Bulletin of Glaciological Research 23 (2006) *33–39*

Hydrological observations at July 1st Glacier in northwest China from 2002 to 2004

Akiko SAKAI[1], Yoshihiro MATSUDA[1], Koji FUJITA[1], Keqin DUAN[2], Jianchen PU[2], Satoru YAMAGUCHI[3], Masayoshi NAKAWO[4] and Tandong YAO[5]

1 Graduate School of Environmental Studies, Nagoya University, HyARC, Chikusa-ku, Nagoya 464–8601, Japan

2 Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 260 Donggang West Road, Lanzhou 730000, China

3 Nagaoka Institute of Snow and Ice Studies, National Research Institute for Earth Science and Disaster Prevention, Nagaoka 940–0821, Japan

4 Research Institute for Humanity and Nature, 335 Takashima-cho, Kamigyo-ku, Kyoto 602–0878, Japan

5 Institute of Tibet Plateau Research, Chinese Academy of Sciences, 100085, Beijing China

(Received May 30, 2005; Revised manuscript accepted September 14, 2005)

Abstract

Hydrological observation was carried out at the July 1st Glacier in the Qilian mountains, northwest China, during the glacier melting season from 2002 to 2004. Water discharge was measured using two methods, current meter and salt water. The results of these methods showed a good correspondence. A logger for water level was settled at the glacier terminus in 2002, and at the foot of the end-moraine in 2003 and 2004. Then, variations in discharge were evaluated based on the relationship between discharge and water level. Total observed runoff depth from the basin was 834 mm in 2002. The average value of water budget components, such as precipitation, glacier mass balance, evaporation at the glacier and glacier-free area, were evaluated in 2002 from observation and meteorological data. The results indicated that the discharge from the glacier area was 6 times larger than that of the glacier-free area mainly due to glacier shrinkage.

1. Introduction

Precipitation in the mountainous area is relatively high in the arid region of northwest China. Glaciers in the mountain area store the precipitation and then have a role as the reservoir of precipitation in the mountain area (Fountain and Tangborn, 1985). The water from the mountains has been important for the water resources in the lower side of the basin, oasis cities and desert. Therefore, variations in the meltwater from the glaciers impact the human activity. For example, there had been oasis cities in the desert long ago, but at present those ancient cities lie in ruins and have become excavation sites. These environmental changes were caused by changes in water resources due to the reduction of discharge from mountain areas. Therefore, the primary purpose of this study was to estimate the historical changes in discharge from glaciers in the Heihe River basin.

Water discharge from the glacier has been studied by many researchers from the viewpoint of model calculations. Ye *et al.* (1999) and Collins (1987) have investigated the long-term variation of discharge from this glacier area analytically. Fountain and Tangborn (1985) discussed the relationship between glacier discharge and glacier area ratio based on annual variations. Braun and Aellen (1990) compared two models for their observed discharge and mass balance of the glacier.

There are many observations and analyses on the discharge from glaciers in the middle Tibetan Plateau and Tien Shan Mountains, China. There is also an observation report of the discharge from glaciers in the Tibetan Plateau by Ohta *et al.* (1994), regarding seasonal variations in the discharge from glaciers in basins of several sizes. Kang *et al.* (1992) has evaluated discharge from a glacier area from observed discharge, calibrated precipitation and estimated evaporation at the Urumqi River in the Tien Shan Mountains. Kang *et al.* (1999) have applied the HBV model to some river basins in China, and estimated future discharge from glaciers. Ye *et al.* (2003) also calculated the discharge from the glacier in Tien Shan, China, taking into account the glacier area change. They suggested that the timing of the peak discharge depends on glacier size. Liu *et al.* (2003) have evaluated the variation of glaciers in northwest China since the

Little Ice Age, and also estimated discharge from the glaciers. However, there are few analyses based on observations of glacier mass balance and discharge from glaciers in the Qilian Mountains.

In order to analyze the observed discharge from the glacier, we have here summarized the observations of its discharge, and evaluated each water budget component, such as precipitation, evaporation, and glacier mass balance.

2. Location and features of the glacier

The July 1st Glacier is located in the Qilian Mountains in northwest China (Fig. 1), 70 km south from Jiquan, one of the oasis cities along the Western Corridor of the Yellow River. Figure 2 shows the topographical map of the July 1st Glacier, which was made by Shi (1988) in 1978. The glacier is located on the northern slope of the Qilian Mountains.

