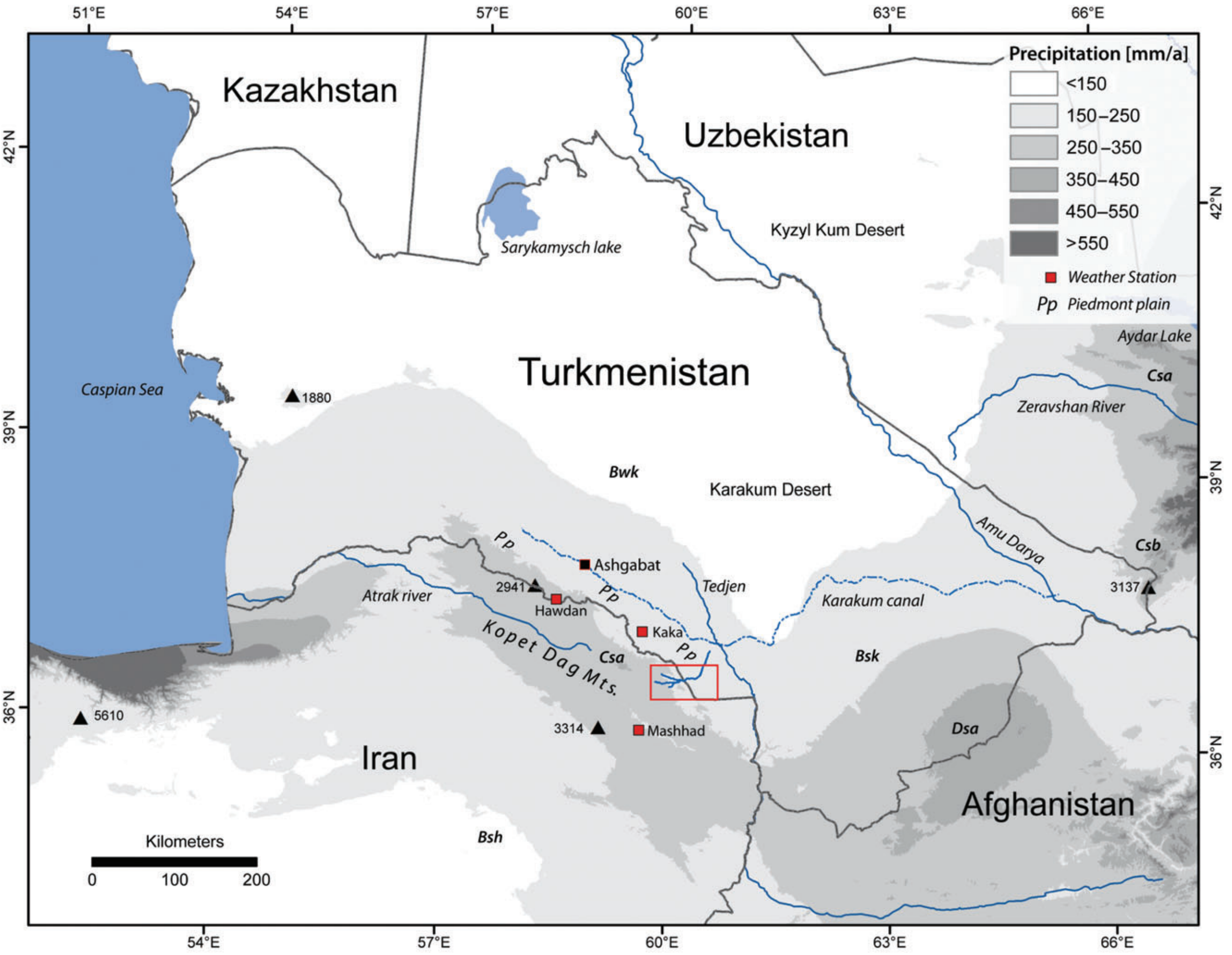

FIGURE 1 | General climatic setting of Turkmenistan and the surrounding countries. Gray layers depict the annual mean precipitation (data from 1950 to 2000, worldclim.org database). Indicated in italic bold letters are the Koeppen–Geiger climate zones. The red box delineates the area of interest, see also Figure 2.

from the dependency on natural water availability and supply.

The study area is characterized by low precipitation and a high amount of insolation (Figure 1). Even without any human impact, these dryland ecosystems with their sparse or initial vegetation and soil cover are vulnerable to the impacts of climate change, earthquakes, or floods.[9]

The main question tackled in this study is: how irrigation and management of water supply changed through the long history of the study region, including the major shift that occurred with the construction of the Karakum canal. In this sense, the scope of the present study is to combine and discuss data from (1) sediment chronologies, (2) archeological investigations, and (3) modern climatic and hydrological data.

Much of the analysis and results presented focus on the discharge history of two small rivers in the region. The hydrology of these two rivers, the Meana [Meana (loc. Miana) = name of settlement and river] and Chacha [Chacha (loc. Çaaça or Chaacha) = name of settlement and river], are assumed to be representative for the problems stated above.

During the fieldwork and informal interviews with locals in the region in 2011 and 2012, we were told that these rivers became ever dryer and their runoff behavior changed within the last decades. In the living memories of local residents, they were once perennially flowing streams, which at the time contributed the majority of water available for irrigation and drinking purposes. Such a perennial, rather than the current ephemeral, river regime would offer an explanation for the long history of irrigation in the area. However, in the modern situation the rivers are dry for much of the year and deep wells (more than 15 m) no longer reach the groundwater.

