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Full Length Research Paper

Human impact on climate and eco-hydrological systems in the Badain Jaran desert in northwest China

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The Badain Jaran Desert in northwest China has the world's largest stationary sand dunes and an impressive lake–dune system. During last decades, many lakes in the Badain Jaran Desert have disappeared and the process is still accelerating. Using remote sensing (RS) and geographic information system (GIS) methods, we identified 132 lakes from satellite images taken in 1987 in the area between 101.79 – 102.58E and 39.69– 40.19N, but this number had fallen to 68 in 2006. The rapid decrease of lake numbers and concurrent shrinking of the lake area have been attributed to groundwater reductions in the drainage areas as a result of rapid socioeconomic changes, including urbanization, irrigation, and water diversion, along with an overall population increase. The area also show an exaggerated warming from 1960 to 2006, imply the arid desert area in NW China possibly response quickly and contribute a great deal to human induced global warming. The human-induced runoff water redistribution and lake disappearance in the Gobi-desert area not only impact on the climate and eco-hydrological equilibrium today, but also resulted abandon of the compacted town in the oasis in 1732 and the death of vast area of the Popular Diversifolia forest in Ejina basin.

Key words: human impact, climate, eco-hydrological systems, desert, northwestern China

INTRODUCTION

In recent decades, environmental problems throughout China have attracted global interest and have caught the attention of governments and scientists domestically and internationally (Liu & Diamond, 2008). The extensive water usage in Hexi Corridor in northwestern China started as early as 121 BCE during the Han dynasty along with the massive immigration and began to develop agriculture (Feng, 1964). The water and land resources were then exploited rapidly as the population increased. Large-scale water conservation and water resources development took place after 1949, especially since late 1980's to early 1990's. During the time migration of people from the high-populated and/or infertile areas took place. More and more agricultural oases were set up in virgin lands, from the lower reaches to the upper reaches of the river. The irrigated area increased dramatically, even with the application high-efficient irrigation technologies, the water amount, which comes from both the surface runoffs and wells, needed for irrigation was huge.

As a result, ground-water has been extensively affected. This is a result firstly of an increased surface runoff utilization, which led to a reduction in ground-water recharge. At the same time, overexploitation of ground-water resources combined with increasing surface water use has led to aquifer storage depletion and a decline in ground-water levels (Chen and Qu, 1992). Increasing utilization of water resources has also led to great temporal and spatial changes in the inter-annual water distribution and ground-water recharge across the upper, middle and lower reaches of the river, which in turn has resulted in serious ground-water and environmental problems (Ma et al., 2005).

Several features make the Badain Jaran Desert in northwest China a unique landscape: it has the world's largest stationary sand dunes with a maximum height of 500 m, and dozens of lakes of various sizes are scattered among the dunes, forming an impressive lake–dune system. As the second largest active sandy desert in China, it covers an area of 49,200 km^2 (Zhu et al. 1980),

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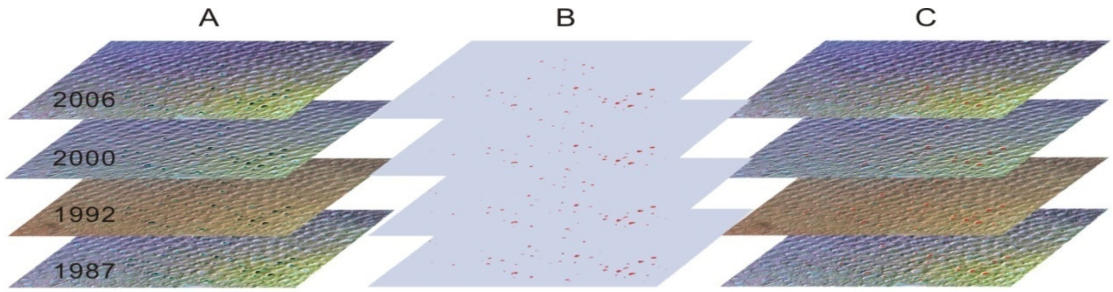

Figure. 1: Procedures to extract lake statues from Satellite imagines (A. the original TM741 images; B. extracted signals of the lakes; C. superimposed vector image with extracted lakes)

