Water resources, land exploration and population dynamics in arid area
- The case of Tarim River Basin in Xinjiang of China

Jiang Leiwen[1], Tong Yufen[2], Zhao Zhijie[3], Li Tianhong[3] and Liao Jianhua[3]

[1]Institute of Population Research, Peking University and Watson Institute for International Studies, Brown University (Leiwen_Jiang@Brown.edu)
[2] Institute of Population Research, Xinjiang University
[3] School of Environment Sciences, Peking University

Abstract: Water source is at the root of any lives and development in the arid areas like Xinjiang Autonomous Region of China. As one of the driest place in the world, melting glaciers is the exclusive water source of Tarim Basin in Xinjiang. Population growth – in particular in-migration -- greatly changes the ecological conditions of Tarim River Basin in the past 2500 years. Our research aims at studying the interactions between population growth, water and land resources changes, and cross the boundaries of different reaches in the Tarim River Basin over the past 50 years. Time series data on population changes and economic development, water volume and quality, land use and land cover changes, prevalence of morbidity relevant to water quality, are collected to study the relationship between these factors. Adopting statistical analysis and systems dynamics approach, the effect of population growth on water use and land degradation is quantified.

1. Introduction:

Of all natural resources, water is the major factor shaping the history of rise and fall of great civilizations (El-Ashry, 1998). Today, water goes into the very heart of the increasing worldwide concern of sustainable development, since various critical environmental threats with global implications have linkages to the water crises (Serageldin, 1999; Seckler et al., 1999; Giordano and Wolf, 2003; Gleick, 2000). Particularly, water is one of the essential in arid and semi-arid regions where one-sixth of world population lives and poses the highest population growth rate (World Bank, 1999; UNDP, 1999). Rapid population growth increasingly generates pressure on existing cultivated land and other resources, and induced migration to the marginal land of the arid semi-arid areas in many developing countries, e.g Tanzania (Darkoh 1982), Sudan (Ibrahim 1987; Little 1987; Bilsborrow & Delargy 1991), Egypt (Findlay, 1996), Yucatan Peninsula, Mexico (Ericson et al. 1999). Population migration to those arid and semi-arid areas exacerbates the problem of water shortage and worsens the situation of land degradation in the destination, and in turn caused sever problems of poverty, social instability, population health threats (Moench, 2002). Consequently, the enforced out-migrants from arid and semi-arid areas account for a large sheer of the annual 13-26 million environmental refugees in the world (Jacobson, 1988; Homer-Dixon; 1991; Myers, 1995, 1997; Hugo 1996; Mackeller et al., 1998; Lonergan 1998; Leighton 1999; Bates 2002; Lest Brown, 2004).

Although there are still disagreements on the terminology and causes of environmental refugees (e.g. Kibreab, 1997; Suhrke, 1994; MacKeller et al., 1998; Myers, 1995, 1997), it has become clear that population growth, water shortage and land degradation in the arid and semi-arid regions are interlinked with and jointly cause the problems of poverty, social insecurity, and environmental refugees. Therefore, solutions to these concerns can not be formulated in isolation or sector-by-sector. An integrated approach is required to seek the opportunities of economically, socially and environmentally sustainable development (Muda and Rl-Ashry, 2000).

This paper, basing on the case study in Tarim River Basin in Xinjiang of China, aims at analyzing the interactions of water, land resources and population dynamics, under a holistic framework. However, to simultaneously and equally study all the factors relating to population, water resource, and environmental changes is daunting. Therefore, a priority list and a simplified approach are pursued.

Our first objective is to explicitly understand the role of population dynamics in the interactions between population, water and land resources in the arid and semi-arid areas. Recently, there are increasing number of studies paying close attention to the environmental impact of population changes (e.g. Hecht, 1985; Hecht & Cockburn, 1990; Schmink & Wood, 1993; Pichon, 1997; Pichon & Bilsborrow, 1999; FAO, 1997, 2001; Heckandon & Mckay, 1984; Joly, 1989; Schelhas, 1996; Oberai, 1998; Heyzer, 1995) while others investigating the effects of environmental changes on population (World Resources, 1998-99; WHO, 1997; Mackeller et al., 1998; Lonergan 1998; Bates 2002; Hugo 1996; Leighton 1999). Our research is designed to analyze the population dynamics as both the cause and consequence of environment changes, based on qualitatively descriptive analysis and quantitatively modeling simulation.

The second objective of this study is to stress and examine the patterns of regional interactions and cross-boundary effect of changes in population, water and land resources within a system of the river basin in the arid and semi-arid area. There are number of studies look at the transboundary aspect of water bodies and its implications in environmental management and conflict between jurisdictions (e.g. Wolf, 1999; Gleick, 1994), while many other studies deal with the environment related cross-boundaries population migration which is already mentioned above. This research will explore the relationships between water, land and population under a framework of dynamic system, within which different parts of the Tarim River Basin are interlinked through the flows of both population and water resources cross the boundaries of these areas in the river basin.

In the next section, a brief introduction of the research site is firstly presented. It is followed by a descriptive analysis of the historical patterns of changes in population, water and land resources in different parts of the Tarim River Basin. The statistical analysis and a systems dynamics approach are employed to understand quantitatively the relationship between these three main components cross different river reaches of the whole river basin. In the particular, the effect of population changes is explicitly analyzed. Conclusions and discussions are given in the final section.

2. Research site

Locating at the heart of Eurasian Continent, the Tarim River Basin is one of the driest lands in the world (Figure 1). Although it is dry, the Tarim River Basin is rich in heat and light. Therefore, it could be ideal for irrigating agriculture when water resource is available (Zhou et al. 2000). Snow is the main form of precipitation which increases dramatically on mountain slops. Small water streams generating from the snowmelt in the southern slop of Tianshan Mountains converge and eventually form China’s longest in-land river – Tarim River. In the local Uygur language, tarim means "converging of waters" (World Wildlife Fund, 2001). The water source of the Tarim River is mainly from its three tributaries – the Aksu River, Yarkant River and Hotan River, which converge at the place of Xiaojiake, then flow to the east. The whole basin can be divided into four parts: (1) source region: the areas of the three tributaries; (2) the upper reaches: from Aral to Yingbazha; (3) the middle reaches: from Yingbazha to Qara; (4) the lower reaches: down from Qara. Tarim River Basin is typically a closed, independent, and self-balanced hydrological area. While the annual runoff depends on the volume of melting glacier and varies with the alteration of temperature, the total volume of water source is rather stable.

Running through China's largest and driest desert - Taklimakan, the Tarim River waters a strip of Hutong poplar forest which stabilizes the sand and moderates the local climate. One thousand and four hundred years ago, the river water eventually filled into Luobupuo Lake in the lower reach, where the Luolan civilization was bred. Loulan city was one of the largest towns along the ancient Silkroad. However, rapid population growth in Louan City generated heavy pressure on cultivated land, and increasingly pushed people out to the frontier in the upper reaches where more and more oases was established. As water consumption increased dramatically in the upper reaches, the severe water shortage eventually drove Luolan City extinct circa 500.