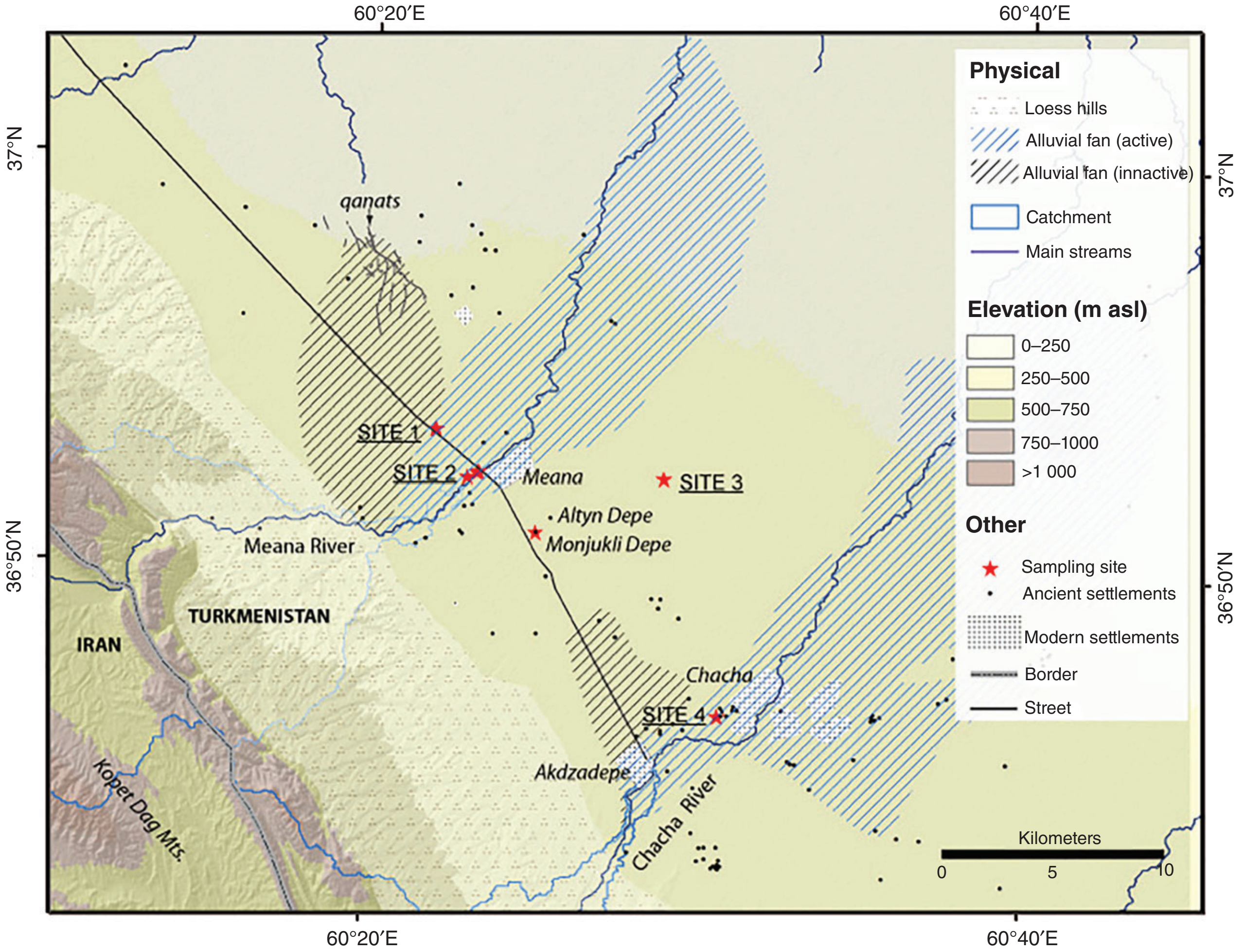

FIGURE 2 | Study site map with the main landscape features.

Historical Background

Turkmenistan´s agricultural sector depends on irrigation, as is the case for most of central Asia. Consequently, access to water plays a major role in its political, economic and social history. The *longue durée* history of irrigation in the region spans more than 8000 years, from its beginnings in the Neolithic through the Tsarist and later Soviet Union rule, before the modern state of Turkmenistan emerged in 1991.[11]

Since more than 90% of Turkmenistan is virtually uninhabitable desert, major settlements are—today as in the past—bound to locations of water surplus. These locations are the strips along the major rivers and the piedmont region at the Kopet Dag footslopes, the latter of which is the focus here. The earliest examples of settlements date to the Neolithic to early Aeneolithic periods of the late seventh through fifth millennia BCE, the remains of which are dispersed over much of the piedmont region of the Kopet Dag.[12,13] In some of the excavated settlements, cereals such as barley or einkorn have been found, pointing to the earliest agricultural endeavors (Ref 14; Miller in Ref 15). The earliest approach to irrigation may have combined naturally favorable locations such as the floodplains of the rivers that emerge from the Kopet Dag, with simple ditch and canal constructions to raise the soil water content.[1,3,16–18]

Settlement activity during the Aeneolithic and later Bronze Age is evidenced by sites on the piedmont plain that most probably utilized the same schemes of floodwater irrigation, but with increasing scales. From the fourth millennium onward, these settlements grew significantly in size, and large urban centers such as Altyn Depe and Gonur Depe emerged (for the location of Altyn Depe, see Figure 2). Later, from the first millennium BCE to the first millennium CE, Iron age, Achaemenid, Seleucid, Parthian, and Sasanian settlement systems emerged. At least since Sasanian time, the ever growing importance of the

Silk Road, which passed through the plains north of the Kopet Dag, must have boosted the local economy.[19]

The last two centuries brought a distinct change in irrigation schemes, because the distant and centralized governments of the Russian Tsarist and later Soviet rule introduced and installed modes and means of water management and large-scale irrigation plus agricultural planning. This culminated in the construction of the longest canal in the world, the Karakum canal, between 1954 and 1988, which annually redirects approximately 13 km^3 of water from the Amu Darya river and transports the water through Turkmenistan along the fringe of the Karakum Desert, with a length of approximately 1375 km.[20] Two consequences of the construction of this canal were: (1) the availability of vast newly cultivable areas (about 1 million ha) now detached from their local water dependency, and (2) the slow desiccation of the lower Amu Darya reaches, manifested in the shrinking and desiccation of the Aral Sea.[11,20] Like other former Soviet states, Turkmenistan's land and water management experienced problems since its independence in 1991. Especially the loss of the former management of irrigation systems, mainly for the cotton industry, and the high cost of maintaining the Karakum canal have led to a severe deterioration of the water structures.[21]

Regional Setting

The area of interest is the transitional zone between the Kopet Dag Mountains and the Karakum Desert in southeastern Turkmenistan. Fieldwork was undertaken in the summers of 2011 and 2012 in the area surrounding the modern villages of Meana and Chacha (Figure 2).

The area is best described as a piedmont zone that interlinks the dominating erosional processes in the highlands with the depositional processes in the lowlands. The resulting landforms can accordingly be described as erosive (pediments, glacis) or depositional (alluvial fans).[22]

The upper Kopet Dag consist primarily of Cretaceous and Paleogene sandstone and limestone, leading to erosional material composed of sandy, loamy or marl sediments.[23] The Kopet Dag Mountains are tectonically active, which is also expressed in their linear mountain ranges (strip faulting) along with recent earthquake activity; the 1948 earthquake of 7.2 on the Richter scale killed more than 100,000 people in the capital Ashgabat.[24] The lower part of the Kopet Dag is covered by a thick loess layer which gradually merges with the piedmont plain (Figure 3).

The two rivers in the focus of this study, the Meana and Chacha, are small dryland rivers, representative of many small streams that emerge from the higher Kopet Dag Mountains. They show a sharp decrease in their velocity when flowing through the piedmont plain and later into in the Karakum Desert where they desiccate.[25] The two streams are each characterized by a set of conically shaped active and inactive alluvial fans. Today they are ephemeral and only carry water during and after the rainy season or snow melt.[1] Their recent wadi beds are several meters deep and up to 20 m wide. Framed by the alluvial fans is an area that is not directly shaped by the periodic wadi runoff, but rather by surface runoff after rainfall events (cf. Ref 25). Multiple archeological sites have been identified there, among them Monjukli Depe (MD) with a stratigraphy spanning the late seventh to mid-fifth millennia BCE, and the much larger, third millennium BCE Bronze Age city of Altyn Depe (for early periods: Refs 15,26–28; Altyn Depe: Ref 29; see also Ref 30).

The piedmont plain is characterized by sparse vegetation and high Eolian activity. This high activity is due to prevailing winds from northern directions, which transport mainly silt-sized particles from the inner deserts to the mountainous foreland, where they precipitate as loess.[31] Soils are only weakly developed, mostly as initial AC-soils (Syrosems), and no paleo-horizons could be identified. Salty crusts on abandoned fields are visible and solonchaks, salty soils, emerge where standing water occurs over a longer period.[32]

The climate of the area is twofold with dry climates and a high variability in the lowlands and wetter conditions in the higher regions, which is mainly due to the continentality and topography of the area.[33] The region is classified as a dry steppe (Koeppen–Geiger Classification: BSk) with very hot and dry summers, cold and mostly dry winters and a short rainy season in early spring.