Table 1: The meteorological stations used for study

Station name	Latitude	Longitude	Elevation
Ejinaqi	41.57	101.04	940.5
Guaizihu	41.22	102.22	960.0
Dingxin	40.18	99.31	1177.4
Jinta	40.00	98.54	1270.2
Bayanmaodao	40.45	104.30	1328.1
Gaotai	39.22	99.50	1332.3
Linze	39.09	100.10	1453.7
Jiuquan	39.46	98.29	1477.2
Zhangye	38.56	100.26	1482.7
Shangjingzi	39.13	101.41	1509.7
Yumenzhen	40.16	97.02	1526.6
Wutonggo	40.43	98.37	1591.0
Shandan	38.48	101.05	1764.6
Minle	38.27	100.49	2271.0

neighboring the Gobi Desert (Ejina basin) in the northwest. Opinions differ about how this desert and the dune–lake system were formed (Chen et al, 2004; Zhang & Ming, 2006; Yan et al, 2001), in part because the harsh environment and inaccessibility make acquiring information difficult. As one of the remote hyperarid inland areas in central Asia, Ejina-Badain Jaran desert has attracted the attention of geoscientists from all over the world (Lü et al, 2010; Hölz et al, 2007; Wünnemann et al, 2007).

The lakes in the dunes have changed dramatically during last decades. The disappearance of the lakes may affect the landscape-ecological systems established in the area profoundly. In addition, these changes may also influence the regional or even global environment because the Badain Jaran Desert serves as the main source of Asian dust transport, which strongly influences ocean biogeochemistry and global climate (Pye & zhou 1989; Jickells et al, 2005). Therefore, the study of the relationships between the dunes and lakes in the desert is of great impotence.

METHODS

To address the recent climate specialties and change processes, the meteorological data from the monitoring stations at north and south of Badain Jaran Desert and Ejina Basin were statistically analyzed (Table 1). Using the RS and GIS technique, the lakes among the dune field were investigated to understand both their numbers and changes during last decades. The procedures to extract lake statues in the area between 101.79 ~ 102.58E and 39.69 ~ 40.19N in different years could be described as following: A, the TM images of 7 July 1987, 2 June 1992, 20 September 2000 and 9 June 2006 were selected (data from China Remote Sensing Satellite Ground Station, *www.rsgs.ac.cn*) for study. B: Using RS-GIS method and RGB741 channel signals, the data of the lake boundary for each image was collected after the geometrical correction and it was verified in the field. C: Based on superimposed image analyses, the lake temporal-spatial variation of the lakes and their weighted centrals were determined (Figure. 1). Because of the

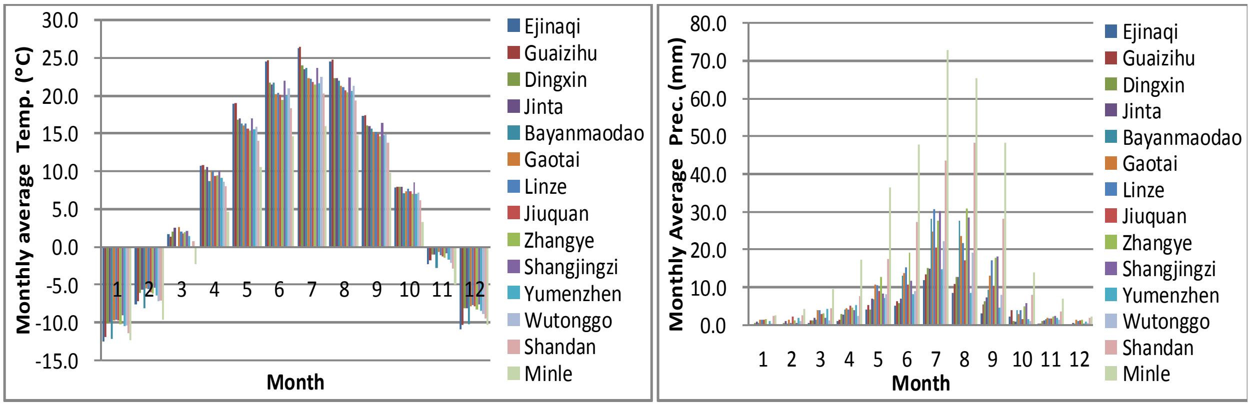

Figure 2: The monthly average temperature and precipitation variation patterns of the 14 meteorological station, average data between 1951 and 1980.