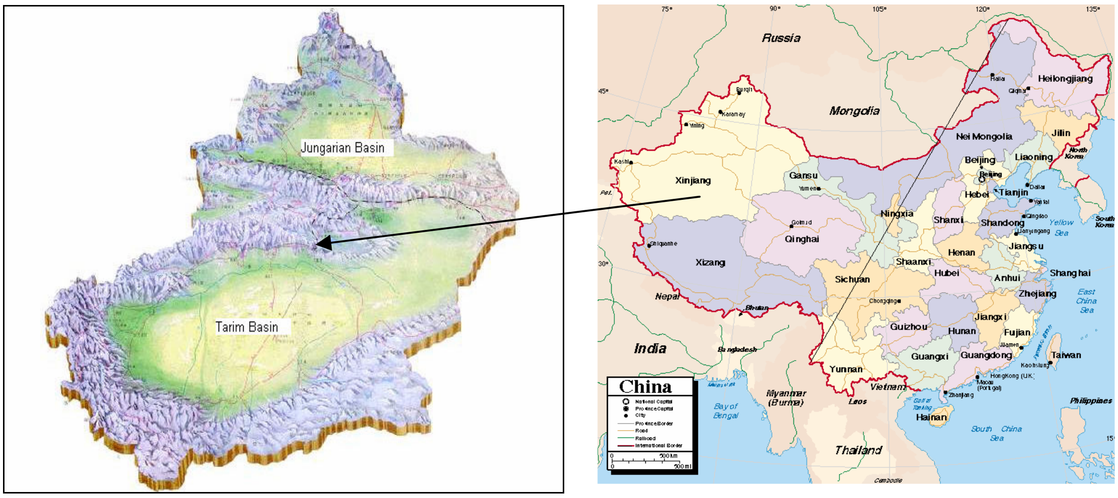


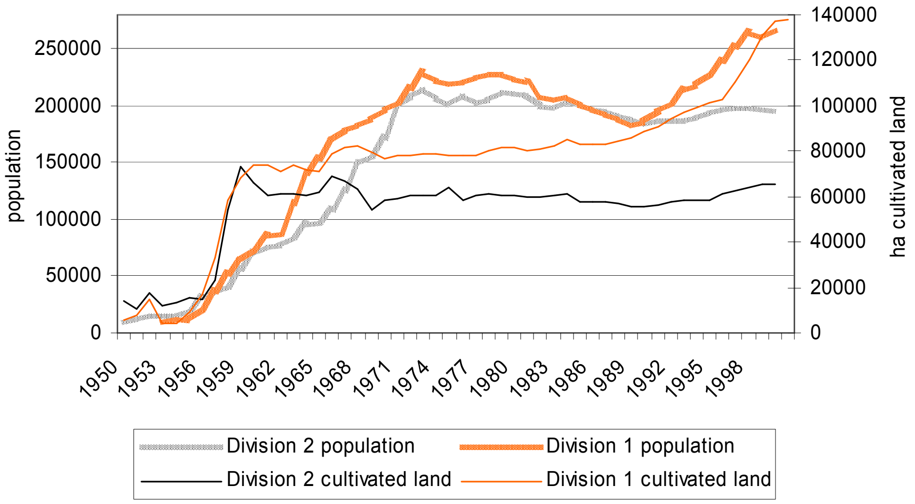
Figure 1 Map of the Tarim River Basin

Although the ecosystem in the lower reaches of Tarim River was already deteriorated since the 600 A.D, the biggest change happened after the early 1950s when Tarim River Basin became one of the most important migrants-receiver and cultivation bases in China. In the 1950s, the Division 1 and Division 2 of the Xinjiang Productive and Construction Troops were established respectively in the upper reaches and lower reaches of Tarim River Basin. Large scale of population growth, agricultural production induced heavy pressure on water and land resources. By the 1980s, Tarim River was shortened by more than 320 kilometers, while land degradation severely threatens human health and survival. In particular, population growth and cultivated land expansion in the upper reaches dramatically reduced the volume and degraded the quality of water available to the downstream, and caused severe land desertification and population out-migration there (Jiang et al., 2003).

3. Population and Cultivated Land Growth

Since the foundation of the People's Republic, Tarim River Basin has become one of the most important cultivation bases in China. The Division 1 and Division 2 of the Xinjiang Productive and Construction Troops were established in the 1950s. From then, large number of demobilized soldiers, intellectual youth, peasants from the east moved into the areas, constructed more than 70 reservoirs to irrigate the reclaimed cultivated land. The total population of these two divisions increased from less than 20,000 in 1950 to 420,000 in the middle of 1970s, and further to 460,000 in 2000 (Figure 2). Population growth in these two divisions was rapid and almost linearly in the period of 1950-1970. However, population growth was stagnant and even slightly reversed in the 1980s, before it resumed since the early 1990s. The decline of population size in the 1980s is because the previous in-migrants returned to the east where economic development was much faster than in the west after China introduced economic reform and the Coastal Development Strategy in the end of 1970s. However, in the end of 1980s, China experienced a significantly economic recession. Most of the main migrant-receiver in the densely populated east provinces pushed out the floating population who moved for employment opportunities without changing their household registration. Many of the rural out-migrants turned to seek chances in the vast west regions. Moreover, the central government, facing the enlarged socio-economic development gaps between the east and the west, started the new west development strategy in the late 1990s. This explains the population growth in the Tarim River Basin in the 1990s.

Figure 2 Population and cultivated land changes in Division 1 and Division 2 of Xinjiang Production and Construction Troops



More specifically, population regrowth in the Tarim River Basin in the 1990s was affected by the booming cotton production. Xinjiang has a global reputation of producing high quality cotton – the long fiber cotton. When China became one of the biggest textile and clothing exporter in the world, booming cotton demands in the market drove the prices historically high. Responding to the market expansion, most of the cultivated land in the Tarim River Basin was engaged in cotton production. Moreover, a large volume of unused land was transferred into cotton field. When forest and pastures were explored, the unfavorable land with higher salt content was also reclaimed. Increasing volume of water from the river was drawn to flush the salt content of the reclaimed land, and then was channeled back to the river. The more land reclaimed, the less amount and the poorer quality of water reached the downstream. Cotton plantation as a labor intensive business also absorbed large inflow of floating population. There is no accurate statistical report on the number of floating population. The estimate based on labor demand of cotton plantation indicates that floating population accounts for 15 to 30% of permanent residents in the Division 1. Therefore, once the floating population is taken into account, population growth in the 1990s will be much significant than what is plotted in figure 2.

As population size growing, the area of cultivated land has been also expanding. There observed an enormous increment of cultivated land in Tarim River Basin in the 1950s. The total amount of cultivated land in the two divisions jumped from less than 20,000 hectares in 1950 to 142,000 hectares in 1959. Although it was stabilized in the 1970s and 1980s, it increased again since the end of 1980s. The reasons to explain the pattern of changes in cultivated land over time is general the same as that of population changes. Investigating the compositional changes in the functions of cultivated land, it shows that 60-80% of the cultivated land was used for grain production before 1980s. However, this proportion gradually dropped down to less than 30% in the end of 1990s. In the meantime, the proportion of cultivated land engaged in cash crop production increased from less than 20 percent to more than 70%. Moreover, the biggest changes are the increase of cotton production and the decrease of rice plantation. The drop of rice plantation is mainly due to water shortage.

Looking beyond the general trend of population and cultivated land changes in Tarim River Basin, we find different patterns of these changes between the upper reaches and lower reaches of the Basin reflected by the two divisions. Population size of the Division 1 in the source region and the upper reaches was smaller than that of the Division 2 in the downstream in the early 1950s. However, the population size in the Division 1 quickly caught up and exceeded that in the Division 2. Since the 1970s, population growth in the Division 2 has been generally stopped and even reversed in some years. However, population size in the Division 1 kept expanding in the 1990s, and surpassed that of the Division 2 by more than 30% in year 2000. Providing that natural population growth rates did not differ much, the differences of population changes between these two divisions almost exclusively attributed to the varied patterns of population migration. Existing statistics indicate that the Division 1 had been kept receiving migrants in the 1990s. However, the inflow of migrants almost stopped but out-migrants increased in the Division 2 in the meantime. Moreover, this comparison does not take into account the inflow of floating population which is much more prevalent in the Division 1 than in the Division 2. The estimate, according to the labor demand for cotton cultivation, indicates that the size of floating population in the Division 1 is three times of that in the Division 2.

