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Responses to land-use change and water resources in the Tarim River watershed of Central Asia

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Abstract The Tarim River is the largest internal river system in Central Asia. However, in recent years conflicts between farmland expansion, vegetation loss, bare lands with salt deposits, and desertification problems, have caused significant water resource tensions within the watershed. Results from a study assessing streamflow trends and land use in the Tarim River basin are presented. Land-use changes in the upper, middle and lower reaches of the basin during the years 1960–1972, 1972–1990 and 1990–2000 are quantified with remotely sensed data, and are compared to trends in observed discharge at the ALAR, Ying Bazha and Qiala gauging stations.

Key words land-use change; mainstream of Tarim River; response; streamflow

INTRODUCTION

The Tarim River basin is a typical arid region watershed, located within the Central Eurasian continent. In the last 40 years, intense land development is thought to be a major cause of changes in the streamflow regime. Streamflow response to land use changes in the upper and mid reaches of the basin may subsequently result in land use changes elsewhere in the watershed, especially in the lower reaches, as the ecology of the river environment and related wetlands may be sensitive to radical changes in flow characteristics. A number of studies have been carried out in response to these land use and streamflow changes in order to quantify the relationships, feedback mechanisms, and other changes in flow characteristics such as floods and runoff distribution (Wang, 2000; Li, 2002; Deng, 2003). Many studies of streamflow trends throughout the Tarim River have been conducted. Lei (2003) found the correlation between the water consumption change and streamflow in the source and mainstem of the Tarim River. It was found that a decrease in water consumption resulted from the decrease in streamflow. Chen (2003) found that economic development and insufficient consideration towards the proper usage of water resources caused water over-use in industry and irrigation, in the upper and middle reaches. The consequential removal of water from the river resulted in the cessation of flows in the lower reaches. Xu (2003) analysed the features and trends of streamflow at each stream gauging station in the mainstream Tarim River, and found that streamflow in the headwaters area has increased, although streamflow in the lower basin has decreased over the last 10 years. While recent studies have analysed the correlation between land-use change and streamflow, little attention has been devoted to more specific land-use change relationships, such as farmland, poplar (*Populus euphratica*) forest, scrub-grassland and streamflow, which is the focus of this research.

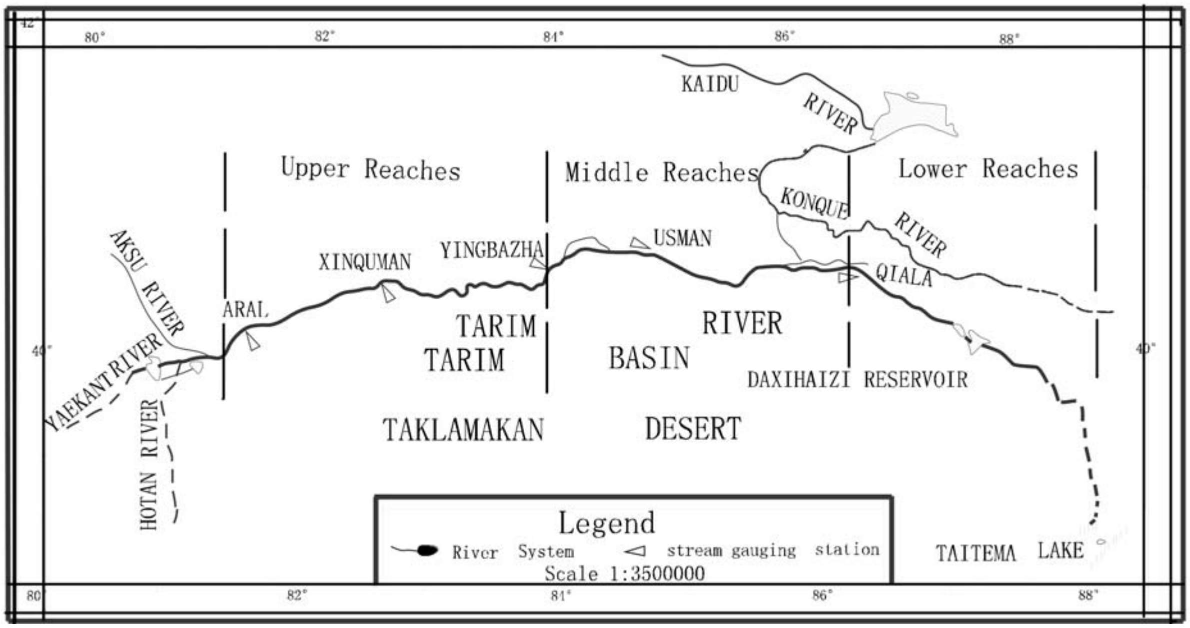

Fig. 1 Locations of stream gauging stations and mainstream Tarim River.