This distinct annual divide is due to atmospheric patterns that are either influenced by offshoots of the stable Siberian anticyclone, leading to very cold and dry conditions, or interrupted by the intrusion of warmer air masses mostly from the northwest, bringing relatively warm and humid air. These conditions are the main factors influencing the availability of moisture in the upper elevations, which often precipitate as snow. During the summer period, the radiation from the bare surfaces is the main factor that leads to the cessation of nearly all cyclonic activity and lowers the humidity level (cf. Ref 31; further climate analyses are presented in the *Results and Discussion* section.)

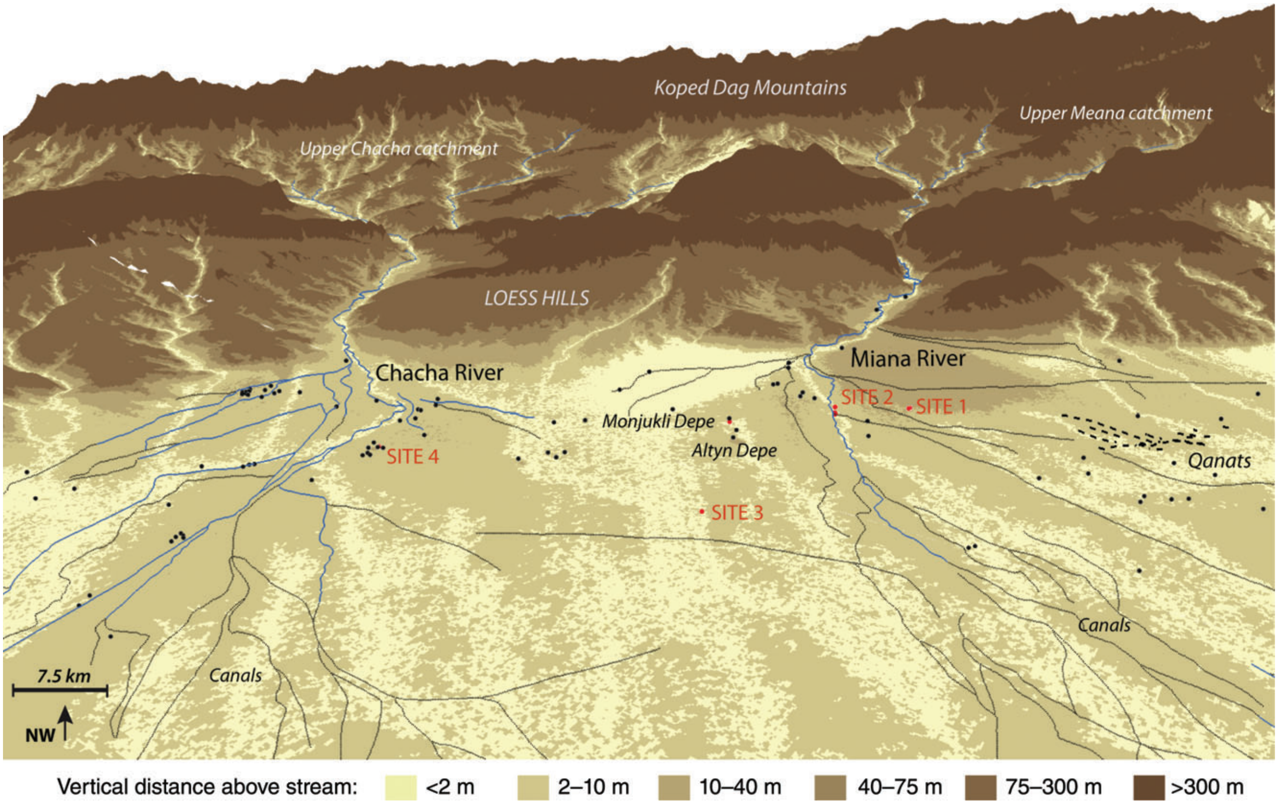

FIGURE 3 | Three-dimensional visualization of the study site. Blue lines indicated water-bearing channels on the 1:50,000 topographic maps (reference see below).

The area is scattered with agricultural fields and small irrigation canals, many of them probably for cotton growth. Since direct precipitation in the piedmont is not sufficient to sustain rain-fed agriculture, irrigation is mandatory. It appears that since the construction of the Karakum canal, all irrigation water is taken from it.

METHODS AND MATERIALS

Special interest during field surveys was given to locations with the potential to provide insights into the river and sediment history of the region. The investigation of the river bed sediments was restricted to the lower parts of the catchments; the upper portions are located in Iran and crossing the border was impossible. All landscape archives, sample points, and areas of interest were recorded using a standard GPS, described in the field and later combined in Geographic Information Systems (GIS).

The sediment profiles analyzed show rather homogenous sequences of either (1) fluvial sediment (sand and gravel) or (2) Eolian or fluvially redeposited silt or loess facies. No distinct layering or even (paleo-)soil horizons were found, apart from initial Syrosem topsoils, supporting sparse vegetation. The sediment properties were studied macroscopically and *in situ*.

Russian topographic maps [Turkmenskaja SSR, 1:50,000, General´nyj Stab, Moskva (1954–1958, renewed 1973), map sheets: J-41-109-B, J-41-109-G, J-41-110-A, and J-41-110-V] turned out to be very helpful by (1) providing detailed information on archeological remains and stream patterns and (2) representing the setting before 1950, when the landscape was probably much less modified than today (cf. Ref 34).

Hydrological, Climatological, and Digital Data Treatment

Terrain and relief information was derived from a Digital Elevation Model (SRTM 1, acquisition 2000, published 2014, http://earthexplorer.usgs.gov/). Hydrological properties, such as catchment delineation, stream network generation, and vertical stream distance were calculated in Saga-GIS on the basis of the SRTM (for Saga-GIS, see: http://www.saga-gis.org).

Monthly river discharge (m^3/second) was obtained from the UNESCO water database which provides quasi-continuous data of the Meana and Chaacha rivers from 1936 to 1974 and more scattered data from 1981 to 1985. Since the gauging stations no longer exist, we approximated their location (data: http://webworld.unesco.org/water/ihp/db/shiklomanov/).

Daily precipitation data were obtained from Global Historical Climatology Network (GHCN) and from the International Research Institute for Climate and Society (IRIDL; downloaded 2015 from http://iridl.ldeo.columbia.edu). Gridded precipitation data for annual means 1950–2000 were obtained from the Worldclim database and the DEKLIM VASClim project.[35,36] The next available weather stations are Kaka and Hawdan (Figure 1). Quasi-continuous data are available for Kaka 1936–1965 and 1977–1991. For Hawdan, it is 1936–1961.

Because most of the variance of monthly river discharges can be explained by the precipitation in their upper catchments, the available monthly climatic datasets for the upper regions were investigated (Table 1).

Since the gauging stations on the Meana and Chacha do not exist anymore and it is unclear how the discharge measurements were taken, some errors cannot be excluded.

The data were analyzed using standard statistical procedures in SPSS 10.0, Microsoft Excel and Libre Office Calc. Visualization was performed with the GIS software packages Saga-GIS 2.1.4, Quantum-GIS 2.1, and Esri ArcGis 10.1.