Sakai *et al.* (2004) indicated that the shrinkage of the July 1st Glacier has accelerated in recent years. This belongs to the polar type of glaciers (Huang, 1990), and the ice temperature was quite low (−6℃ in August in the 1970s) (Xie *et al.,* 1985). Therefore, some portion of the meltwater refreezes in the snow layer, and it is necessary to take into account the refrozen amount in order to estimate the mass balance of a glacier (Fujita *et al.,* 1996; Fujita and Ageta, 2000).

3. Observations

An automatic Weather Station (AWS) was set up and started measurements near the glacier terminus as of June 10, 2002, and data were collected until September 2004. Matsuda *et al.* (2004) and Sakai *et al.* (2006) reported the meteorological data, while Sakai *et al.* (2006) calibrated the observed precipitation.

Discharge observation was carried out from June 11 to September 10 in 2002, from August 16 to September 21 in 2003 and from May 28 to September 12 in 2004. We could not carry out observations at the beginning of the melting season in 2003 because of the outbreak of severe acute respiratory syndrome (SARS).

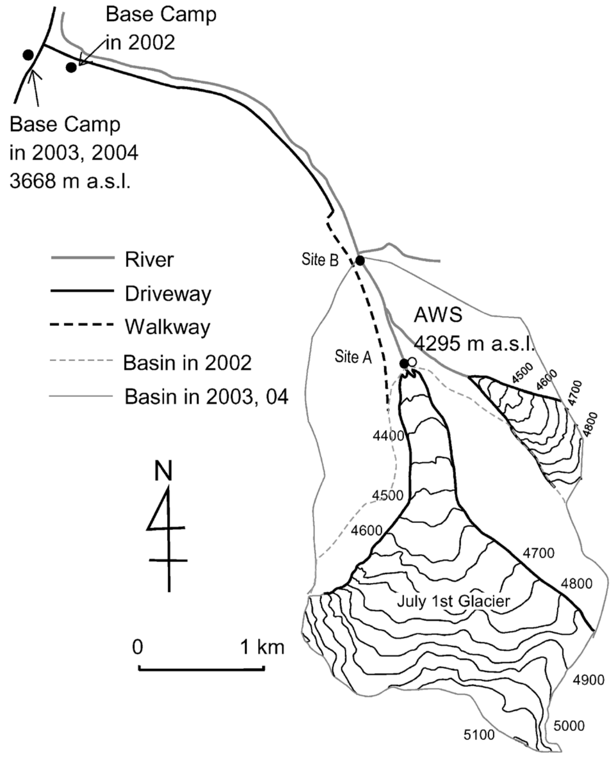

Fig. 2. Observed basin in 2002 and 2003–2004. Sites A and B indicate discharge measurement sites in 2002 and in 2003, 2004, respectively. Empty circles show location of Automatic Weather Station. Lysimeters were set up at AWS site and Base camp in 2004.

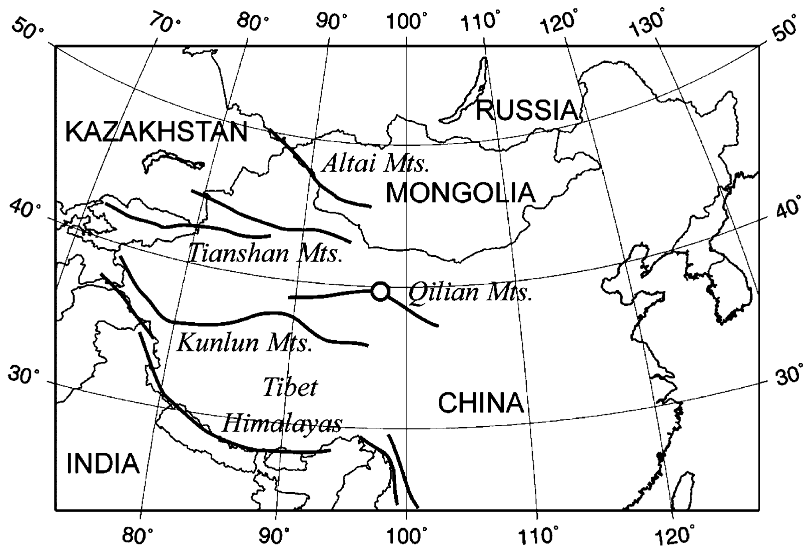

Fig. 1. Location of July 1st Glacier in Qilian Mountains, and Urumqi No. 1 Glacier in Tian Shan Mountains. Thick lines represent mountain ranges. Chain lines indicate country borders.