STUDY AREA

The Tarim River is bordered by coordinates 80°55′~88°37′E, 39°18′~41°31′N, and is the major river of the Xinjiang Uygur Autonomous Region in China. It is formed by the confluence of three rivers in the far west; the Aksu, Yarkand and Hotan rivers, and is the longest inland river in China. It flows along the northern edge of the Taklamakan Desert before turning southeast to its terminus, Taitema Lake. The Tarim River basin is characterized by a typical desert climate, producing minimal runoff, with average annual precipitation ranging from 20 to 80 mm across various parts of the basin, and a mean annual air temperature of around –3.2°C. The river flows across arid, semi-arid scrub, and semi-scrub areas. The vegetated areas fall mainly along the river, and vary in width from about 1 to 20 km. Vegetation mainly consists of *Populus euphratica*, scrubland and grassland, which survives mainly on flood waters and groundwater (Liu, 2000). There are five long-term stream gauging stations, Alar, Xin quman, Ying Bazha, Uaman and Qiala (Fig. 1).

For the purposes of this study, the river is divided into three parts, defined by stream gauging station. The upper reach, from Alar to Ying Bazha, is about 495 km. The stream channel is straight, with a width of 500–1000 m. The middle reach is defined as from Ying Bazha to Qiala, and is about 398 km. The stream channel is extremely shallow and meanders, with sections of the riverbed experiencing significant scour and fill. Sedimentation is a serious problem in this reach. The river has insufficient storage capacity to mitigate major floods, sending more than 90% of flow from large floods outside its banks at the Ying Bazha gauging station. The lower reach extends from Qiala to Taitema Lake, and is about 428 km long. The channel is relatively stable, with a width of about 50 m.

LAND-USE CHANGE DETECTION

Topographic maps from 1960 at 1:100 000 scale, and satellite images from 1972 (MSS), 1990 (TM), and 2000 (ETM) were entered into a GIS data base. All temporal data were acquired during the summer months.

Based on the Tarim River special location and environment, the following land cover classes were identified for the 1960, 1972, 1990 and 2000 database: farmland, dense poplar forest, sparse poplar forest, scrub-grassland, unused (bare) land and salt deposit land (Table 1).

Table 1 Land-use classification scheme in mainstream Tarim River.

Number	Land-use class	Description
1	Farmland	With irrigation facilities
21	Dense *Populus euphratica* forest	Near the river, dense
23	Sparse *Populus euphratica* forest	Far away from river, sparse
3	Scrub-grassland	Scrub land with grass
4	Water	Water and conservancy facilities
5	Construction land	Rural residential land and industry factory
61	Bare land	No vegetation on the surface, sand
63	Salt deposit land	Land with salt deposit, only sparse halophytic vegetation

Visual interpretation was used for the database of the 1960 topographic maps, 1972 MSS, and 1990 TM data, while automatic interpretation was used for the 2000 ETM data with eCognition software.

LAND-USE CHANGE ANALYSIS

Land-use change magnitude

Land-use change magnitude, R_d, reflects change in area of the different classes, and is defined as:

$$R_d = [(U_b - U_a)/U_a] \times 100\% \qquad (1)$$

where U_a and U_b are the total area of a certain class at the beginning and end of the time interval.

Land-use change speed

Land-use change speed is an indication of the change rate, R_s, of a certain class during a study interval (Wang *et al.*, 1999), and is given by:

$$R_s = \frac{Ub - Ua}{Ua} \times \frac{1}{T} \times 100\% = \frac{\Delta U_{in} - \Delta U_{out}}{Ua} \times \frac{1}{T} \times 100\% \qquad (2)$$

where, ΔU_{out} is the total area of a certain class that is converted to other classes, ΔU_{in} is the total area that is converted to a certain class from other classes during a study interval, and T is time (years).