Age Determination

During fieldwork, several sediment trenches were investigated to help understand the respective fluvial, geomorphological or climatological history. From these sediment profiles, seven charcoal pieces were collected for radiocarbon dating and six bulk samples for Optically Stimulated Luminescence (OSL) dating.

OSL sampling was conducted on Eolian loess or sandy loess samples, taken in opaque plastic tubes during nighttime. Additional material was sampled for gamma spectrometry. In the laboratory, activity concentrations of 40K and several nuclides from the uranium and thorium decay chains were measured using high-resolution gamma-ray spectrometry.

OSL dating for two samples (LUM 1 + 4) from the 2011 campaign was carried out by the Luminescence Dating Labor OSL Laboratory (OH, USA; http://www.laberosl.com/). The laboratory utilized bulk (MAR-protocol) values from a Daybreak Reader. Due to this older methodology, the results should be treated with caution. The age results are shown in Table 2.

OSL dating for the other four samples (Turk-OSL 1, 2 and Turk-OSL 5, 6) from the 2012 field campaign was carried out by the Netherlands Centre for Luminescence dating (NCL; Wageningen, The Netherlands). For OSL dating, two quantities are determined: the received accumulated dose during burial (palaeodose) and the environmental dose rate of the sample surrounding. For dose rate determination, the activity concentrations of 40K and typical nuclides from uranium as well as thorium decay chains were measured using a high-resolution gamma-ray spectrometer. To calculate the effective dose rates, the activity concentration results were combined with information on the burial, water, and organic content history. The resulting dose rates are listed in Table 2. For more information on dose rate determination and the OSL method in general, the reader is referred to Preusser et al.[37]

To determine the palaeodose of the samples, the single-aliquot regenerative-dose (SAR) protocol[38] was applied to purified sand-sized quartz extracts (90–180 μm fraction). The reliability of the measurement procedure was checked by a dose recovery experiment; an average dose recovery ratio of 0.99 ± 0.05 ($n = 14$) confirmed the suitability of the measurement setup. To obtain a meaningful estimate of the palaeodose received by the samples during burial the palaeodose measurements were repeated on 18–39 aliquots per sample. The single aliquots palaeodose distributions of the two younger samples under investigation (Turk-OSL 1 and 2) were significantly

TABLE 1 | The Utilized Hydroclimatic Datasets

Station	Unit	Period	Resolution	Location	Elevation (m)
Meana M/C	m^3/second	1936–1985	Monthly	36.8780 N 60.3875 E	299
Gridded	mm	1951–2000	Monthly	Cell center: 60.25 E 36.75 N	—
Hawdan	mm	1961–1990	Monthly	37.6515 N 58.4025 E	1480
Kaka	mm	1939–1991	Daily	37.3460 N 59.6149 E	293
Mashhad	°C	1950–2003	Daily	36.3270 N 59.7903 E	927

overdispersed, i.e., the palaeodose distributions were more scattered than expected based on the measurement uncertainties. Given the palaeodose distributions (right-skewed) obtained and the depositional environment of the two younger samples, this scatter is most likely caused by heterogeneous signal resetting (poor bleaching). To obtain meaningful palaeodose estimates from those scattered palaeodose distributions, we employed the bootstrapped Minimum Age Model (bootMAM: Ref 39). The two older samples (Turk-OSL 5 and 6) show no indication of heterogeneous signal resetting. For these two samples the palaeodose was calculated using the Central Age Model (CAM: Ref 40). The resulting palaeodoses of the samples were divided by the dose rates to obtain the burial ages of the samples. Palaeodoses and ages are listed in Table 2 together with an estimate of the validity.

Radiocarbon dating was performed by Accelerator Mass Spectrometry (AMS) on charcoal pieces at the Poznan Radiocarbon Laboratory (http://www.radiocarbon.pl/). Calibration was carried out by the laboratory using OxCal v4.1.5 Bronk Ramsey (2010).

RESULTS AND DISCUSSION

The results presented encompass the following points:

1. the chronostratigraphic analysis, which is discussed with respect to the broader landscape historical context; and
2. the hydrological and climatological analysis, which are discussed with respect to the fluvial and irrigation historical context.

Chronostratigraphic Analyses

The radiocarbon and luminescence age determinations are presented in their chronological order and discussed in the next paragraph.

The two oldest OSL ages are the samples ‘Turk OSL 5’ and ‘Turk OSL 6’ at *Site 1* (Table 2 and Figure 4). They were taken from a small loess lens, intercalated in an open gravel quarry. Sample ‘Turk OSL 5’ was taken 160 cm below the surface (of the gravel quarry) and points to a late Pleistocene age of 29.8 ± 1.5 ka. Sample ‘Turk OSL 6’ was taken 30 cm below the surface (of the gravel quarry) at the top of the gravel and points to a very late Pleistocene/Younger Dryas age of 13.6 ± 0.9 ka.

From *Site* 2, three OSL samples were taken from the banks of the Wadi Meana. Sample ‘Turk OSL 1’ was sampled at 135 cm below the modern surface and reveals an age of 3.1 ± 0.6 ka. Sample ‘Turk OSL 2’ was taken at the same location at 70 cm below the modern surface and reveals an age of 2.5 ± 1.1 ka. Sample ‘LUM 1’ was taken 275 cm below the modern surface and reveals an age of 3.4 ± 0.1 ka.

The sample ‘LUM 4’ reveals an early Holocene age of 8.5 ± 0.2 ka. It was taken in the context of the archeological excavation at the site of MD (Ref 41 in Ref 42).

TABLE 2 | OSL-Dating: (a) Sample Location and Age Determinations, and (b) Laboratory Results

(a)

Sample	Lat. N	Lon. E	ELV (m a.s.l.)	Depth (m)	Age (ka)	Site
Turk OSL 1	36.870491	60.383136	299	1.35	3.1 ± 0.6	Site 2
Turk OSL 2	36.870491	60.383136	299	0.7	2.5 ± 1.1	Site 2
Turk OSL 5	36.88974	60.36678	290	1.6	29.8 ± 1.5	Site 1
Turk OSL 6	36.889975	60.366219	290	0.3	13.6 ± 0.9	Site 1
LUM4	36.872367	60.3881	290	3.66	8.5 ± 0.2	MD
LUM1	36.872367	60.3881	300	2.75	3.4 ± 0.1	Site 2

(b)

Sample	NCL Code	Palaeodose (Gy)	Water Content (%)	LOI (%)	Dose Rate (Gy/ka)	Systematic	Random	Validity	Comments
Turk OSL 1	NCL-7114003	7.5 ± 1.4	1.15 ± 0.29	0.95 ± 0.09	2.46 ± 0.08	0.1	0.57	Q	bootMAM
Turk OSL 2	NCL-7114004	6.1 ± 2.7	1.15 ± 0.29	0.95 ± 0.09	2.47 ± 0.08	0.08	1.09	Q	bootMAM
Turk OSL 5	NCL-7114005	76.9 ± 3.1	1.47 ± 0.37	1.11 ± 0.11	2.58 ± 0.08	1.01	1.15	lo	CAM
Turk OSL 6	NCL-7114006	32.4 ± 1.8	1.56 ± 0.39	0.84 ± 0.08	2.37 ± 0.08	0.45	0.78	lo	CAM

bootmam, minimum age model; cam, central age model; lo, likely okay; MD, Monjukli Depe; Q, questionable.