Water level was measured at site A from June 11 to September 10 in 2002, and at site B from August 16 to September 21 in 2003, from May 28 to July 19 in 2004 and from August 12 to September 12 in 2004 as shown in Fig. 2. The drainage area of these basins is summarized in Table 1. Water level was measured at 30-minute intervals by water level sensor using the pressure transducer with a resolution of 1 cm. The water level was also measured manually using a pole with a scale when the discharge was measured.

In July 24, 2004, the water level sensor and the water level pole were carried away by heavy discharge. A cross section of the river was also changed dramatically. Therefore, a new water level pole was set in place again on 28 July 12, and the water level sensor was also replaced on 12 August 2004.

Discharge was measured by two methods, one velocity-area method using the water current meter, and the other a salt water dilution gauging method. By the water current meter method, mean flow velocity was measured as the 60% water depth velocity was obtained by a Price-type current meter (Sanei Co.). The cross section was measured by a scale with an interval 10 to 20 cm in width.

Table 1. Summary of glacier, glacier-free and total basin area in 2002, 2003, and 2004.

Year		Glacier	Glacier-free	Total
2002	Area km^2	2.46	1.29	3.75
	(Area %)	(66)	(34)	(100)
2003, 2004	Area km^2	2.85	3.36	6.21
	(Area %)	(46)	(54)	(100)

The method using salt water and electric conductivity referred to by Hayakawa (1998) is as follows. First, salt-rich water is made in a bucket, and the water volume (: V_s) and electric conductivity (: C_o) of the salt-rich water are measured. The salt-rich water is then dumped into the upper stream and electric conductivity is measured downstream (about 30 m down from the dumping point) at intervals of 5 seconds (: C). If the distance between the dumping point and the electric conductivity measurement point is too short, the mixing length of the salt-rich water would not be enough to mix with the river water. On the contrary, if the distance is too long, the distribution of measured electric conductivity would not be unclear. We selected the distance to be 30 m from the above two limitations. The discharge level can then be derived from the following equation by measuring the conservation of its salt mass:

$$Q=\frac{C_o V_s}{\int (C-C_w)dt} \quad \text{or} \quad Q=\frac{C_o V_s}{(C_{ave}-C_w)\Delta t}, \qquad (1)$$

where C_{ave} = average of electric conductivity measured downstream.

Δt = period of electric conductivity measurement of dumped salt water.

C_w = electric conductivity of the stream.

It is not necessary to measure the cross-sectional area in order to calculate discharges by this method. Therefore, this calculation is easy to apply to complicated river flow such as in mountain areas. One example of diagrams of the observed electric conductivity variations is shown in the Figure 3. The observed

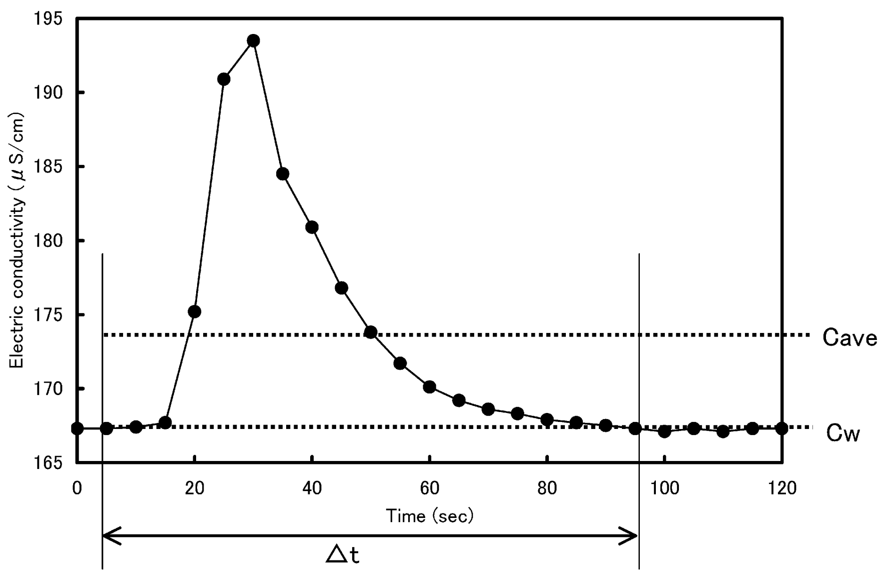

Fig. 3. Example of fluctuation of electric conductivity, when the discharge was measured by salt water dilution gauging method. *t*, C_w, and C_{ave} correspond with parameters in Eq. (1).