Land use integrated dynamic degree

Integrated dynamic degree, R_t, is the annual integrated areal summed rate of change for all classes in the entire study area (Zhu *et al*., 1999), and is expressed as:

$$R_t = \frac{\sum_{i=1}^{n} \left| \Delta U_{in-i} - \Delta U_{out-i} \right|}{2\sum_{i=1}^{n} U_{ai}} \times \frac{1}{T} \times 100\% \tag{3}$$

U_{ai} is the land class area at the beginning of time interval, ΔU_{out-i} is areal sum of a certain class that converts to other classes, and ΔU_{in-i} is the areal sum of other classes that convert to a given class.

Land use changes and streamflow correlation analysis

Land-use change and streamflow relationships were analysed. The trends and features of the streamflow records from the Alar, Ying bazha, Qiala gauging stations for the years 1960, 1972, 1990 and 2000 were analysed by linear regression. The correlations between incoming streamflow at the Aral, Ying Bazha, Qiala gauging station and the land-use changes in the upper, middle and lower reaches were calculated, as well as the correlations between the land-use changes in the upper and middle reaches and the outgoing streamflow at the Ying Bazha and Qiala gauging stations.

QUANTITATIVE RESULTS

Land-use change magnitude

The land-use change magnitude as determined from equation (1) is indicated in Table 2. In the upper reaches of the basin, farmland has maintained continued growth, indicating a relatively strong agricultural economy, especially during the last 10 years of the study period. However, a small decrease in farmland was noticed in the lower basin. Other noteworthy changes include a significant decrease in poplar forest area, an increase in scrub-grassland in the upper reaches, and a decrease was observed in the middle and lower reaches. Salt deposit land increased in the upper and middle reaches, but decreased in the lower reaches. Abandoned lands decreased significantly in the upper basin, while increasing in the middle and lower basin. It has also been shown that decreases in forested areas and increases in abandoned lands have been accompanied by sharp increases in livestock grazing. The net result of these changes points toward significant environmental deterioration.

Table 2 Land-use change magnitude in Tarim River (%) basin during the indicated time period.

Land use class		Upper reach			Middle reach			Lower reach		
		60–72	72–90	90–00	60–72	72–90	90–00	60–72	72–90	90–00
1	Farmland	1.23	10.32	35.96	0.01	0.96	0.36	9.59	–4.81	–7.38
21	Dense *Populus* forest	–4.23	–20.08	–13.59	–17.77	–7.19	–34.28	–0.13	–1.79	–5.34
23	Sparse *Populus* forest	27.91	–13.88	–16.71	26.52	9.26	15.08	–2.87	–6.98	–43.84
3	Scrub–grassland	1.00	15.98	64.12	–13.16	–40.27	–67.94	–2.30	–19.98	–58.79
4	Water	14.85	–6.37	6.33	31.19	–18.09	–2.81	3.92	–5.57	–5.35
5	Construction land	–0.02	0.09	0.03	0.01	0.03	1.22	–0.01	0.09	0.40
61	Bare land	–34.16	–42.82	–70.12	19.00	19.53	27.40	33.66	48.27	51.78
63	Salt deposit land	–6.59	1.76	83.69	–37.46	13.54	80.97	–0.19	–14.78	–21.47

Table 3 Land-use change rate per year in the Tarim River basin (%) during the indicated time period.

Land use class		Upper reach			Middle reach			Lower reach		
		60–72	72–90	90–00	60–72	72–90	90–00	60–72	72–90	90–00
1	Farmland	0.22	1.76	4.65	3.18	52.42	19.60	3.73	–0.18	–0.65
21	Dense *Populus* forest	–0.15	0.67	–4.03	–11.07	–3.63	–7.02	–13.67	–11.23	–27.96
23	Sparse *Populus* forest	3.57	–1.24	–2.68	25.67	–4.60	3.54	–1.98	–2.03	–9.49
3	Scrub–grassland	0.06	2.79	5.87	–1.16	–1.91	–6.82	–2.65	–4.50	–10.94
4	Water	2.55	–3.03	4.72	22.99	–2.26	–1.23	2.00	–4.37	–9.27
5	Construction land	–0.13	0.46	3.25	9.72	23.51	14.57	–9.89	5.88	3.90
61	Bare land	–0.59	–0.80	–1.52	1.84	0.47	1.72	0.77	0.51	0.85
63	Salt deposit land	–0.54	0.15	23.16	–7.51	34.84	4.31	–13.23	–7.29	–18.04

Land-use change speed

Results of the land-use change rate per year analysis as determined by equation (2) are presented in Table 3. Annual change rates for the various classes vary considerably throughout the basin, and more-or-less mirror the change magnitudes indicated in Table 2.