Table 2: The air temperature and humidity change rates from 1960 to 2006 at Guaizihu

Season	ΔT_{2m} /yr	ΔT_{max} /yr	ΔT_{min} /yr	ΔHumidity/%/yr
Winter	**0.064**	0.010	0.086	-0.098
Spring	0.038	0.028	0.084	**-0.137**
Summer	0.044	0.017	0.070	-0.121
Autumn	0.051	**0.050**	**0.092**	-0.099

limitations of the available images, we used the images of June to September, but we have checked that the lake area difference between these periods is not very big, therefore, it doesn't influence our final results on the lake areas. At last, the social development, especially the population changes were compared with the groundwater level changes to address the human impacts on the lake evolution and ecosystems in the deep desert.

RESULTS

Base on the average meteorological data from 1951 to 1980, the monthly average temperature and precipitation of 14 meteorological stations in/and around Badain Jaran Desert show that firstly, there are four months during that the temperatures are lower than ^{0}C, when the monthly temperature rises to above the ^{0}C, the rise rates in the lower basement area are larger than that in the higher area; The rainfall amounts between May and September of the year take most of the annual precipitation and along with the elevation increase the precipitation also increase sharply, indicating the water supply into the basin comes mostly from the upper reaches of the drainage (Figure. 2). In the deep desert, a 47-year long meteorological data from the north and south Badain Jaran Desert indicate uniform annual climate change but at a slightly different magnitude, with a colder early winter and a warmer summer in the north compared to the south. Statistical analyses of the data at Guaizihu show that the annual average air temperature has increased progressively in 8–11-year cycles, with the strongest average temperature increase in the winter season. However, the greatest increase in rates of both averaged maximum and minimum temperatures has occurred in autumn, and the averaged minimum temperature especially increased at a significantly high rate (Table 2). As one of the typical inner continental hypearid desert, the precipitation amount in the area is very low; nevertheless, the wavelet power spectrum analyses shown except a strong annual period, there are 2.5 and 6-year periods, which are different from that of the temperature variations (Figure. 3). These data may indicate a strong regional response in the Badain Jaran Desert to the unprecedented global warming mainly induced by human activities (IPCC, 2007).

Field investigations in the 1970s identified 144 lakes in the Badain Jaran Desert (Zhu et al, 1980). Using remote sensing and geographic information system methods, we identified 132 lakes, with a total lake area of 21.39 km^2 and a maximum lake area of 1.51 km^2, from satellite images taken in 1987. These images covered the area between 101.79–102.58E and 39.69–40.19N (Figure. 4). Further analysis showed that the lake numbers had dropped to 97 in 1992, 78 in 2000 and 68 in 2006, the total area had also diminished to 19.22 km^2 in 1992, 17.06 km^2 in 2000 and 16.44 km^2 By 2006 (Table3)