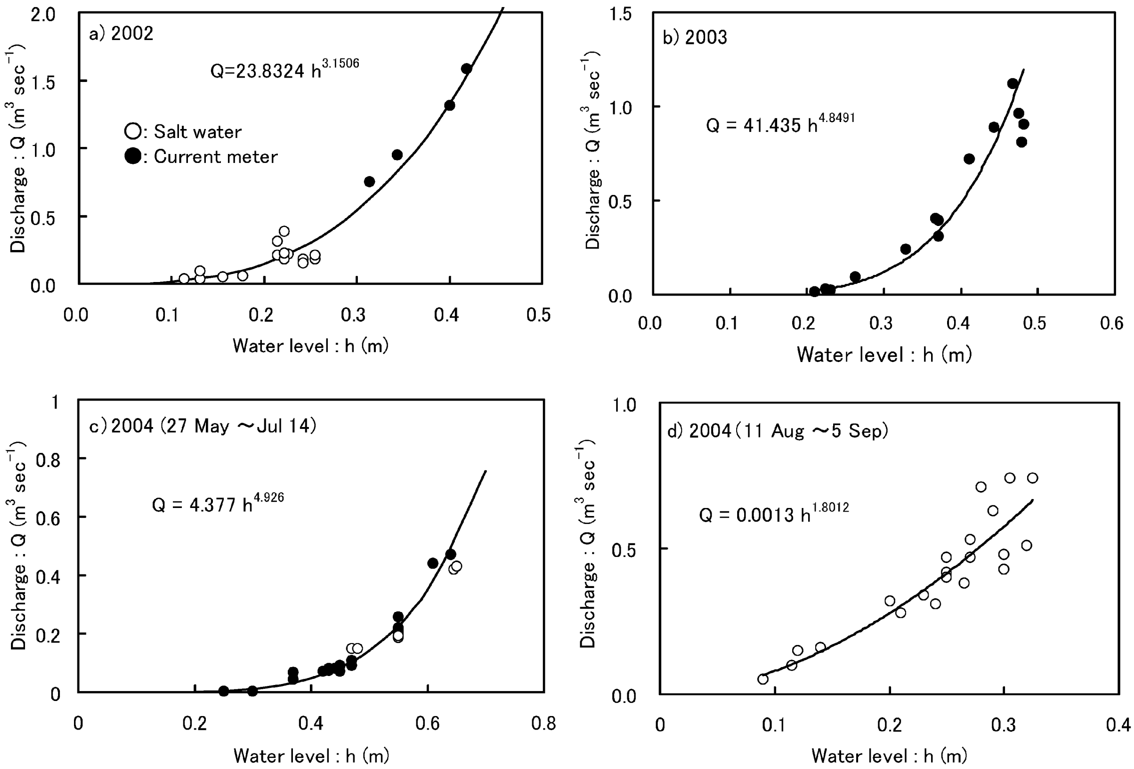

Fig. 4. Relationships between water level and discharge observed from 2002 to 2004. Discharge measurement by salt water dilution gauging method is shown by empty circles and velocity-area method using the water current meter by solid circles.

value necessary to calculate discharge in Eq. (1) is indicated in Fig. 3.

4. Results of observations

The relationship between water level and discharge using the above two methods is shown in Fig. 4. All correlation coefficients of the approximated curve were more than 0.85. The result of the discharge using the salt water method corresponded well to that using the current method as shown in Fig. 4(c). The daily averages of observed discharges calculated from each observed water level using the relationship between the water level and discharge (Fig. 4) are shown in Fig. 5. The values of the observed discharge obtained manually when there was no logger for the water level in August 2004 are also shown in Fig. 5.