Land-use integrated dynamic degree

Results of the land-use integrated dynamic degree analysis as determined by equation (3) are presented in Table 4. The integrated dynamic degree in the upper reaches is 2.58% in 1990–2000, indicating that agriculture development is fast in the period. The integrated dynamic degree in the middle reaches are all above 1%, the lower reaches integrated dynamic degree in the year 1990–2000 reaches up to 1.59%, which indicates that the mainstream Tarim River is under great development and that land-use change is fast.

Table 4 Land-use integrated dynamic degree in the Tarim River basin (%).

	1960–1972	1972–1990	1990–2000
Upper reaches	0.33	0.59	2.58
Middle reaches	1.98	1.42	1.68
Lower reaches	1.07	0.87	1.59

Feature and trend of streamflow

Based on streamflow records from the Alar, Ying Bazha and Qiala gauging stations, the average annual streamflow at each station was analysed. Streamflow for the three stations was plotted for each of the four years that were analysed. Regression analysis indicates that runoff volume in the Tarim River basin has decreased at each station, with slopes corresponding to –3.824 (Alar), –3.460 (Ying Bazha), and –2.449 (Qiala) (Fig. 2). Actual streamflows are reported in Table 5.

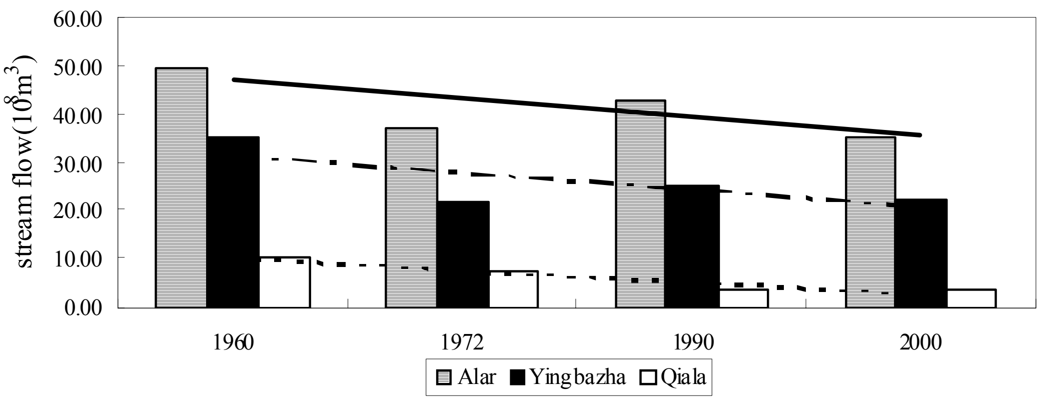

Fig. 2 Streamflow trends at the Alar, Ying Bazha and Qiala gauging stations (10^8 m^3).

Table 5 Streamflow at Aral, Yingbazha and Qiala gauging station (10^8 m^3) (source of measured data).

Year	Alar	Ying Bazha	Qiala
1960	49.70	35.00	10.52
1972	37.26	22.00	7.34
1990	42.70	24.90	3.73
2000	35.14	22.50	3.56

Correlation between land-use change and streamflow

Individual correlation analyses between streamflow at the head of a given reach and land-use change within the reach was conducted (Fig. 3), and give an indication of the effect of streamflow on land-use change. A negative correlation is observed between total farmland area and streamflow volume in the upper basin, while no meaningful correlations are observed in the middle and lower reaches. The majority of agricultural lands are also located in the upper basin. Positive correlations between streamflow and natural vegetation, including poplar forests and scrub-grassland, are observed throughout the Tarim basin, except for sparse poplar forest in the upper reach. While vegetation near the stream channel thrives as a result of normal streamflow levels, vegetation further removed from the river depends largely on flood flows and groundwater. Weak correlations were found, for the most part, between streamflow and salt deposit lands.