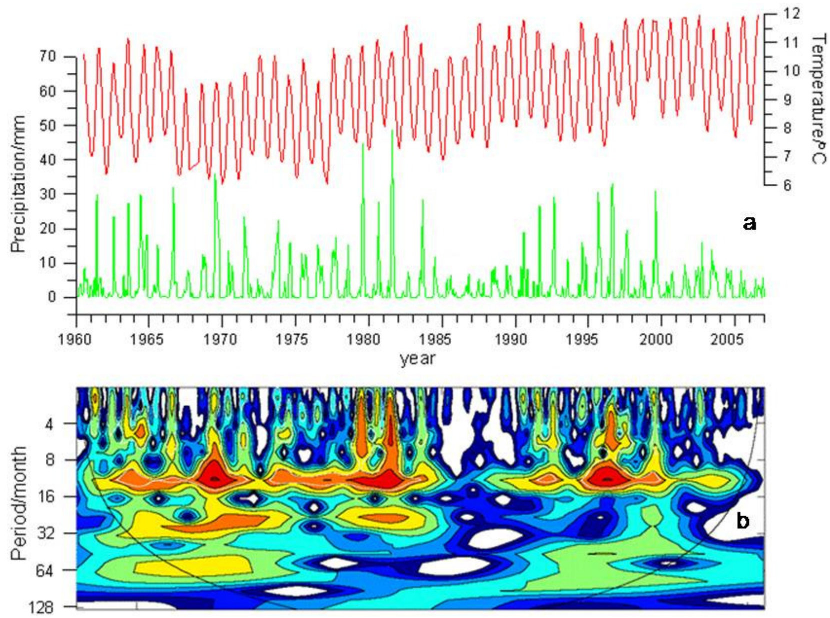

Figure. 3: The monthly average temperature (weighted average with 11 degrees) and precipitation (a), and its wavelet power spectrum at Guaizihu station (b)

Table 3: The lake statues in Badain Jaran Desert

Year	Number of lakes	Min. area (m^2)	Max. area (km^2)	Total area (km^2)
1987	132	1875	1.510625	21.386250
1992	97	625	1.461875	19.224375
2000	78	625	1.419375	17.056875
2006	68	625	1.381250	16.439375

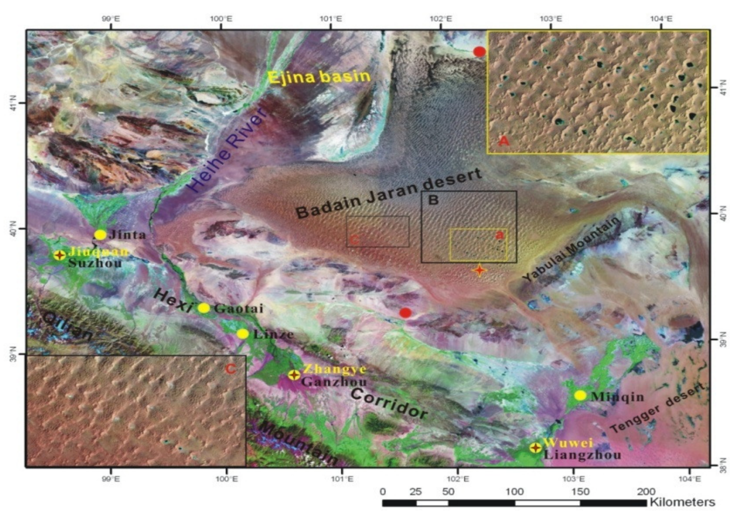

Figure 4: Geographic map of the Badain Jaran Desert-Ejina basin (Gobi desert) and surrounding areas in northwest China.