5. Discussion

Observed runoff depth at the basin (: Q_d) was composed of runoff depths from the glacier area (: Q_g) and glacier-free area (: Q_f). The runoff depth can then be expressed as follows:

$$Q_d = Q_g + Q_f. \quad (2)$$

Water balance equations at the glacier and at the glacier-free area can then be expressed as follows:

$$Q_g = Q_{gp} - Q_{ge} - Q_{gm} - \Delta S_g, \quad (3)$$

$$Q_f = Q_{fp} - Q_{fe} - \Delta S_f, \quad (4)$$

where Q_{gp} = precipitation from glacier area,
Q_{gm} = mass balance at glacier,
Q_{ge} = evaporation at glacier ice surface,
ΔS_g = changes of the stored water in the glacier,
Q_{fp} = precipitation at glacier-free area,
Q_{fe} = evaporation at glacier-free area, and
ΔS_f = changes of the stored water in the glacier-free basin.

All units are in mm. Stored water in the glacier can be assumed to be zero, since the July 1st Glacier is a polar-type glacier (Huang, 1990), and the glacier ice temperature was less than −5℃ (Matsuda *et al.*, 2004). Also, there are rocks, debris and little vegetation or soil in the glacier-free area of this basin, making for little water storage capacity. Therefore, it can be assumed that the change in the stored water in the glacier-free basin is zero.

Precipitation measured and calibrated at the AWS site during the observation period in 2002 was 309 mm (Sakai *et al.* 2006). Precipitation at the glacier and glacier-free areas during that period were 203 mm and 106 mm, respectively, in the entire observed basin (3.75 km^2). Total glacier mass balance in 2002 during the summer was −911 mm in the glacier area (2.46 km^2) (−598 mm in the entire observed basin) which was calculated from the data in Matsuda *et al.* (2004).

Evaporation (: E) (mm sec^{-1}) at the glacier surface

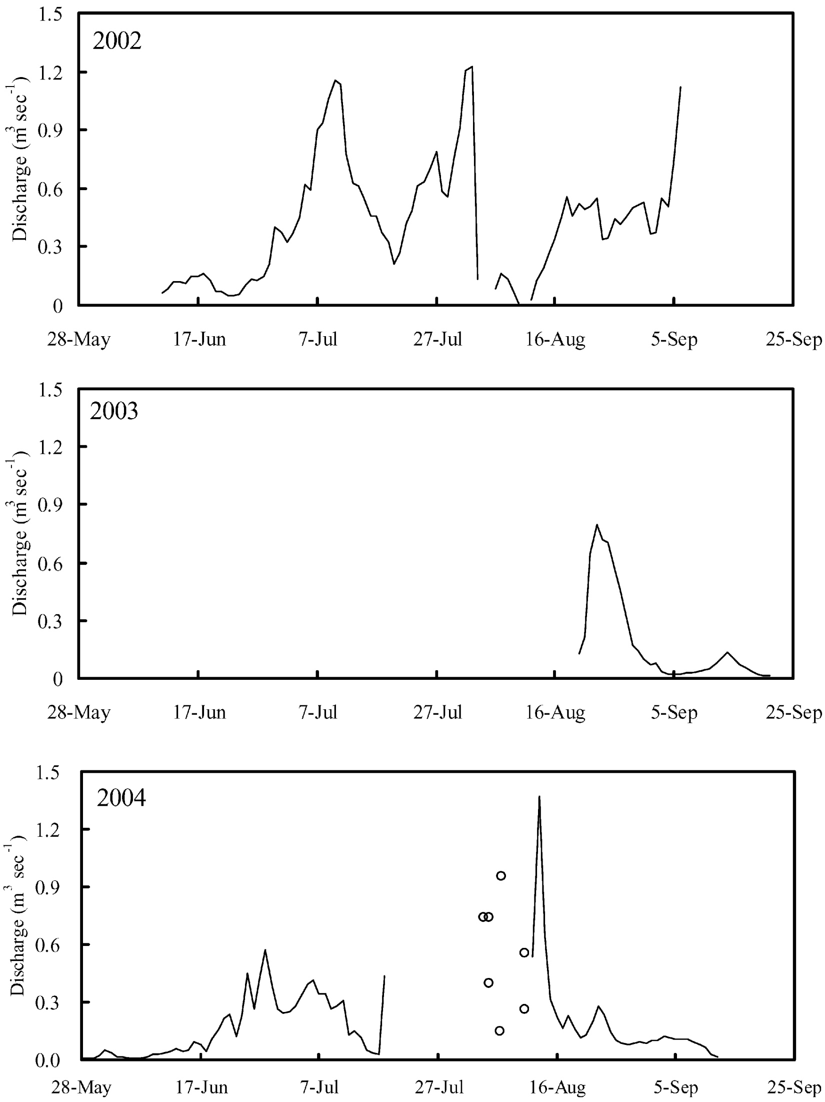

Fig. 5. Variation of discharge during melting season in 2002, 2003 and 2004. White circle shows instantaneous value (not daily) of observed discharge calculated manually from observed water level.