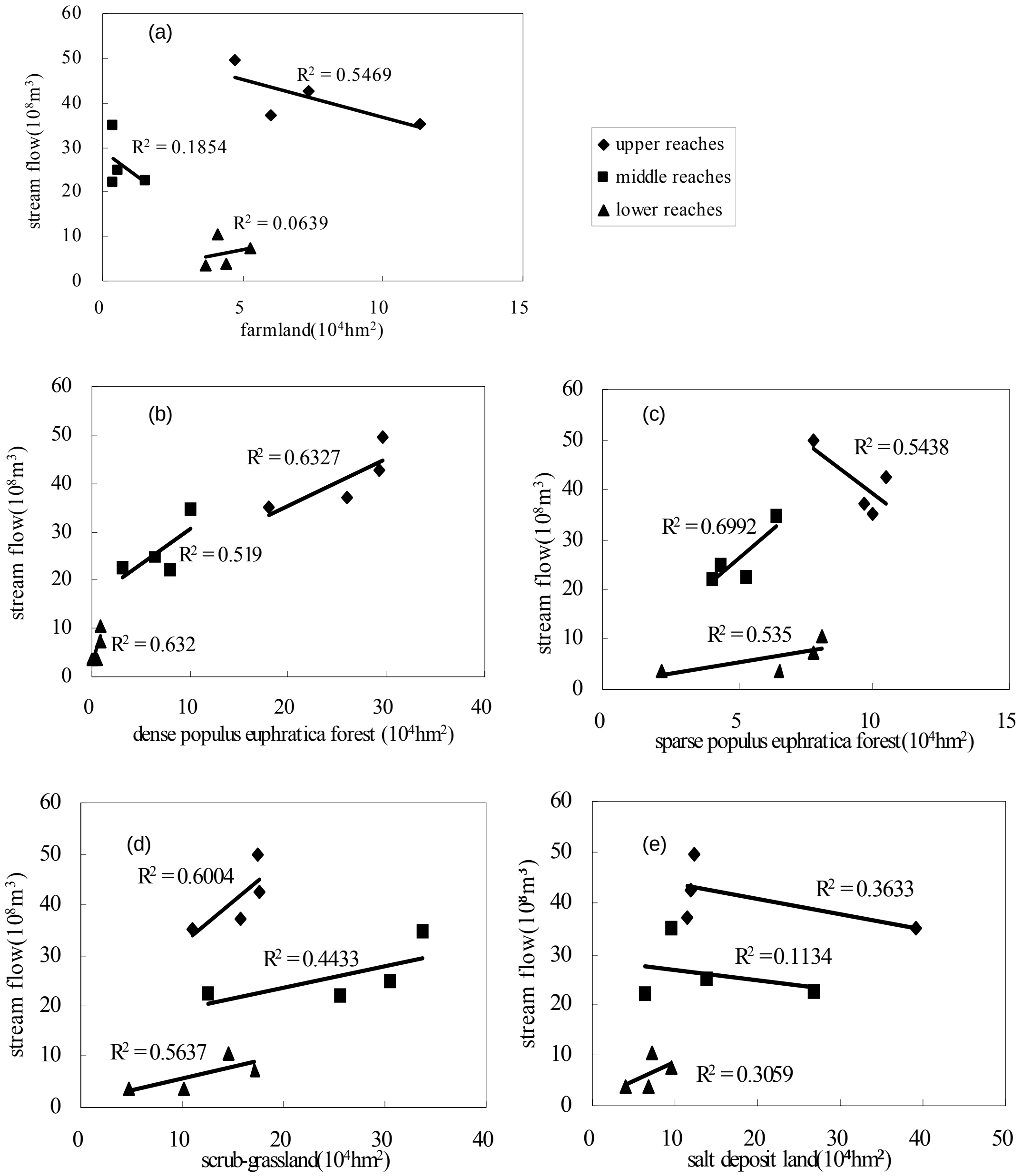

Fig. 3 The cross-correlation between indicated land-use class and streamflow: (a) farmland; (b) dense poplar forest; (c) sparse poplar forest; (d) scrub-grassland; and (e) salt deposit land.

Correlation between land-use change and outgoing streamflow

Individual correlation analyses between land-use change and streamflow at the downstream end of the reach were also conducted (Fig. 4), and may give an indication of land-use changes on the resulting streamflow. The data appear to be very similar to those observed in Fig. 3, with the resulting variances also seen to be similar.