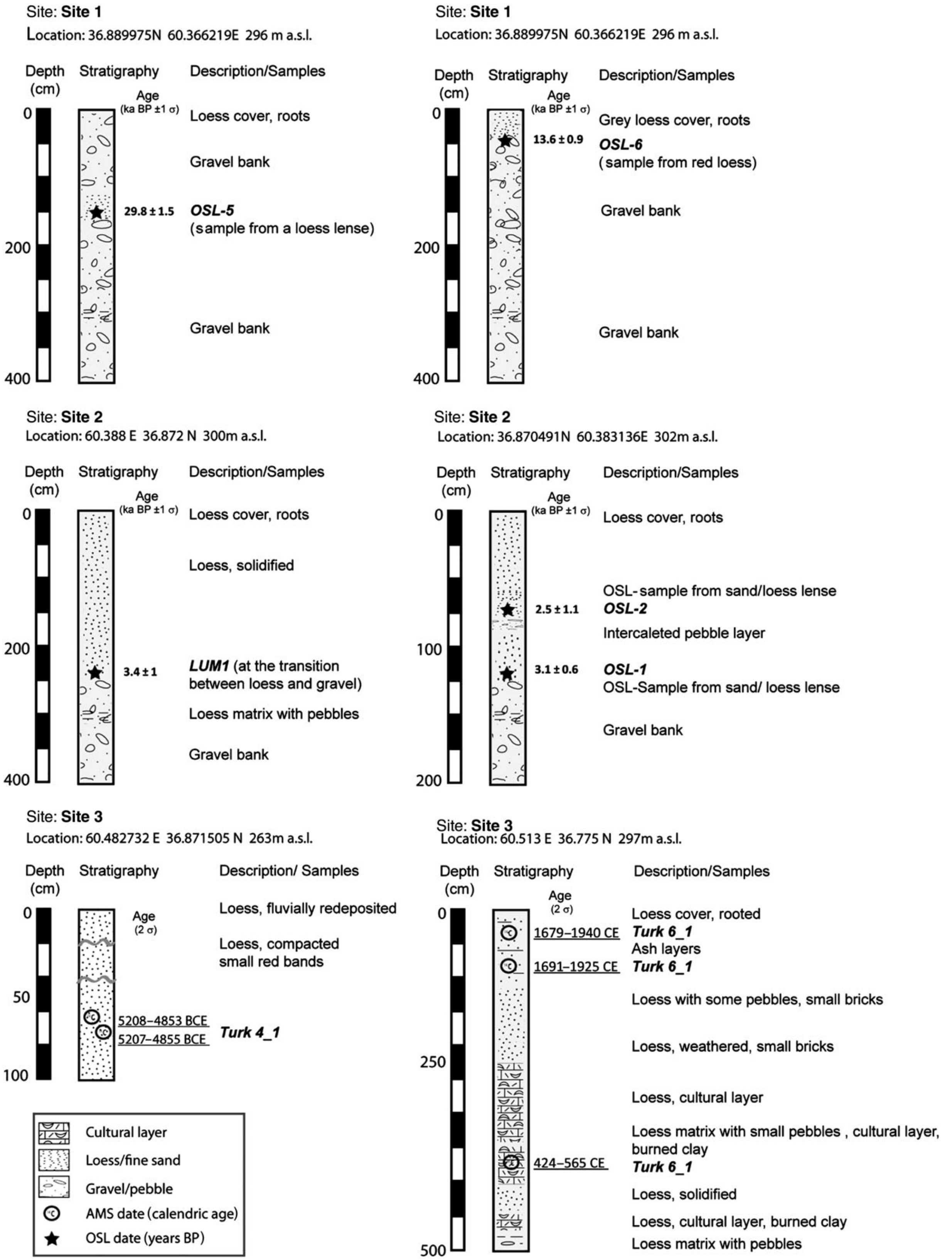

FIGURE 4 | The presented profiles and their sedimentological sequence (for pictures, see Appendix C).

The oldest 14C-sample is 'Turk_9,' which is calibrated to a Middle Holocene date of 5983–5746 BCE. It was taken in the context of the archeological excavation at MD (the sample and the site description is published in Ref 41 in Ref 42).

Two charcoal samples 'Turk 4_1' were taken at *Site 3* from the infill of a small wadi, at 65 and 70 cm below the surface, respectively (see Figure 4). They reveal statistically identical Mid-Holocene calendric ages of 5208–4853 BCE and 5207–4855 BCE. Three samples were taken at *Site 4*, at the side walls from a 5-m-deep incised wadi near Chacha (see Figure 4 and Appendix C). The samples 'Turk 6_1' reveal late Holocene to modern calendric ages of 424–565 CE at 410 cm depth, 1691–1925 CE at 80 cm depth, and 1679–1940 CE at 30 cm (Table 3).

Landscape Historical Context

Since the Pleistocene the piedmont plain of Turkmenistan has experienced times of changing climatic and hydrological conditions. It was subject to different dominating landscape formation processes such as mass movements, Eolian or fluvial processes, and human activity.

For the Pleistocene penultimate and last glacial cycle, more arid conditions are assumed for the Kopet Dag, including increased Eolian activity and probably increased erosional activity, which led to the deposition of coarse materials (cf. Refs 43,44).

The deposition of this coarser material of Pleistocene age is attested by the sample OSL Turk 5 intercalated in the quarry gravel formation (Table 2). At the end of the Pleistocene/beginning of the Holocene, a last drop to colder and more arid conditions probably occurred during the Younger Dryas stage, which is represented by the OSL Turk 6 sample in the upper part of the gravel (Table 2 and Appendix).[45]

With the onset of the Holocene, the climate became more humid and a period of relative stability began. It is assumed that the dry cold steppes of the Pleistocene and Younger Dryas were successively replaced by forest-steppe vegetation with a maximum increase of arborescent species.[46,47] At a remarkably early time, people started to populate the area, settling in the area toward the end of the Neolithic some 8000 years ago. They probably introduced a whole 'Neolithic package' of domesticated plants and animals, among them sheep, goat, and dog, as well as einkorn and two-row barley, and a largely sedentary way of life (Ref 48, p. 33–44 and Ref 2).

For the broader area of lower Turkmenistan, climatic changes and oscillations through the Holocene were probably minor, as indicated by several biostratigraphic, geomorphological, and archeological proxy data.[3,45,47,49] In archeological terms, the region was more or less continuously settled from the Neolithic to at least Late Sasanian times (Castro Gessner in Ref 42). Several small Neolithic to early Aeneolithic settlements of the seventh to late fifth millennia are followed by increasingly complex settlement systems in the Later Aeneolithic with Ilgynly Depe (see Ref 50) as a center, and later, in the late third and early second millennia BCE, Altyn Depe as a major city.[51] Both of these population concentrations must have had a sustained supply of water consisting of a canal system that provided these extensive settlements with drinking water. Judging by their closeness to the Chacha or Meana rivers, respectively, these canals were likely rather short. These relatively simple irrigation technologies led to settlement patterns in which major sites were constrained to locations favored by natural water flow. Unfortunately, much of the nonurban use of this landscape as well as the intricacies of the settlement patterns of the prehistoric periods, including not just small sites but also features such as canals or terracing, remain concealed under thick layers of loess. However, for the Middle Bronze Age (Namazga V period), a reconstruction of a highly centralized settlement pattern appears likely, with Altyn Depe at