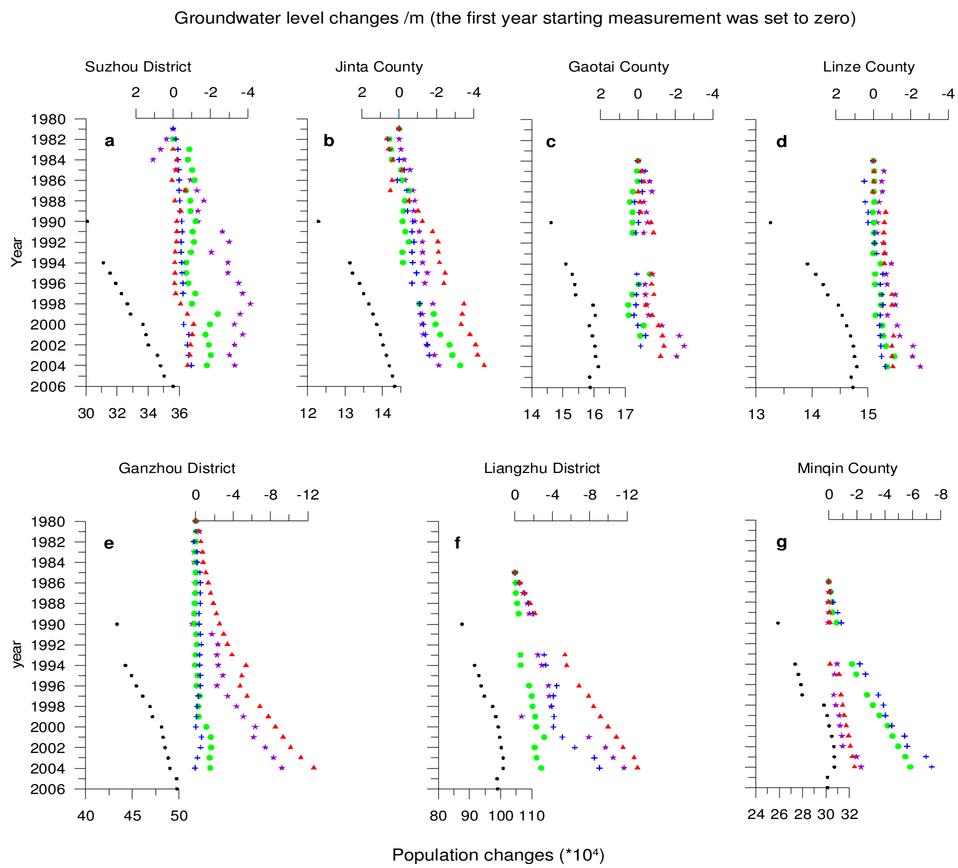

Figure 5: Correlation between the population (black dots) and groundwater level (color symbols: from red-triangle, pink-start, green-dot to blue-cross indicate a reduced evaluation of the monitoring sites in each area) changes in Hexi Corridor since 1980's, where serves as the upper reaches of the runoff following into Ejina basin and main groundwater feeding areas to the Badain Jaran desert. Among them, **a** and **b** belong to the Jiuquan City administrated areas in the west part of the Corridor; **c**, **d** and **e** are administrated by Zhangye City located in the middle part of the Corridor from there the mast important river, Heihe (Black river) in the area follows into the Ejina basin; **f** and **g** is administrated by Wuwei City in the east end of the Corridor. (Data compiled from the annual report by the Gansu Provincial Hydrological Bureau and Gansu Provincial Chorography, 1982-2004).

DISCUSSION

With an annual mean precipitation of 49 mm in the north (Guaizihu) and 113 mm in the south (Alashanyouqi/Shangjingzi), in strong contrast to the annual potential evaporation of 4,110 mm and 3,940 mm, respectively, the existence of lakes in the Badain Jaran Desert indicates a net balance between evaporation and groundwater supply. Study results show that the unsaturated zone thicknesses in Badain Jaran Desert range from over approximately 300 m on the highest dunes to very shallow (<1 m) near the lakes. The estimated annual vertical water recharge of 0.9-1.4 mm in the eastern part of the Badain Jaran Desert (Gates et al, 2008a, 2008b; Ma et al, 2009) implies the moisture movement in the dune sand makes no contribution to the lake water changes. Because there have been no significant changes in evaporation observed, even with the temperature increase, the rapid disappearance of the lakes and diminishing water surface areas can be mainly attributed to groundwater reduction in the drainage areas. Monitoring data in Hexi Corridor show that groundwater levels have declined dramatically during recent decades because of rapid socioeconomic developments including urbanization, irrigation, and water diversion, along with a total population increase in the Hexi Corridor of more than 30% from 3.6 million in 1982 to 4.8 million in 2004. The groundwater level decline correlates well with the population increase in the region (Figure. 5), fast growing of the farmland areas and the booming city-town constructions, which all consuming large amount of water, including both surface runoff and ground water.