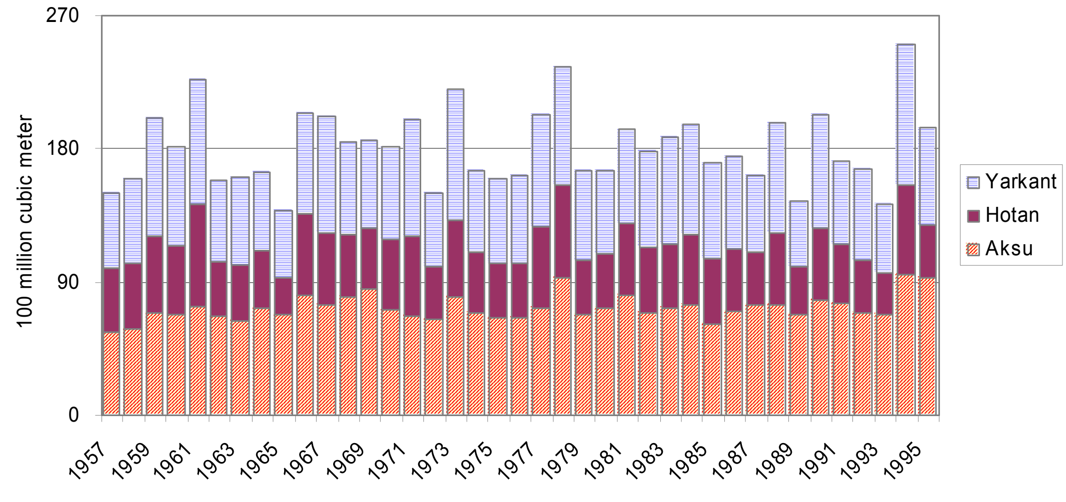
The differences in terms of cultivated land between the two divisions are even more substantial. In the early 1950s, the volume of cultivated land in the Division 2 was about three times that in the Division 1. It did not lose this advantage until the end of 1950s, when the area of cultivated land in both of the divisions increased up to the level of 150,000 hectares. However, the volume of cultivated land in the Division 2 decreased afterwards and never came back to the level of 1959, while the cultivated land area had continuously increased in the Division 1. The gap between the two divisions enlarged, particularly after the end of 1980s. By the end of 1990s, the total number of cultivated land in the Division 1 is more than doubled than that in the Division 2[1]. Studying the compositional changes of sown areas, it indicates a general pattern of decline in the proportion of grain plantation in both the divisions. However, this decline is more consistent in the Division 2 than in the Division 1, since rice plantation dropped much more significantly in the Division 2. Statistics shows that the proportion of rice sown areas in the Division 2 dropped to about 5% in the late 1990s, while it had been kept at the level of 20% in the Division 1. Given that rice plantation is very water-consuming, water shortage is the major (if not the single) reason of reduction in rice plantation in the Tarim River Basin. While people in the downstream had to give up most of their rice production, those in the upper reaches still expand rice sown areas considering that the total cultivated land areas in the Division 1 was almost doubled.

Since no land could be cultivated without irrigation in this arid and semi-arid region, changes in the volume of cultivated land of the different regions in the Tarim River Basin were clearly determined by the water quantity and quality. Water availability also determines other types of human production and consumption, and changes the eco-system and environmental condition, which in turn affect human livelihood and becomes the main pull and push factor of population migration. The next sections, therefore, is devoted to the study of changes in water source in the different parts of the Tarim Basin over time.

4. Water resources

The statistics shows that water resource from the three major tributaries of the Tarim River (Aksu River, Hotan River and Yarkant River) is rather stable in the past four decades. It was fluctuated around the average level of 18 billion cubic meters annually (Figure 3). However, the volume of water reached Aral - the starting point of trunk Tarim River, decreased from 5.62 billion cubic meters down in the late 1950s to 3.94 billion cubic meters (indicating a 30% of decline) in the middle 1990s (Table 1).

Figure 3 Annuall total water resource in the major attributes of Tarim River



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[1] Underreported cultivated land is not taken into account in this comparison. During our fieldwork in the Tarim River Basin, we learned and observed that the problem of underreporting cultivated land is a general practice in many areas, and in particularly in the upper reaches.

Since the 1950s, the Division 1 established Aral and Jingsezi Cultivation bases in the source regions. More than 40 different scale reservoirs (a total capacity of 1.6 billion cubic meters) were built in the Yarkant River and Aksu River basin. Reservoirs in the arid region suffer a very high evaporation rate. More than 50% of the water in the reservoir was evaporated. With backward facilities in the irrigation system, its canal effective utilization coefficient was only 0.35 to 0.4. Moreover, groundwater which is usually an important irrigation water source in the arid areas was only used by 3% in the source region of the Tarim River Basin. Since the extremely low water price (0.006 RMB Yuan, or less than 0.1 US cent per cubic meter) does no induce economic incentives for the users in the source regions to regulate their water consumption. The volume of water used for irrigating each hectare of cultivated land in the source region was as high as 15,000 to 22,500 cubic meters. Historical records for Aksu River, that provides more than 75% of water source of trunk Tarim River, show that most and increasing proportion of its water sources were drained in situ. The volume of water flew out of this area decreased from about 50% in the early 1980s to only about 35% in the 1990s. The decline of water contribution from other two tributaries was even much more dramatic. For example, since the middle 1970s, Yarkant River did not provide water source for the trunk Tarim River any more. The only stream flowing from Yarkant River to the trunk Tarim River was the used water spoiled from the irrigation or after flushing the salt content of the newly reclaimed land.

Table 1 Changes in water consumption in different parts of Tarim River Basin

	run-off volume at Aral	water consumed (100 million m^3)			water consumed (%)		
Time period	100 million m^3	Upper	Middle	Lower	Upper	Middle	Lower
1957-1959	56.2	14.8	25.8	15.6	26.4	45.9	27.7
1960-1969	53.2	16.4	24.4	12.4	30.8	45.9	23.2
1970-1979	43.2	15.0	22.1	6.7	34.2	50.6	15.2
1980-1989	44.8	18.2	22.7	3.9	40.6	50.7	8.7
1990-1995	39.4	17.1	19.2	3.1	43.5	48.7	7.8
average	46.5	16.3	22.5	7.7	35.1	48.4	16.5

Table 2 Changes in water volume of Aksu River

Year	water flow-in	water drained	water to Tarim River
1980	73.5	45.6	33.7
1981	81.5	41.7	46.5
1982	69.1	43.0	31.3
1983	72.7	44.2	34.8
1984	75.7	41.9	33.0
1985	62.4	41.8	17.3
1986	71.2	47.0	35.4
1987	75.6	42.4	40.9
1988	75.6	47.3	38.4
1989	68.5	56.1	29.2
1990	78.1	57.5	29.2
1991	75.7	58.0	20.1
1992	69.9	57.4	26.9
1993	69.2	59.7	25.2
1994	96.3	61.0	37.1
1995	93.7	64.4	37.8
average	75.5	50.6	32.7

In the period of 1950 to 2000, the cultivated land in the source region almost doubled. The large scale of reclamation in the past had already exhausted the land resources which are suitable to cultivation. The uncultivated area left over was only the land with the second or third degree salt content. However, the Division 1 pledged to “build one more Division 1” and aimed at reclaiming land of more than 50,000 hectares in the period 1995-2000, while the Aksu local government was engaged in reclaiming another 67,000 hectares of land in the same time. To enable the newly reclaimed land to be cultivable, 67 million ton salt had to be flushed out. If only half of the flushing water was discharged into the Tarim River, the annual salt content of the river should increase by 6.7 million tons. As the result, the water quality of Tarim River was greatly deteriorated. According to the monitoring records at the Aral Hydrological Station, the monthly salt content of Tarim River dramatically increased in the period 1960s to the 1990s (figure 8). The annual average salt content of the river increased from 0.75 g/L in the 1960s, to 0.86 g/L in the 1970s, 1.4 g/L in the 1980s and 2.6 g/L in the 1990s (Zhou et al. 2001). Recently, people in the middle reaches of the Tarim River was also engaged in large project of land reclamation and ecological construction which decreased the quantity and quality of water available for the downstream.