TABLE 3 | Radio Carbon Dating Results

Sample	Lab	Lat. N	Long. E	ELV (m a.s.l.)	Depth (cm)	14C Age	Calendric Age (Calibrated 2 Sig)	Site
Turk 4_1	Poz-51988	36,871505	60,482732	267	65	6090 ± 40 BP	5208–4853 BCE	Site 3
Turk 4_1	Poz-51989	36,871505	60,482732	267	70	6090 ± 35 BP	5207–4855 BCE	Site 3
Turk 6_1_a	Poz-51990	36,775146	60,51254	297	410	1560 ± 30 BP	424–565 CE	Site 4
Turk 6_1_b	Poz-51993	36,775146	60,51254	297	80	75 ± 30 BP	1691–1925 CE	Site 4
Turk 6_1_c	Poz-51994	36,775146	60,51254	297	30	120 ± 30 BP	1679–1940 CE	Site 4
Turk_9	Poz-51995	36,84858	60,418182	290	370	6980 ± 50 BP	5983–5746 BCE	MD

Dating material was charcoal.

the top of the settlement hierarchy and much smaller secondary satellite sites around it. In the Iron Age (late second to first half of the first millennium BCE) the population must have shrunk, only to pick up again in the Sasanian period. During that time, an unprecedented number of people settled in numerous large sites that were more evenly spread out across the Kopet Dag foothills (Castro Gessner in Ref 42). This is the most likely period for the introduction of a qanat irrigation system. The Sasanian system, with its unconstrained spread of larger sites across the foothill zone, differs quite markedly from the Bronze Age one, which was dependent on canals leading from the rivers. Qanat irrigation frees settlement locations from dependence on above-ground natural water courses. Traces of such a system can still be found in the area today.

In fact, the piedmont area is better characterized as an ecosystem that does not primarily depend on its local but rather regional hydroclimatic conditions, here the adjacent Kopet Dag mountains. In this sense, it is better compared to the numerous central Asian riverine or oasis landscapes that have long been nuclei of human settlements and that depend predominantly on their respective 'water towers.'[10] Hence changing hydrological conditions in distant areas appear to be of higher significance concerning questions of the regional irrigation history than local conditions. Possible distant drivers of hydrological changes are monsoonal patterns in southeast Asia, glacier melt in the central Asian highlands (Pamir Shan, Altai, and Tian Shan) and the subsequent change in fluvial patterns, e.g., of the Amu Darya River or of the disappeared Usboy River, and finally the Holocene oscillations of the Aral Sea.[52–55]

The only weak indication for a slight change in fluvial activity during Mid-Holocene in the area are the two charcoal samples Turk 4_1 a and b which were taken from the fill material of a small Meana tributary. However, the interpretation of a distinct change or higher fluvial activity, and radiocarbon dates of fluvial regimes are problematic.[25,56]

During the transition from the Middle to the Late Holocene, the area must have experienced a major change in Eolian depositional processes. This is manifest in the two neighboring sections from the banks of the Wadi Meana. Here a thick loess layer overlies the older river gravel. The OSL dates from the lowest part approximate the onset of this loess deposition between 3.1 ± 0.6 and 3.4 ± 0.1 ka (samples Turk OSL 1 and LUM 1, respectively). Comparative active loess depositions are reported from the Iranian plains and might point to more arid conditions.[43,57] However, interpretation is difficult, because different reasons might cause the deposition of the loess layer, which here is up to several meters thick. Reasons might be: (1) less vegetation or changing wind directions in the potential source areas, leading to intensified deflation, (2) more vegetation in the sink area, leading to more deposition, (3) the fluvial redeposition of loess, which is readily available in the lower Kopet Dag range, and (4) the alteration of vegetation or fluvial patterns by humans.[58] However, the incision of the Wadi Meana through this loess layer and into its own gravel bed shows the relative stability of the valley position (Ref 42, see picture in Appendix C).

The latest three dates were taken in a branch of the Chacha river and also refer to loess depositional processes. The river branch is interpreted as a modern gully incision that naturally exposes piedmont plain sediments. The dated charcoal remains, which range from the first millennium CE to the present (samples Turk_6 a,b,c), were taken from a context of archeological layers buried under loess including pottery (picture in Appendix C). At least the earlier date matches the archeological evidence of cultural phases dating to Sasanian times. The fact that these cultural layers are enclosed by loess-like material indicates that loess and Eolian deposition may have prevailed since the Middle Holocene. This might resemble the modern dust activity reported for Turkmenistan in general.[31]

Hydrological and Climatological Analyses

Several small rivers drain the Kopet Dag Mountains, flow eastward and eventually desiccate in the Karakum Desert. Two of these, the Meana and Chacha rivers, are the focus of this analysis. It is assumed that their fluvial history and runoff behavior together with their climatological setting are representative of much of the piedmont area concerning its natural water budget. Both rivers show very similar runoff behavior and their catchment character is comparable (Table 4). The mean annual discharge of the Meana river for the observed period is 0.013 km^3 and that of the Chacha 0.011 km^3. Both have their peak runoff in April.

By comparing the discharge of both rivers in Figure 5(a) and (b), two features are evident: (1) their runoff behavior is very similar and (2) they show a distinct reduction in discharge between 1965 and 1985.

For (1): The monthly discharge values of the Meana and Chacha show a very high correlation ($R^2 = 0.98$ and Pearson coefficient = 0.99). So to

TABLE 4 | Catchment Character of the Meana and Chacha River

Catchment	Area (km^2)	Min_Elv	Max_Elv	Mean Discharge from 1936 to 1965 (m^3/second)	Mean Discharge from 1965 to 1985 (m^3/second)	Reduction Between Discharge Periods (%)
Chacha	2219.9	332	2606	0.4	0.16	63
Meana	1702.0	268	2622	0.45	0.18	66