can be calculated from bulk aerodynamic formulas as follows:

$$E = 1000\rho_a C_H U(hq(T_a) - q(T_s))/\rho_w, \qquad (5)$$

where ρ_a = air density (= 0.819 kg m^{-3} at 4000 m a.s.l),
C_H = heat transfer coefficient (= 0.002 (Kondo and Yamazawa, 1986), non-dimensional),
U = wind speed (m sec^{-1}),
T_a = air temperature (℃),
T_s = surface temperature (℃),
$q(T)$ = saturated specific humidity at air temperature T (℃)(non-dimensional),
h = relative humidity (0–1) , and
ρ_w = water density (1000 kg m^{-3}).

The heat transfer coefficient, 0.002 (Kondo and Yamazawa, 1986), which was induced at the snow surface, was applied. Surface temperature of the glacier can be assumed to be 0℃ during the melting season. Evaporation at the glacier surface was calculated using meteorological data near the glacier terminus at an interval of one day. Total evaporation from June 11 to September 6 in 2002 was 47 mm in the area of the glacier (31 mm in the whole drainage area) from Eq. (2). Total discharge from the glacier (: Q_g) during the observation period can then be evaluated to be 1173 mm in the glacier area from Eq. (3) and 769 mm in the entire drainage. Discharge from the glacier-free area can be calculated to be 65 mm in the entire drainage area (188 mm in the glacier-free area) as a residual value between observed total discharge and discharge from the glacier area from Eq. (2) by assuming that there was no stored water change at the basin. Precipitation in the glacier-free area should be equal to that in the glacier area, 309 mm. Thus, evaporation should be 121 mm in the glacier-free area (42 mm in the whole drainage area).

The above elements of total discharge from the basin have been summarized in Table 2. Discharge

Table 2. Summary of all components of runoff depth from total basin from 11 June to 6 September in 2002. Precipitation observed at AWS site. Evaporation from glacier calculated by bulk aerodynamic method. Evaporation from glacier-free area observed by lysimeter. Mass balance evaluated from observation by staken method. Total runoff depth from glacier induced from each component.

From 11 June to 6 Sep. in 2002		Runoff from each area (mm)	Area (km^2)	Runoff from entire basin (mm)
Glacier	Precipitation	309		203
	Evaporation	47	2.46	31
	Mass balance	−911		−598
	Runoff	1173		770
Glacier-free	Precipitation	309	1.29	106
	Evaporation	123		42
	Runoff	186		64
Total		—	3.75	834

from the glacier area in the glacier area (1173 mm) was more than 6 times that from the glacier-free area in the glacier-free area (188 mm) since the decreasing glacier mass balance contributed to the discharge.

6. Concluding remarks

Variation in the discharge from the basin during the melting season from 2002 to 2004 has been evaluated on the basis of the relationship between water level and discharge measurements.

In 2002, each component of discharge from the basin, such as precipitation, evaporation, and glacier-mass balance was evaluated from observed data and calculation from the residual value. In the 2002, discharge from the glacier was more than 6 times that from the glacier-free area because of the glacier shrinkage.

Unfortunately, there are not enough data on water levels, in other words, discharge to analyze the variation of discharge in the basin from 2002 to 2004, because of many missing values. In further study, we will have an applicable estimation of discharge after analysis of the glacier-mass balance and evaporation in the glacier-free area.

Acknowledgments

We would like to express our thanks to Prof. Yutaka Ageta of the Institute for Hydrospheric-Atmospheric Sciences, Nagoya University for his valuable suggestions on these analyses. We wish to thank all of the members of the Project for their valuable support in the field. The field research and data analyses were funded by a Grant-in-Aid for Scientific Research (Project No. 14209020) from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and The Sumitomo Foundation. This is a contribution from the Oasis Project (Historical evolution of adaptability in an oasis region to water resource changes) being promoted by the Research Institute for Humanity and Nature (RIHN).

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