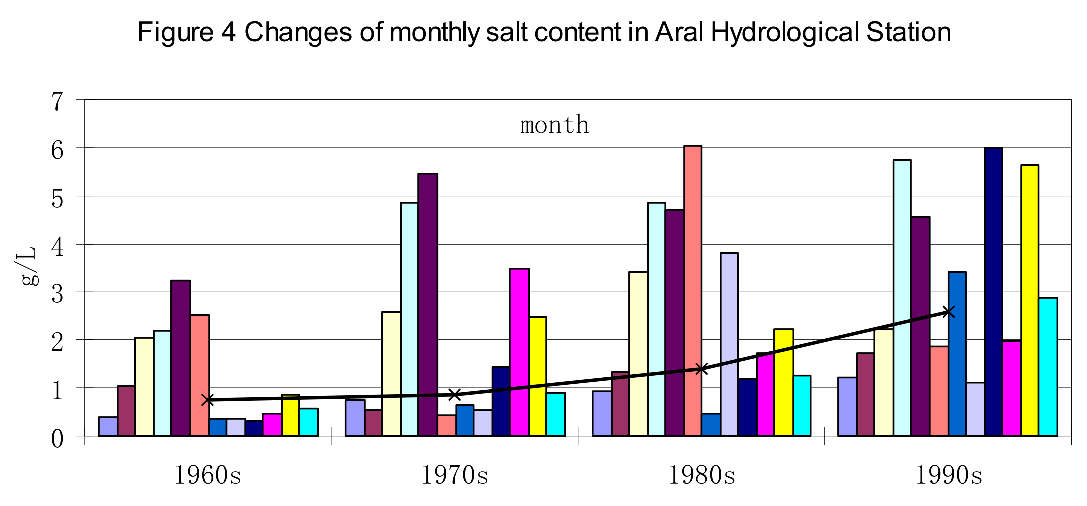


Figure 4 Changes of monthly salt content in Aral Hydrological Station

Statistics shows that the water volume flowing through Qara Hydrological Station into the downstream decreased from 1.56 billion cubic meters in the end of 1950s to only 0.28 billion cubic meters in 1995 (account for a 560% reduction). Dramatically reduced water volume can hardly support human production and consumption in the downstream, let alone the other nature species. As a result, the ever China largest lake Luobupo in the lower reaches was eventually dried out and buried under the desert in the late 1960s. The other ever big lake Taitema lost water supply in the late 1980s and only left a dry lake basin. Tarim River is now ended at Daxihezi Reservoir, and had been shortened by more than 320 kilometers comparing to its length in the early 1960s.

5. Land degradation

Historically, Tarim River Basin is rich in terms of biodiversity. The swinging streams of Tarim River watered a large range of plants, and made a home for various wildlife, including *Populus euphtatica, E. angustifolia, Pantera Tigris, Cervus elaphus, Gazella subguturosa, Aspiorhynchus laliceps,* and *Ciconianigra.* Seepage of floods provides 75% of the source of groundwater which is the water source for the forest, bush and meadows. However, as 70-80% of the water source was controlled by increasing population and channeled to the irrigation system and other human settlement, ecological water use was marginalized. Consequently, the landscape of Tarim Basin was greatly altered. Moreover, since different reaches of the river basin were at different status of water availability, the changes in land use and land cover follow different paths.

A comparative study conducted by the scientists from Xinjiang Institute of Ecology and Geography shows that there are different patterns of land use and land cover changes (LUCC) among different areas in the Tarim River Basin (Song, 2000). In the study, Aral, Yingbazha and Alagan were chosen as the representatives of the upper, middle and lower reaches of the Tarim River Basin. Exploiting the aero-photographic imageries in 1959, 1983, 1992 and 1996, the changes in land use and land cover of the three areas were obtained and compared.

- Studies on Aral in the upper reaches indicate that the cultivated land expanded by about 90% in the period of 1959-1996, at expenses of Hutong Poplar forest, pastures, and bush areas. Moreover, some large scale man-made reservoirs substituted the natural water bodies. Desertification is not a problem in Aral. In fact, the total desert area slightly declined, although Aral suffered a serious problem of land degradation in the form of secondary salinization, due to the ineffective drainage system and excessive water use for irrigation.
- In the middle reaches of Yingbazha, landscape was greatly changed by in-migrants in the 1960s and 1970s. The deserted areas increased by about 10 percent in 1960-1980. However, the rate of desertification decreased in the 1980s because of the establishment of two natural protection zones. Unfortunately, the natural vegetation recovering process was blocked and reversed in the 1990s when Yingbazha was designated as one of the important base of Tarim Basin Oil Exploration Program.
- Land degradation was the most serious in the Alagan in the downstream. Due to water shortage, 86.98% of the total area was already covered by desert in year 1959. This situation was worsened when more migrants came, more lands were cultivated, and more water was drained in the upper and middle reaches of the river basin. The proportion of desert in Alagan reached 94.78% in 1996. Because there was no river water reaching this area any more since the early 1980s, the aquifer level decreased from 7 meters in 1973 to 10.40 meters in 1989 and further down to 12.65 meters in 1997 (Ji 2001). Consequently, plants, animals as well as human being were all driven out completely from this area.

The comparative analysis conveys clear evidences that given the increasing total water consumption and different status of water accessibility, LUCC in different parts of the Tarim River Basin varies considerably. While the landscape in the upper reach has been improved to some extent, LUCC in the middle reach presented a mixed picture. However, a more important message received from the study is that the land in the lower reaches had been degraded the most. Since the problems, which were caused by basin-wide rapid population growth, large scale land reclamation, excessive water consumption and pollution, were eventually cumulated and seriously degraded the land in the lower reach.

One may argue that the above-mentioned study was only based on the samples of the three small areas which might be biased in representing the whole river basin. It would be ideal to analyze the evolution of LUCC for the whole river basin based on time series data. However, such a thorough study would be very resource- and time-consuming.

The first difficulty is the huge territory of the whole basin. For example, Yuli County which comprises the utmost of the downstream of Tarim River Basin has an area of 60,000 square kilometers. This size is larger than that of several provinces and autonomous regions, although Yuli is only one of the more than 2400 counties in China. To examine the LUCC of Tarim River Basin indicated by the above-mentioned study, we conducted two fieldtrips in year 2002 and 2003 along the river from its origin to the dead end. Our observations in general testify the findings from the study. Moreover, we realized that Alagan might not be a good sample for the study in the downstream. Since it had already been highly deserted in the end of 1950s, the process of accelerating land degradation due to increasing water shortage can hardly be captured and compared. Considering the dramatic LUCC and serious problem of land degradation in the downstream, we conducted an analysis of LUCC covering the whole area of the downstream over the past four decades.

For our analysis, three types of data sources were employed: (1) The 1:500,000 map of Yuli County in year 1958-59 which was derived from the aero-photographic imageries. After a series of works of categorization, map editing, scanning and digitization, ground truthing and statistical analysis, we obtained the statistics of land use and land cover of Yuli County of 1958-59 when the Division 2 was just established. (2) Remote sensing data for Yuli County in the year 1973 (MSS) and 1999 (ETM) from NASA. The year of 1973 is the earliest time when Landsat data is available. It is also the time when population growth in the Division 2 reached its highest records, and land reclamation became stagnant. ETM data of the 1999 reflect the present situation of land use and land cover in this area. (3) Using statistics from the first and second National Land Use Survey, we obtained LUCC data of Yuli County for the two time points of 1985 and 1995.