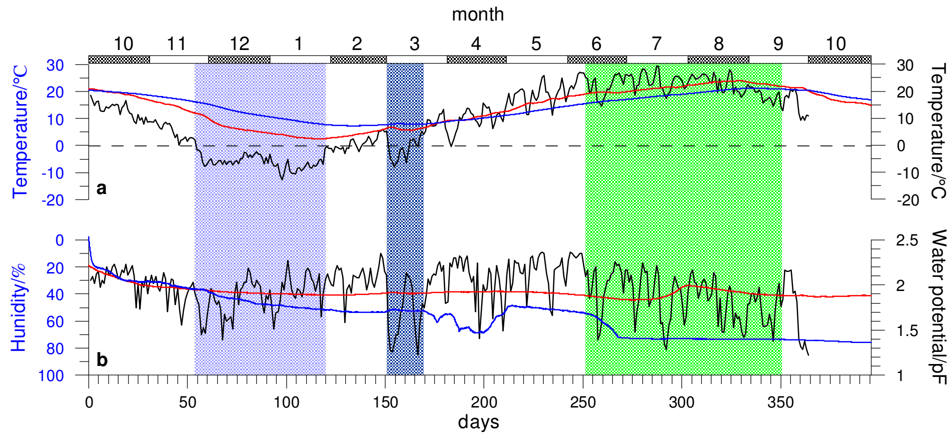

Figure 6: The daily temperature and humidity changes in Alashanyou Qi meteorology station (black lines; 39°13'N, 101°41', 1510 m asl) between Oct. 1, 2006 and Sept. 30, 2007. Ground temperature and water potential, a parameter describing moisture statue in dune sand measured by a pf-meter (GeoPrecision Company, German) at 1 m (red line) and 1.5m (blue line) depth in the dune (39°32'55″N, 102°20'41″, 1253 m asl), hourly data between Oct. 1, 2006 and Oct. 31, 2007

The water divisions, damming of the rivers all have contributed to the interruption of the hydrological recycling system in the Hexi Corridor, associating intensified human impacts with the re-adjustment of hydrological equilibrium and thus cause the shrinking or even disappearance of lakes in the Badain Jaran Desert. This is only one of the possible assumptions for the shrinking and disappearance of the lakes on the mega-dunes. Much more works need to be done to fully understand the mechanism of the lake changes in the dunes.

The hydrological circulation in the area is complex and not fully understood. Though it is difficult to give a reliable amount of evaporation and precipitation in each component because the numbers we have vary considerably, it is clear that the groundwater budget is negative as the water lever has been lowering in all part at an accelerating rate. For example, the water table has lowed for 12 to 28 m in Minqin Oasis (administrated by Wuwei district, Figure. 1) where 6.24×10^8 m^3 groundwater was pumped for irrigation in 2000. The volume of spring water in Heihe drainage in Hexi corridle has declined from 18.01×10^8 m^3 in 1986 to14.74×10^8 m^3 in 1998, along with a concurrent decrease in the elevation of springs by 200 to 600 m on average. This process resulted in more water being utilized at the expense of lowering groundwater level and eco-environmental deterioration. Utilization of the water resources has long been a regional problem promoting much study (Dong et al, 1995; Yang et al, 1999; Yan et al, 2001; Ma et al, 2003; 2006).

The climate–eco-hydrological systems in this arid-hypearid area in NW China are frangible. On-site monitoring data indicates that the ground temperature at different depth changes following the surface temperature but with very gentle and low amplitude (Figure. 6a). The moisture statue in the dune generally has no relationship with the air humidity (Figure. 6b). It also shows that in this dry area, the moisture statue in the upper part of the dune (i.e. within 1 m deep from the surface) is easy to get equilibrium, but the deeper part (i.e. >1.5 m from the surface) needs much more time to get stabilized. It reveals at least two very important facts: that is the moisture statue in the dune in Badain Jaran desert is very stable, it does not change very much with the air humidity, and second, as soon as the stable condition be interrupted, or the dune statue be disturbed, it needs a long time to reach a new stable condition.

Human activities, either constructive or destructively exerts pressure on natural systems, such kind of impacts are not only changing the climate and eco-hydrological systems today, but also in the ancient times (Zhang et al, 2005; Zhang et al, 2007; Yancheva et al, 2007; Yang and Liu, 2003). The difference is that human impacts on the eco-hydrological system in the ancient time was much more strong, some times might be vital to the local people, the civilizations might be destroyed completely and ruined eco-hydrological systems might never be recovered. For example, Khara khoto (in Mongolian language) or the Hei Cheng (Black City in English), it was also called Heishui Cheng (Black Water City), was a military administration site in Xi-Xia (West Xia) Dynasty (982-1227) and served as a thriving trade and culture centre during the 11th century (Figure. 7). It was a cosmopolitan Buddhist city where Buddhists, Manicheans, and a few Nestorians lived together. It was under the control by Mongolian Empire since 1226 and Yuan Dynasty in 1286. The relics of 10-m-high ramparts and 3.7-m-thick outer walls with up to 410 m long, and a