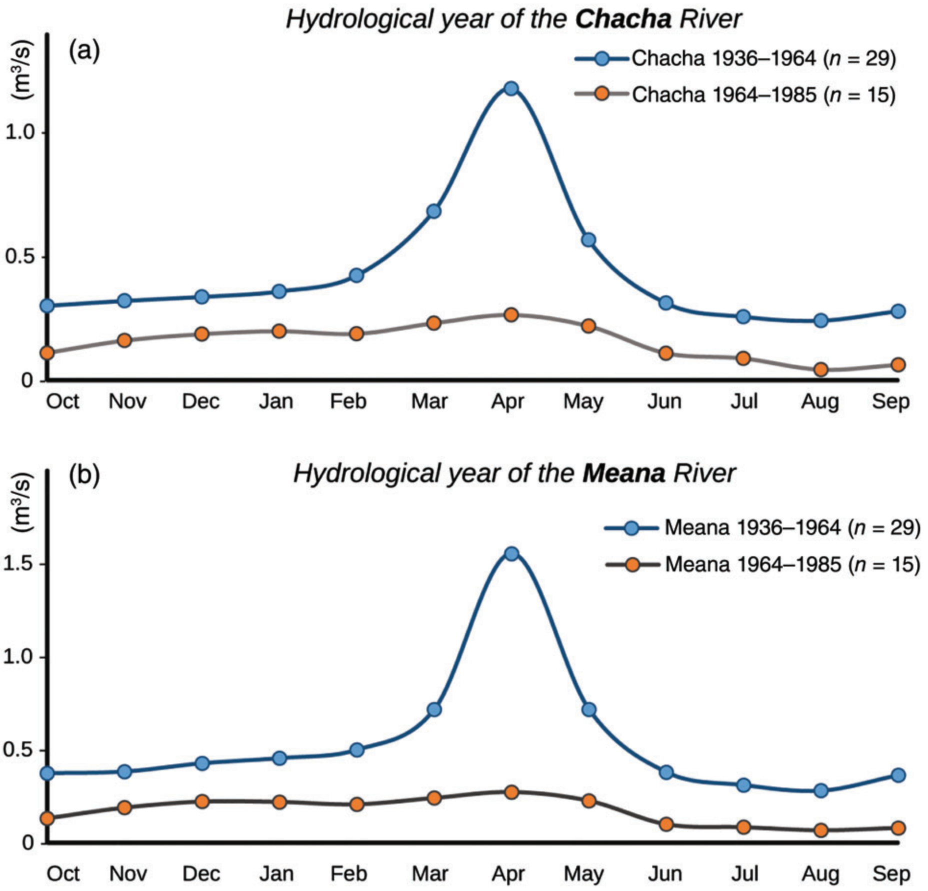

FIGURE 5 | The hydrological year of (a) the Chacha river and (b) the Meana river.

reduce the scope of the following analysis, it is sufficient to display the Meana river observations (see also Appendix A).

For (2): From 1965 onward, the Meana and Chacha rivers' mean annual runoff values permanently drop below the all-year mean. For the Meana, the reduction in discharge from 1965 onward is approximately 66% and for the Chacha it totals approximately 63%. In addition, the previously high April value is evened out.

In a first step, the monthly runoff values were compared to monthly precipitation data (Figure 6). The result shows that precipitation data from the Hawdan weather station in the Kopet Dag best fits the seasonal and monthly discharge ($R^2 = 0.82$), despite its location about 200 km away from the Meana river. The maximum precipitation at this station is in April, as is the maximum observed discharge. The weather station of Kaka is assumed to represent the climatic conditions on the lower piedmont plain, which shows less agreement with the discharge values ($R^2 = 0.57$) (details and data in the Appendix B).

In a last step, the discharge history with the pronounced drop in discharge was compared to the climatic datasets over time. Especially the precipitation was checked for indications of altering conditions or climatic change. In fact, none of the examined climatic datasets show distinct changes or trends over the respective years, but stay within their standard deviations over their entire time series (Figure 7 and Appendix B).

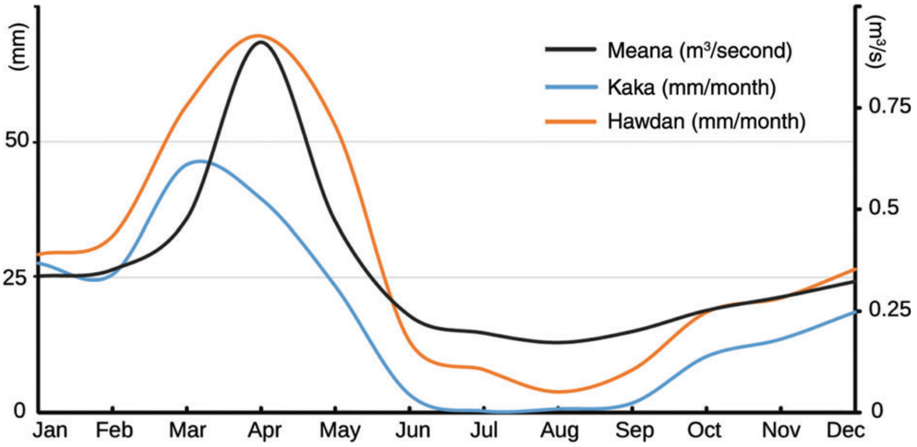

FIGURE 6 | Annual discharge of the Meana in comparison to monthly precipitation values of the Kaka and Hawdan weather stations.

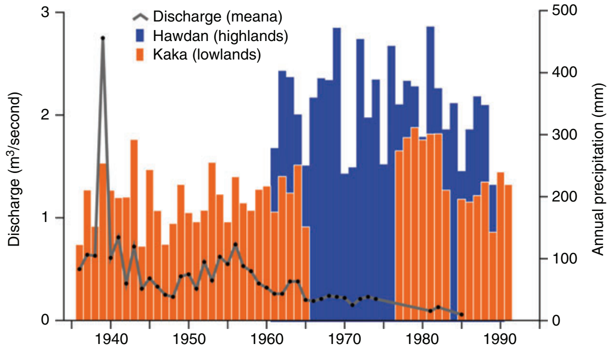

FIGURE 7 | Annual time series of the Meana river's discharge and precipitation at Kaka and Hawdan.

However, the datasets used differ in their resolution, period covered, and distance to the area of interest, and must be interpreted with caution.

Fluvial Landscape History

The modern diversion of water from the Karakum canal broke up traditional irrigation measures and obscures much of those former usages, making their detailed geomorphological and hydrological reconstruction difficult.[11]

Especially for the Early and Mid-Holocene, it cannot be excluded that there were times of higher rainfall availability in the lowlands that permitted rain-fed agriculture. However, the importance of the Kopet Dag rivers for the piedmont plain and its millennia-long irrigation schemes appears obvious.[59] This is strengthened by the fact that the continuous water and sediment supply through the alluvial fans onto the floodplains provide the most preferable locations for irrigation endeavors.[17]

However, the courses of the Kopet Dag rivers are not stable and show anastomosing and changing flow patterns. These oscillations also lead to new river or wadi incisions and branches, which subsequently lead to active and inactive parts of the alluvial fans. This then implies shifts of agriculturally used areas and/or shifts in settlement locations.[42] The controlling mechanisms of these flow patterns are complex and mostly dominated by upstream processes and conditions, i.e., the climatic and hydrological conditions, lithology and tectonic activity, and human impact. Moreover, a stream is controlled in its lower reaches by its base level, its valley morphology, the prevailing vegetation (density), flood frequency, and again human agency.[60]

The archeological record implies that human agency manifest in irrigation measures must have played a major role. These measures might have ranged from simple floodwater techniques with small canals or ditches and leveling, to larger scale techniques of dam building or water storage (cf. Refs 59,61).

In addition to the direct utilization of surface or river discharge water, groundwater must have played a much greater role in the past than at present. Groundwater tapping conduits or tunnels, so-called qanats, which are well-known from the Iranian plateau, are also widespread in the Turkmen piedmont zone.[62,63] In the investigated area, several qanats totaling about approximately 20 km in length are still visible on aerial imagery (indicated in Figure 2). They directly account for a former groundwater usage, most probably for irrigation. Since they are out of use and dry—as was checked at several shafts—together with dried-out water wells in the area, it is assumed that the groundwater level dropped at some point in time. This might well be connected with the overall observed drop in runoff discharge in the second half of the 20th century. The large drop observed by comparing discharge volumes for the years 1936–1965 and 1965–1985, which is also confirmed by the Russian maps from the 1950s where both Meana and Chacha rivers are labeled as perennial, is remarkable.