Statistical analysis based on these three types data sources points out that in the period of 1959-1999, the desert areas in Yuli increased from 85.5% to 89.2% at expense of forest, grassland, bush and water areas; the biggest relative increase happened to cultivated land and built-up areas; Salina and marsh land also increased which was mainly the results of drain of water bodies, reclamation and abandonment of cultivated land (Table 3 and Figure 5).

However, to just analyze the total changes in land use and land cover of Yuli County might conceal the grievous degree of land degradation in the downstream. Since the vast desert area which had already been that dominant land type before the 1950s was not subject to significant changes. Moreover, in the sense of a stricter definition, most of the desert in the northeast and southwest of Yuli County is not part of the downstream of Tarim River Basin. Instead, only the area along the Tarim River where the five corps (Corp 31 to 35) was established is the major part of the downstream of the Tarim River Basin.

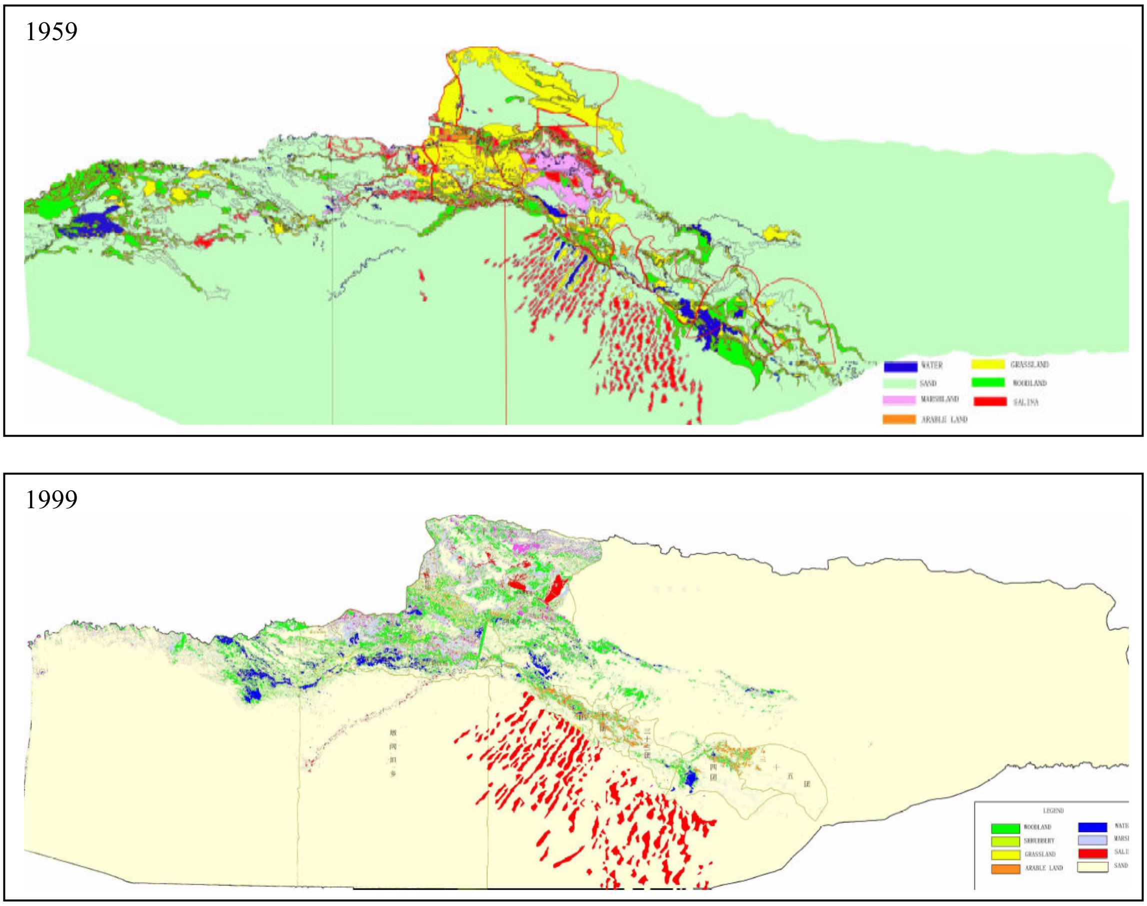


Figure 5 Land use and land cover in Yuli County, 1958-1958 and 1999

Table 3 Compositional changes of land use and land cover in Yuli County, 1959-1999 (%)

	Water	Desert	Salina	Marsh	Cultiv. land	Forest	Bush	Grass land	Built-up area	Total
Total										
1959	0.94	85.49	3.14	1.12	0.41	3.11	2.03	3.73	0.02	100.00
1973	0.78	87.83	3.45	1.54	0.19	2.18	1.24	2.78	0.07	100.00
1985	0.60	89.51	3.78	1.40	0.32	1.25	0.76	2.29	0.09	100.00
1995	0.47	90.23	4.15	1.18	0.51	0.95	0.50	1.90	0.14	100.00
1999	0.39	89.17	5.02	1.58	0.74	0.76	0.23	1.72	0.38	100.00
Construction corps										
1959	8.10	59.53	0.92	0.41	5.60	6.97	10.46	7.86	0.16	100.00
1973	7.46	68.59	2.19	1.57	3.32	5.62	6.46	4.79	0.38	100.00
1985	4.58	72.23	3.34	1.10	5.00	4.48	4.53	4.08	0.66	100.00
1995	3.21	74.09	4.19	0.85	5.66	4.05	2.98	3.75	1.21	100.00
1999	4.09	74.40	4.40	1.14	6.79	2.50	2.04	2.89	1.75	100.00
Local Community										
1959	0.63	86.61	3.24	1.15	0.19	2.95	1.67	3.56	0.01	100.00
1973	0.49	88.65	3.50	1.54	0.06	2.03	1.02	2.70	0.05	100.00
1985	0.42	90.26	3.80	1.42	0.12	1.11	0.59	2.21	0.06	100.00
1995	0.34	90.95	4.15	1.20	0.28	0.82	0.39	1.82	0.09	100.00
1999	0.22	89.87	5.05	1.61	0.46	0.68	0.15	1.67	0.31	100.00

From the statistics, we are able to separately analyze LUCC of the construction corps and the Yuli local communities. While majority of people in the local community are native minorities, the constructions corps consists of in-migrants and their descendents after the foundation of the Division 2. Comparing with the local communities, the construction corps experienced enormous changes in land use and land cover in the period 1959-1999: the woods (forest and bush) decreased from about 17.5% to 4.5%; grassland dropped from about 8% to 3%; water areas declined from 8% to 4%. If these three types of land could be defined as “natural arable area”, they together decreased by about 22 percentage points. The human settings (including cultivated land and built-up areas) increased by about 2.5 percentage points. The biggest increments were desert (15 percentage points) and salina (more than 3 percentage points). Therefore, it is clear that the downstream of Tarim River Basin had a serious problem of land degradation.

6. Effect of land degradation on human health and out-migration

Land degradation and environmental deterioration worsened the living condition in the downstream, induced grave threats to human health and caused net out-migration. As a windy place, sand storms happened very frequently in the downstream of Tarim River Basin as the land being degraded. The frequent windstorms destroyed crops, blocked the transportation vessels, and harmed human health. An investigation in the construction corps indicated that the incidences of respiratory diseases and eye diseases dramatically increased right after sand storms. Moreover, the polluted water also induced adverse effect on human health. Water-born intestine and stomach diseases were very common in the downstream. A survey conducted in the schools of Corp 32 reveals that 40% of the primary and middle school students suffered endemic dental fluorosis due to very high fluoride level in the drinking water (Ji, 2001).