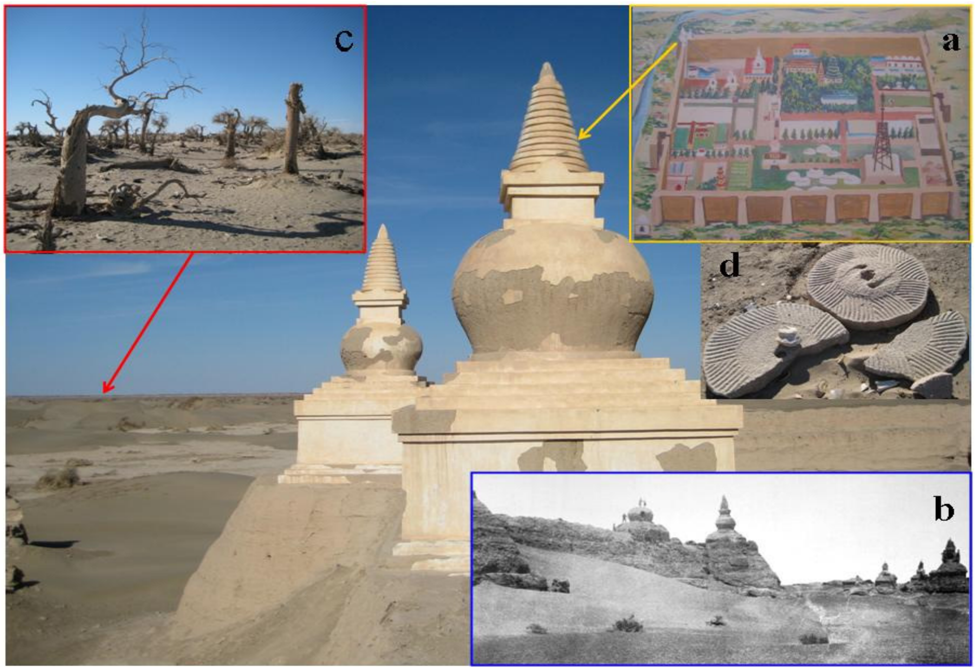

Figure 7: The remained stupa (later repaired) in the abandoned Hei Cheng at 41°45'51″N, 101°08'42″ (**a**: a painting shows the original city and environment); **b:** Hei Cheng in 1908 (by C. P. Koslov); **c:** the dead Popular Diversifolia near the destroyed city; **d:** the milling stone relics

number of chörten still stand after being abandoned more than 700 years shown its grandiose past. More than 2,000 ancient books were uncovered in this abandoned town by the Russian explorer P. K. Kozlov during 1907-1909. This highly developed town was destroyed by Ming army after a long siege by cut the water channel in the upper reaches of the river in 1372. After the war, the river system was changed completely, little surface water flown close to the city and the ground water level decreased dramatically, resulted in the abandon of the once flourished city and the death of vast area of Popular Diversifolia forest not far from the city, since then, both the city and vegetation never recovered.

CONCLUSIONS AND IMPLICATIONS

Lakes distributed in Badain Jaran Desert are important for maintenance of the landscapes. Field investigations and dating results show that the lakes have been occurred in the dunes at least since the Late Pleistocene. The lakes have disappeared from NW direction to the SE of the desert where now most lakes concentrated. The phenomena of accelerated speed of the disappearance of the lakes cannot be fully explained by the climate changes. Therefore, the strong expending of the human activities and water usage in the upper reaches of the drainage inevitably impacts on the lakes in the dunes, and provide a possible assumption to explain why the lakes in the dunes have shrank and disappeared abruptly. Certainly, we here put more emphases on the human influence on the hydrology-landscape in the area. It is one of the possibilities that affect the water balance in the deep desert, more studies are necessary to be done before we have fully understanding of the water circulation in the area.

Understanding the complexity and potential trends of such kind of problems is important for effective management. For example, in the more-developed southeast China, algae blooms resulting from water deterioration have influenced quality of life and also the local gross domestic product. The restructuring of the natural systems in northwestern China may lead to a collapse of regional ecosystems because of their inherent fragility. In addition, these changes may also influence the regional or even global environment because the Badain Jaran Desert serves as the main source of Asian dust transport, which strongly influences ocean biogeochemistry and global climate.

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