What follows are attempts to evaluate this decrease, since there appear to be no straightforward explanation(s) for it. As shown above neither the rainfall data nor the temperature at Mashhad, which was checked for possible trends in evaporation or seasonal changes in snowfall, show any clear trends through their respective time series which could account for the observed runoff decrease. This implies that climatic changes should be excluded as the dominant or prime cause. Other physical processes such as tectonic activity and earthquakes or changes in lithology cannot be excluded, but such evidence is neither published nor does it appear very likely to cause such continuous decrease.

This leaves human water diversion or a change in water management strategies as the most likely reasons. The most obvious sources for such runoff decreases are the constructions of river dams.[64,65] However, no dams have been built in the upper catchment of the two rivers in question during the time frame considered, and a cursory personal communication with local water authorities did not reveal any such information (a list of Iranian dams from the FAO was checked: see reference AQUASTAT). The only dam-like construction visible on recent aerial or satellite imagery is in the upper catchment of the Meana river (at 36.798988°N, 60.078896° E). It was probably built around 1988–1994 and hence later than the time covered here with its observed decrease in discharge. This dam may well, however, contribute to the observed dryness of the recent years in the lower Meana valley (personal communication with local persons).

Hence the drop in discharges must be explained by current land- and water management in the upper Iranian catchments.

A simple GIS analysis of the Meana catchment delineates the upper basin into one major and two minor tributaries, with total flow lengths of about 87 km. The streams appear to represent typical V-shaped mountain valleys with some wider areas (pools) that can be used for cultivation. As indicated by aerial and satellite imagery, a 1-km strip around the stream bed is a reasonable maximum for agricultural field extents. Assuming this simple 1 km buffer, an area of 87 km^2 would account for the irrigable area and the amount of water that is held back in the upper catchment. Comparing the two respective time frames, this would total a mean annual retention of 12 million cubic meters of water per square kilometer (or a water surplus of ~3500 L/day and hectare).

Since this study is unfortunately restricted to the Turkmen side of the valleys, this very high amount of reduced water flow cannot be investigated in appropriate detail and remains an unsolved problem for future studies. Contributing explanations might be: (1) an expansion of river water abstraction and intensified irrigation with surface waters, or (2) a higher outtake of groundwater from wells. Both might lead to either higher infiltration capacities or soil water contents due to different surface properties that might increase evaporation rates, e.g., from open fields or water storages (cf. Ref 66).

It should be considered as a hydrological curiosity that the drop in natural water supply happened exactly during the time in which the piedmont plain of Turkmenistan became detached from dependency on this supply. Since the mid-1960s water could be taken from the Karakum canal. The construction time of the canal matches the time of continuous decrease of runoff from the upper catchments, so that the latter would not have sustained the millennia-long irrigation schemes on the piedmont any longer.

CONCLUSIONS

The main outcome of this study is that an irrigation system that most probably worked for many millennia broke down in the middle of the 20th century. It appears that it was not climate, but rather changing water management and land use in the upper Iranian parts of the investigated catchments that led to the remarkable drop in discharge in the lower reaches of the Chacha and Meana rivers. This drop in discharge and the coincident availability of the waters from the Karakum canal most probably led to a loss of local knowledge concerning historical irrigation and water harvesting techniques that were well adapted to local pre-20th century conditions.

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APPENDIX A. DISCHARGE DATA

TABLE A1 Seasonal Discharge Data (m^3/s)

Station, Time	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Meana, 1936–1965	0.4	0.4	0.4	0.5	0.5	0.7	1.6	0.7	0.4	0.3	0.3	0.4
Meana, 1965–1985	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Chacha, 1936–1965	0.3	0.3	0.3	0.4	0.4	0.7	1.2	0.6	0.3	0.3	0.2	0.3
Chacha, 1965–1985	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.1	0.1	0.0	0.1

TABLE A2 Linear Regression and Person Correlation Coefficient of the Meana and Chacha River Discharge (per Month)

	R	R^2	Standard Error	Correlation (Pearson)	Sig. (Pearson)
1	0.991	0.982	0.035	0.991	.000

APPENDIX B. METEOROLOGICAL DATA

TABLE B1 Monthly Data of the Three Precipitation Datasets (mm/ month) (Note That the Gridded Precipitation Datasets Was for the Sake of Clarity Deleted From Figure 6)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Gridded data	31.8	33.6	50.3	41.8	21.0	2.5	0.4	0.4	1.3	7.5	15.1	24.4	230.0
Kaka	27.6	25.5	45.8	39.5	23.4	3.3	0.3	0.7	1.8	10.4	13.6	18.6	210.3
Hawdan	29.2	32.6	56.7	69.5	52.9	13.2	7.9	3.8	7.9	18.6	21.2	26.5	340.0

TABLE B2 Linear Regression of the Monthly Precipitation Values With the Monthly Meana River Discharge

Meana Mean Monthly (m^3/s)	R^2
With Kaka	0.57
With Hawdan	0.82
With Grid	0.49

TABLE B3 Descriptive Statistics and Linear Regression of Long Term Trend of Each Datasets

	Discharge (Meana)	Precipitation (Hawdan)	Precipitation (Kaka)	Precipitation (Gridded)	Min. Temperature (Mashhad)
N (years)	53	30	44	46	34
Mean	0.4	340.1	210.3	230.2	8.1
Minimum	0.0	180.0	120.0	143.0	4.9
Maximum	2.8	474.0	311.7	340.0	12.1
Standard deviation	0.4	76.7	50.7	51.3	1.5
Linear trend with time (R^2)	0.39	0.05	0.13	0.0	0.14

APPENDIX C. PHOTOS OF THE (SAMPLING) SITES

FIGURE C1 Compilation of the four sampling sites (black stars indicate sampling points).

TABLE C1 Sampling Sites and Chronological Ages (Ages Are “ka cal. BP” for Radiocarbon Values Respectively)

Sample	Profile	Site	Fazies	Type	Age (ka)	Phase
OSL 5	Gravel_Pit	Site 1	Gravel	OSL	29.8 ± 1.5	Pleistocene
OSL 6	Gravel_Pit	Site 1	Gravel	OSL	13.6 ± 0.9	Pleistocene/younger Dryas
Turk 4_1	Dry_Wadi	Site 3	Silt	14C	6.98 ± 0.18	Middle Holocene
Turk 4_1	Dry_Wadi	Site 3	Silt	14C	6.98 ± 0.18	Middle Holocene
LUM1	Wadi_Meana	Site 2	Silt	OSL	3.4 ± 0.1	Middle Holocene
OSL 1	Wadi_Meana	Site 2	Silt	OSL	3.1 ± 0.6	Middle Holocene
OSL 2	Wadi_Meana	Site 2	Sand	OSL	2.5 ± 1.1	Middle Holocene
Turk 6_1	Chacha_Gully	Site 4	Silt	14C	1.456 ± 0.07	Late Holocene or modern
Turk 6_1	Chacha_Gully	Site 4	Silt	14C	0.142 ± 0.12	Late Holocene or modern
Turk 6_1	Chacha_Gully	Site 4	Silt	14C	0.141 ± 0.13	Late Holocene or modern

FIGURE C2 The Wadi Meana (coordinates: 36.8726°N; 60.3904°E).

FIGURE C3 The piedmont plain, the loess hills, and the Kopet Dag mountains (coordinates: 36.8454°N; 60.4147°E).

FIGURE C4 The Gully near Chacha and sample area "Turk_6" (coordinates: 36.7755°N; 60.5150°E).