Driven by adverse effect of the land degradation and reduction in economic reward, people of the construction corps were seeking to leave this area. The old generation of in-migrants was willing to send their children outside or back to the hometown in the east. Young people receiving education in the cities rarely went back to Yuli. As a result, the population of the construction corps aged rapidly. Labor shortage also led to the abandonment of cultivated land. Although the corps tried to attract in-migrants and floating population by offering good benefits, those policies seemed ineffective. There were only coming a few in-migrants who were less educated and skilled or sought to evade from the stricter family planning policy in the east. Even this small group of in-migrants moved out quickly, encountering the harsh life due to water shortage and being terrified by the sandstorms. Those out-migrants often moved to the upper reaches of the Tarim River Basin. Regarding population decline as a problem, the corps in the downstream implemented a family policy that allowed (actually encouraged) young couples to have second child. It turned to be a hard job for the cadres who complained that it was much more difficult to persuade young couples to give more births than to control births in the previous regime. Even the floating population who initially came for giving more births also changed their mind quickly. The aging population structure together with the increasing prevalence of diseases due to environmental deterioration resulted in an increasing crude death rate. Decline of population natural growth rate combining with a negative net-migration shrank the population size in the downstream.

7. Integrated analysis of population, water sources and land degradation

Based on the descriptive analysis above, we firstly conducted a statistical analysis to quantify the relationships between population, water resources and land use changes between the two divisions, and areas in different the reaches of the Tarim River Basin. Table 4 shows the zero-order correlation coefficients between the relevant variables.

It is firstly noted that total water source has no significant relationship with any variables. This indicates that basin-wide total population and land use changes in the past five decades were not determined by the natural water availability. It is human intervention and the ways of water use affected population distribution and landscape. However, population growth, cultivated land expansion, and agricultural production of the Division 1 in the source region and upper reach increased water consumption and deteriorated water quality, so that water available for the middle and lower reaches decreased – these variables are all positively related to the amount of water consumption in the upper reach and water salt content, but negatively related to the amount of water resource flowing into trunk Tarim River. Grain production in the down stream is greatly determined by water availability – grain production and rice sown area in the Division 2 positively related to water volume to the trunk Tarim River. As water volume decreased and water quality deteriorated, land desertification in the lower and middle reaches accelerated – the signs of correlation coefficient clearly reveal these relationships.

It is also interesting to note that salt content of the river water is negatively related to desertification in the upper reach but positively related to desertification in the middle and lower reaches; water consumption in the upper reaches negatively related to desertification in the upper reach but positively related to desertification in the middle and lower reaches. This could be due to the fact that the large volume of water used for flushing the salt for the newly reclaiming land in the upper reach improved the land quality in the upper reaches, but seriously affected water quality and quantity in the downstream and in turn caused desertification there.

Table 4 Correlation coefficient of factors related to population, water and land resources in Tarim River Basin

	Pop1	*Water source*	*Cultiv. land1*	*Sown1*	*Grain1*	*Rice1*	*Pop2*	*Cultiv. land2*	*Water to TR*
Cultiv. land1	0.860	-							
Sown1	0.902	-	0.959						
Grain1	0.613	-	0.642	0.762					
Rice1	0.904	-	0.829	0.900	0.828				
Pop2	0.957	-	0.814	0.906	0.702	0.924			
Cultiv. land2	0.687	-	0.879	0.812	0.377	0.664	0.705		
Water to TR	-0.782	-	-0.702	-0.846	-0.882	-0.82	-0.830	-0.271	
Water quality	0.516	-	0.822	0.867	0.851	0.533	0.403	-	-
WCU	0.417	-	0.593	0.563	0.716	0.647	0.488	0.457	-0.759
WCM	-0.792	-	-0.804	-0.882	-0.841	-0.799	-0.798	-0.523	-0.477
WCL	-0.860	-	-0.797	-0.891	-0.883	-0.917	-0.919	-0.579	0.868
Grain2	0.407	-	0.452	0.691	-	0.628	0.615	0.796	0.921
Rice2	0.656	-	0.426	0.680	0.440	0.768	0.819	0.527	-
DesertL	0.872	-	0.555	0.832	0.736	0.855	0.924	-0.356	-0.526
DesertU	-0.921	-	-0.856	-0.940	-0.757	-0.936	-0.956	-0.738	-0.815
DesertM	-0.638	-	-0.611	-0.633	-	-0.607	-0.663	-0.664	-0.759

	Water Quality	*WCU*	*WCM*	*WCL*	*Grain2*	*Rice2*	*DesertL*	*DesertU*
WCU	0.482							
WCM	-0.887	-0.478						
WCL	-0.758	-0.652	0.909					
Grain2	-0.815	-	-	-0.352				
Rice2	-0.261	-	-0.434	-0.609	0.746			
DesertL	0.641	0.249	-0.759	-0.905	-0.368	0.481		
DesertU	-0.660	-0.625	0.838	0.944	-0.587	-0.696	-0.909	
DesertM	0.383	-	0.377	0.418	-0.742	-0.705	-	0.604

We also use linear regression analysis to study the determinants of land degradation in the lower and middle reaches (the regression model for the upper reaches was not successful since no independent variable could enter the model) (table 5). After controlling other variables, land desertification in the lower reaches positively affected by the rice sown river in the Division 1, but negatively affected by population growth and grain production in the Division 2. It is quite understandable that rice plantation is very water-consuming; the increase of rice sown area in the upper reach decreased water availability for the downstream and cause land desertification. However, one would rather regard population and grain production decline as the consequences than the causes of land desertification. Here, we argue that declines in population and grain production in the downstream are mainly the consequences of out-migration and abandonment of cultivated land; population out-migration as well as abandoned cultivated land and human settlements in the arid area will directly induced desertification. Since cultivation and construction of human settlement had already removed the natural vegetation which was functioning as a protector of the land from desertification; once cultivation stopped and human settlements abandoned and, the land will be deserted as lacking of either natural vegetation protection or human management. Our investigation during the fieldtrips to the Corp 31 and particular Corp35 in the far end of Tarim River reveals that large amount of cultivated land and villages of the corps were abandoned due to water shortage, and then quickly deserted.

Table 5 Linear regression analysis of desertification in the Tarim River Basin

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Dependent Variable: desertification in the lower reach					
Constant)	98.221	1.321		74.331	.000
population of division 2	-1.554E-05	.000	-.317	-2.188	.049
Grain production of division 2	-6.209E-05	.000	-.704	-4.774	.000
rice sown are of division 1	4.478E-05	.000	.246	2.418	.032
Dependent Variable: desertification in the middle reach					
(Constant)	-.003	.013		-.217	.832
Grain production of division 2	-4.121E-06	.000	-.775	-14.262	.000
Grain production of divsion 1	3.121E-07	.000	.314	5.658	.000
Water resource reaches trunk river	-.001	.000	-.162	-3.242	.007

The regression of determinants of land desertification in the middle reach are grain production in the division 1 (positive), water resource reaches the trunk Tarim River (negative), and grain production of division 2 (negative). The effect of former two is straightforward: agriculture in the upper reach consumes water and affects water availability in the middle reach, and then caused desertification. That reduction of grain production of the Division 2 worsened the situation of land degradation in the middle reach can be explained by the same reasons as that in the model of land degradation in the lower reach, given that part of the Division 2 is located in the middle reach.

The simple statistical analysis helps to gain insights on the relationships between population, water and land resources. However, the mechanisms of the interactions between these three components and other relevant factors are complicated, could hardly be understood and clarified by such a simple model. Sometimes, results from the simple statistical analysis can even be misleading. For example, the results from correlation coefficient analysis show that growth of population and cultivated land in the Division 1 is highly related with population growth, cultivation expansion and agricultural production in the Division 2. This should not mean that the former enhanced the later. Moreover, the linear regression model, which points out the negative effect of population decline on desertification in the lower reach, can not clarify the possible effect of the feed back from land degradation from population growth. Furthermore, one of our main objectives is to quantitatively analyze the effect of population growth on water resources and land degradation which could not be done using the simple statistical analysis.