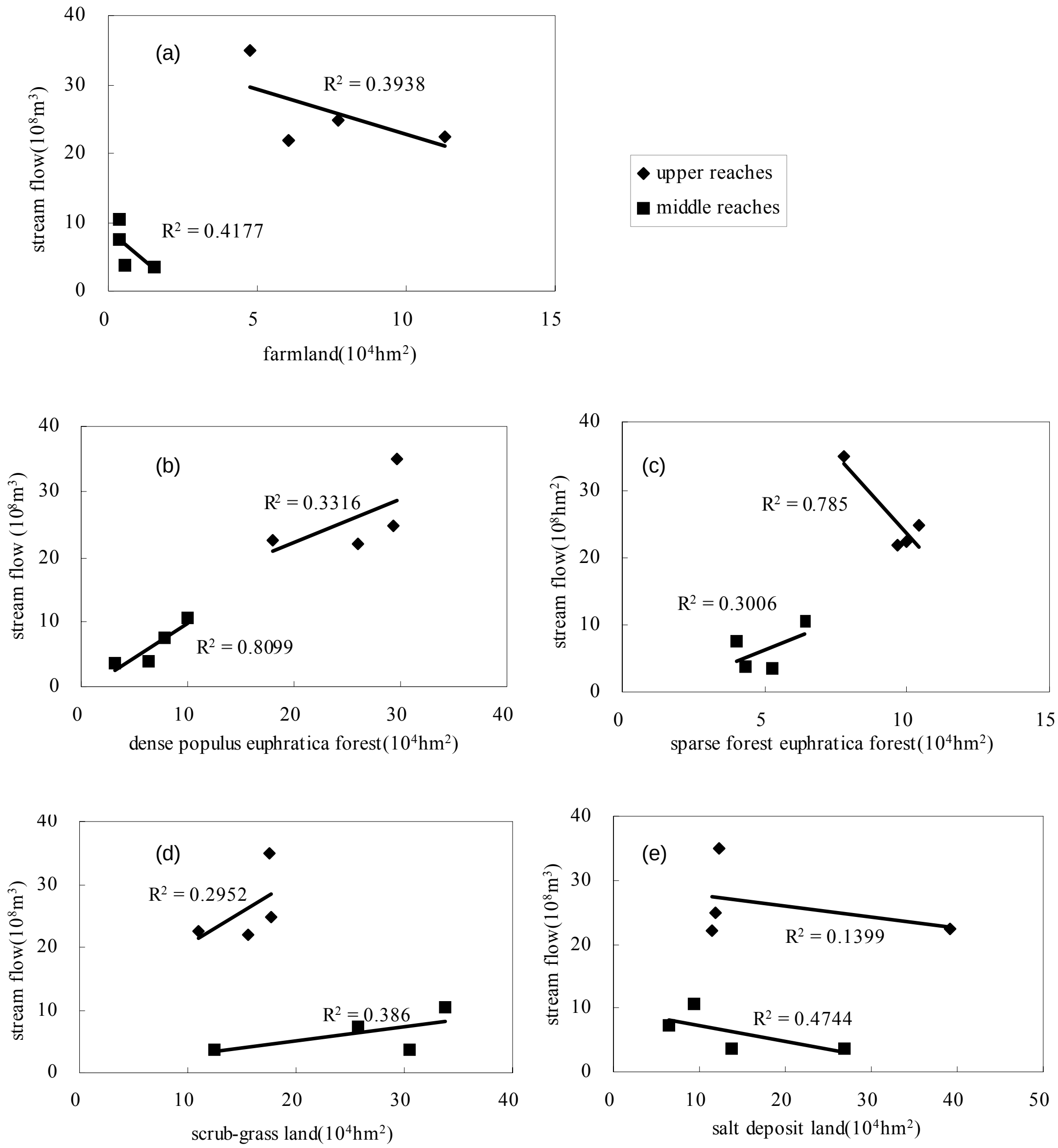

Fig. 4 The cross-correlation between the indicated land-use class and streamflow: (a) farmland; (b) dense poplar forest; (c) sparse poplar forest; (d) scrub-grassland; and (e) salt deposit land.

CONCLUSIONS

A series of quantitative analyses of land-use change and streamflow of the Tarim River basin were conducted. It is clear that the streamflow in arid inland river systems is significantly impacted by vegetation throughout the basin, as vegetation growth depends on the water supply. Higher correlations were found between land change and streamflow, both above and below a given reach. Farmland and poplar forests are seen to be the primary users of water in the river basin. It was found that streamflow was well correlated with changes in farmland area. While streamflow and total area of natural vegetation was found to be positively correlated, farmland had a negative correlation. Water is the primary limiting factor in the expansion of cultivated land area. However, farmland is also the greatest consumptive user of water, and may be partially the reason for the marked decrease in streamflow from the upper gauging station at Alar and the lower station at Qiala. Little correlation was noticed between streamflow and changes in salt deposit lands. Land use changes will continue to have a significant impact on streamflow in the Tarim River Basin.

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