To meet the gaps mentioned above, we exploit the systems dynamics approach in this research. Based on the understandings gained from the descriptive analysis and statistical analysis, we constructed a system dynamic model. This model pays particular attention to the situation in the downstream where problem of land degradation is the most serious. Although the analysis more focuses on the downstream, land degradation in the downstream is affected by population growth, human activities and water consumptions not only in situ, but also in the upper reaches. Therefore, our model is constructed under a framework considering the whole river basin within a single system which comprises three main subsystems: (1) the source region main subsystem, (2) the upper and middle reaches main subsystem, and (3) the downstream main subsystem. Each main subsystem consists of a number of subsystems, e.g. population subsystem, land exploration subsystem, and ecological subsystem. From the main subsystem of source region, to the upper and middle reaches, and then to the downstream, the number of subsystems, factors as well as the complexity of the interactions increases. In this model, water flow and water consumption is the key factor connecting the main subsystems (figure 6). As an example, the inter-correlations between the subsystems and factors within the downstream main subsystem are demonstrated in Figure 7. The frameworks for the other two main subsystems in the upper reaches are basically the same but simplified versions.

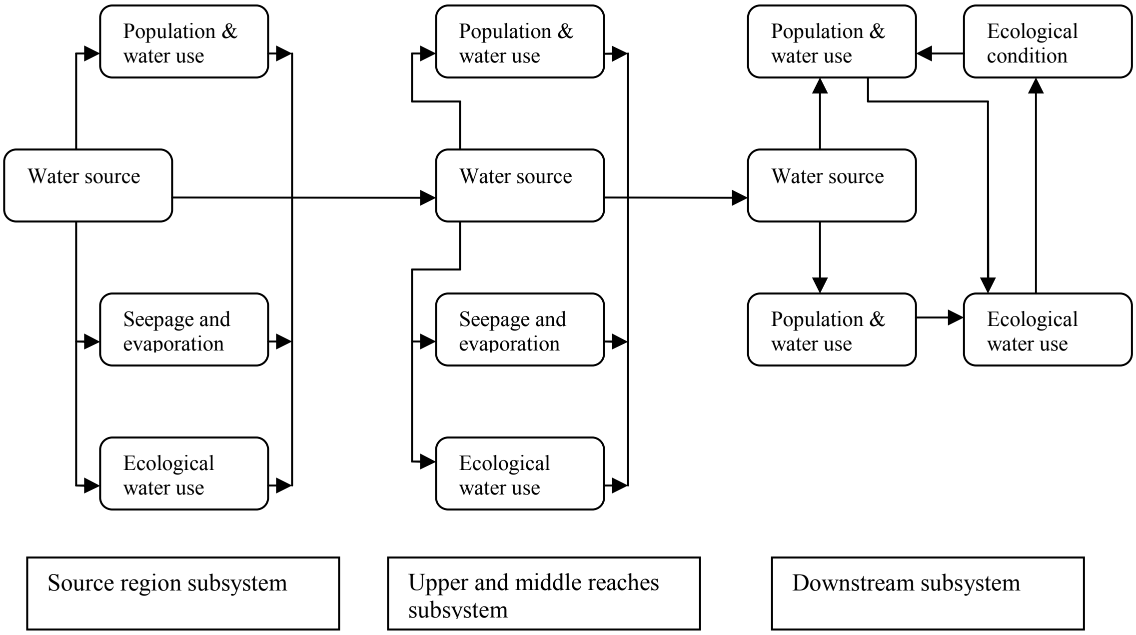


Figure 6 Inter-linkage between the three main subsystems

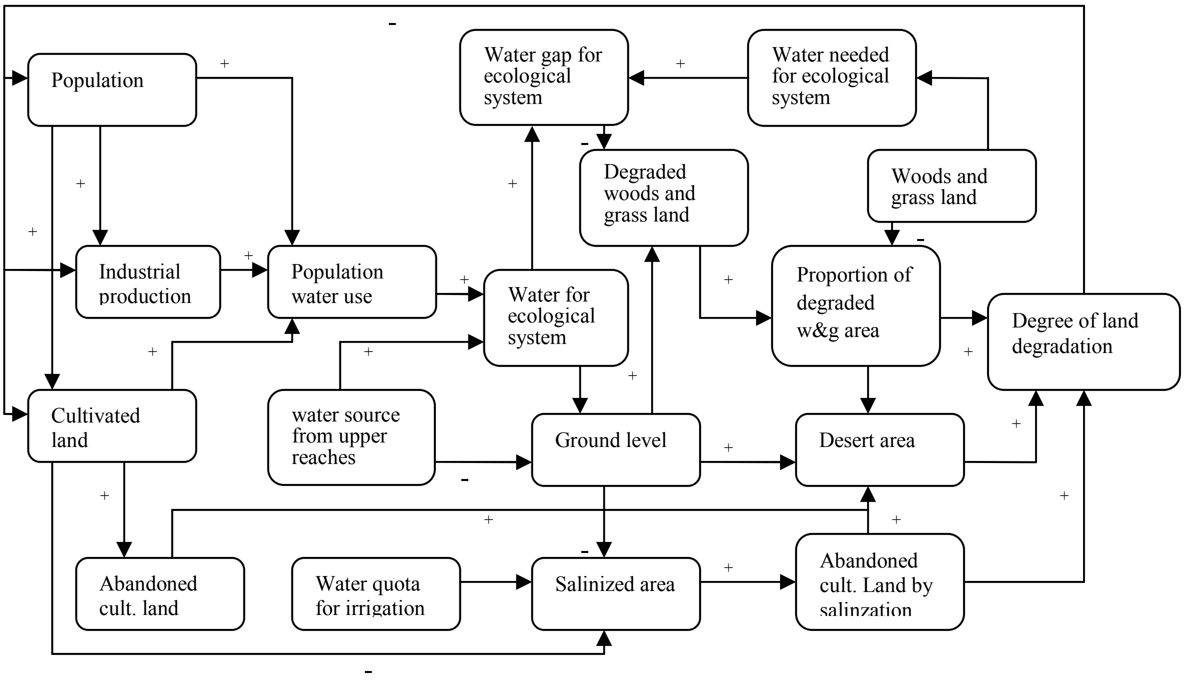


Figure 7 Correlation between subsystems in the downstream subsystem

In the main subsystem of the downstream, population growth, industrial and agricultural production induces water consumption. Given the fixed volume of water sources, increment in water use by human activities will squeeze out the water from ecological system, reduces river run-off and declines aquifer levels. The gap between water supply and water demand for ecological system and drop of aquifer levels cause degradation and desertification of the woodlands, grassland, which is very evident from some existing studies (Liu 2000). Land degradation constrains population growth and economic expansion which forms a complete feedback loop. Moreover, population growth in the main subsystems of source region and the upper and middle reaches alters the water allocation and affects water availability for the downstream.

Due to data limitation, the current system dynamic analysis only covered the period of 1980-2000. Based on this systems dynamics model, the historical changes in population, water sources, cultivated land, and land degradation are simulated. A comparison of the actual values and the simulated results gives a range of relative errors of -1.5% to 2% which is acceptable.

Using this model, we are able to decompose the effects of different factors on land degradation, and quantify the net effects due to population growth. The accounting strategy is simple: to calculate the changes in land degradation of a main subsystem under the scenario of no population growth, then compare it with the actual changes of land degradation so that the net effect of population growth is estimated. The general mathematical equation is as follows,

$$\triangle E_P / \triangle E = (\triangle E - \triangle E_0) / \triangle E$$

Where $\triangle E_P$ is the changes in land degradation due to population change, $\triangle E_0$ refers to the actual changes in land degradation, and $\triangle E$ denotes the changes in land degradation after excluding the effects of population growth.

Under the first scenario, we assume that there is no population change in the whole Tarim Rive Basin for the past two decades, and obtained the consequences of land degradation in the downstream. Comparing with the actual statistics, our analysis indicates that population growth in the whole Tarim River Basin accounts for 49.06% of the land degradation in the downstream (Figure 8). More specifically, population growth alone is responsible for 63.35% of grassland degradation, 25.86% of desertification, and 13.12% of woodland degradation.

Figure 8 Changes of land degradation under different population scenarios

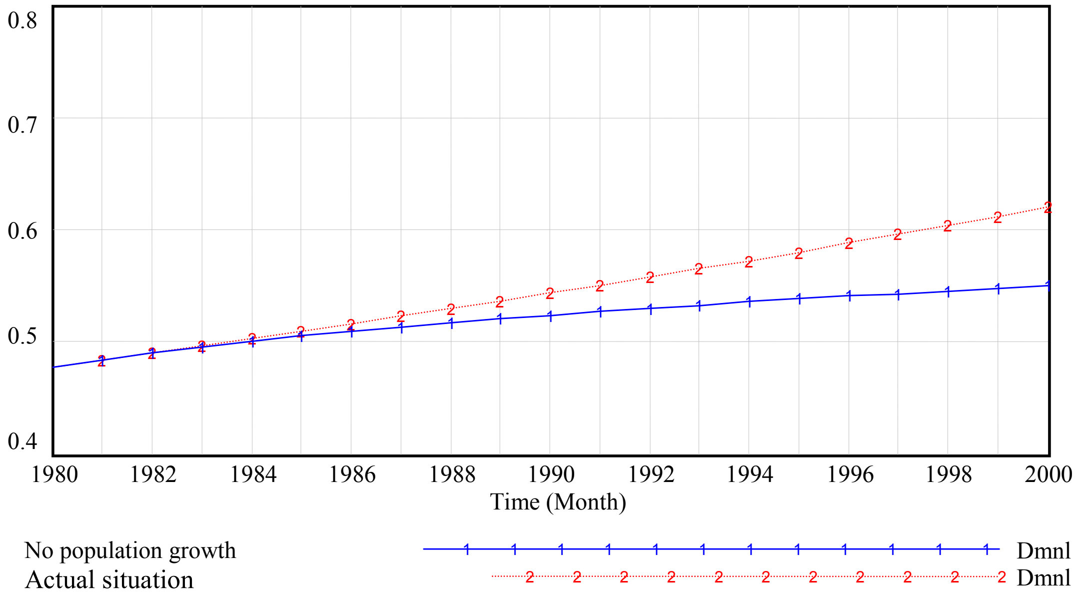
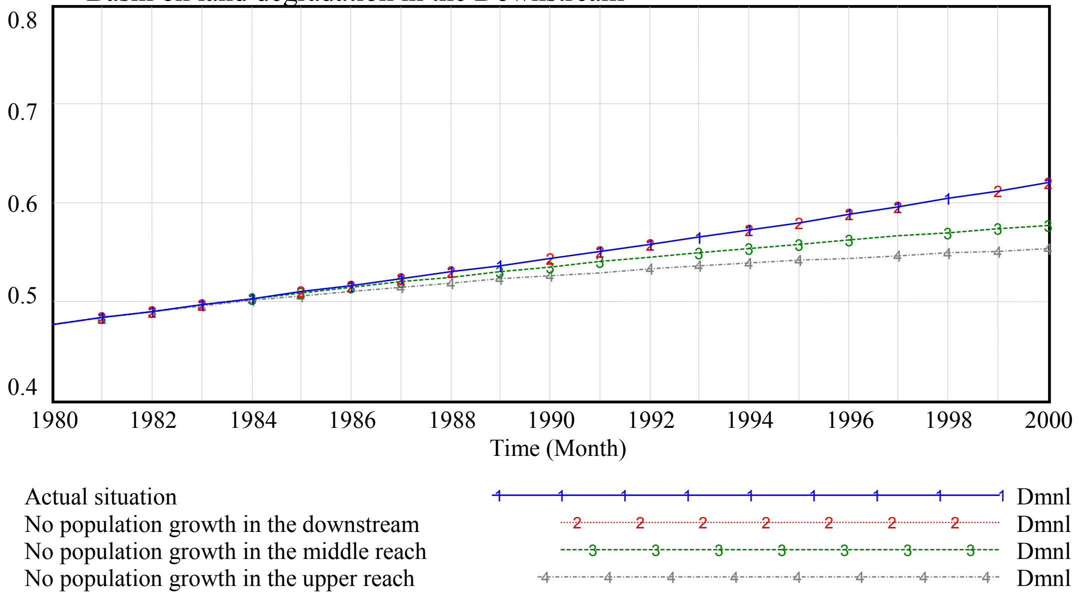


Figure 9 Net effect of population growth of different parts of the Tarim River Basin on land degradation in the Downstream



To separately analyze the effects of population growth in different reaches of the river, we make other three scenarios: (1) no population growth in the source region; (2) no population growth in the upper and middle reaches; (3) no population growth in the downstream. Simulation and comparative analysis shows that population growth in the sources region is the main attributor and accounts for 46.48% of changes in land degradation in the down stream. Population growth in the upper and middle reaches also caused 30.01% of the land degradation in the downstream, while depopulation in the downstream eases the pressure of land degradation in the downstream by 0.14% (Figure 9).

It should be noted that the sum of the effects of population changes of all the main subsystem on land degradation in the downstream does not equal the total effect of population growth of the whole Tarim River Basin. This is because population change only affects the land through other determinants, while the effects of those other determinants may cancel off each other. For instance, population growth in the source region reduces the water source for the upper and middle reaches which will hinder its effort of land reclamation, while population growth in the upper and middle reaches itself induces the needs for land reclamation. Therefore, the effects of population growth in the source region in the one hand, and the effects of population growth in the upper and middle reaches in the other hand cancel each other, and jointly affect the water availability and land degradation in the downstream. This also provides evidence that environmental impact of population growth is not straightforward, and but is effective with other factors in a complex system.

Comparing the results of systems dynamics modeling analysis and linear regression analysis, there is a big difference. According to the system dynamics analysis, rapid population growth in the sources region and the upper reach is the major cause of land degradation in the down stream, while no such effect exists in the linear regression model. Since a simple linear regression model does not take into account the complicated interactions of the factors, does not consider the cross-boundaries effects. However, one finding is consistent in the two models: population change in the downstream has a negative relationship with land degradation in situ. It could be explained as the result of abandoned cultivated land and human settlement as well as lack of effective management due to out-migration. More importantly, the systems dynamics model with a complete feedback loop captures the responding effect of land degradation on population growth.

8. Conclusion

Based on our studies, we tentatively make conclusions as follows:

- Population growth was the main driving force of land degradation in Tarim River Basin where water resource is relatively fixed.
- Interactions between population, land and water resources happened cross boundaries of different reaches through the flows of water and migrants; land degradation in the downstream was mostly the consequences of population growth in the upper reaches.
- Water shortage and land degradation induced threats to human health and ignited population out-migration in the downstream.
- Population out-migration from the degraded arid areas may worsen the problem of land degradation, since the abandoned cultivated land and human settlement is transferred into desert due to the removal of previous protector of natural vegetation and lack of human management.
- In a dryland river basin like Tarim when lacks effective water management, there might exist a common trend – human settlement gradually and continuously move up along the river stream, consequently water resources reaching the downstream decreases and the river length is gradually shortened.

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