

A Geospatial Analysis Approach for Assessing the Impact of Land Use on Groundwater Resources in the SanGong Oasis Region

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Abstract

In this study, the relationship between land use and land cover change (LUCC) and variation of groundwater table and quality in the SanGong Oasis Region in the western China is investigated using a geospatial approach. Specifically, the interactions among groundwater, surface water, and LUCC are analyzed through the utilization of geographical information system (GIS), remote sensing (RS) imagery processing, and geostatistics. Study outputs indicate that recharging into the groundwater in the study area does not change significantly during the period from 1978 to 1998. However, both LUCC and groundwater table have changed substantially in the SanGong Oasis Region, and their variations are closely correlated to each other spatially and temporally over the past two decades. This confirms that urbanization and industry are direct reasons for the decrease in water table and deterioration of groundwater quality.

Introduction

With the lack of surface water, the groundwater resources are not only the main water supply source for the social and economic development but also the crucial component of the ecosystem in the oasis regions (Collin & Melloul, 2001). Particularly, the demands for water and land resources are expanded with the increase of human activities in oasis regions, which results in ecological and environmental concerns (Al-Adamat et al., 2003). Therefore, investigation of the impacts of human activities on water and land resources is important for both economic development and ecosystem protection in the oasis regions.

Earlier studies indicated that human activities altered land use and land cover (Roy & Tomar, 2001; Chen, 2002). Subsequently, LUCC affected water resources, including both surface water and groundwater (Sonada et al., 2001; Honisch, 2002; Kampbell et al., 2003). It is important to quantitatively analyze the relationship between LUCC and water resources. More importantly, the identified relationship will help in planning socioeconomic activities and land uses and improve

water resources management in the oasis regions.

RS-GIS technologies have been widely utilized to study LUCC at different scales. Baban et al. (2001) pointed out that RS-GIS techniques could provide reliable information about LUCC. Treitz et al. (1992) applied RS-GIS to study LUCC at the rural-urban fringe. Filho et al. (1995) studied the dynamics of LUCC for a Watershed region. Yang et al. (2002) used RS-GIS to detect LUCC in a metropolitan area. Weiers et al. (2004) assessed wild life habitats at different scales using RS-GIS. RS-GIS techniques have also been used to study the influences of LUCC on groundwater. For example, Thunnissen et al. (1992) applied land cover data in a soil and groundwater vulnerability assessment system based on a RS-GIS method. Khairy et al. (2001) combined RS-GIS with a soil and water assessment tool for the management of land practices. It is seen that integrated remote sensing and GIS techniques can effectively deal with spatial and temporal information related to the changes of LUCC.

In western China, drought areas and deserts distribute broadly due to insufficient precipitation. The oasis regions are the places where population, economy and cultures grow quickly. Since the implementation of new policies of developing the West of China in 2000, there have been tremendous developments. However, water resource quantity and quality have limited the development. More attention should be paid to the history and evolution of the oases to achieve sustainability.

An integrated RS-GIS approach is developed in this study to: (1) analyze the LUCC and quantify variation of groundwater table and groundwater quality in the SanGong Oasis Region based on historical records from 1978 to 1998 and remote sensing imagery data; (2) assess the effects of LUCC on the change of groundwater resources in the arid and semi-arid areas; and (3) provide decision support for the socioeconomic, water resources, and environmental management in the western China.

Analysis of impact of LUCC on groundwater resources in the SanGong Oasis Region

Study site

The SanGong Oasis Region (43°09′ - 45°29′ N, 87°47′ - 88°17′ E) is located in the northern part of Xinjiang Uygur Autonomous Region, which lies in the west of China (Fig. 1).

The SanGong Oasis Region has a transitional landscape of mountainous regions, oasis and desert. The mountains are located in the south of the region and desert lies in the north. Between the mountains and desert are an alluvial-diluvial fan, a groundwater overflow zone, and an alluvial plain (Fig. 2), which make up of the oasis.

Fig. 1. The study site ‘

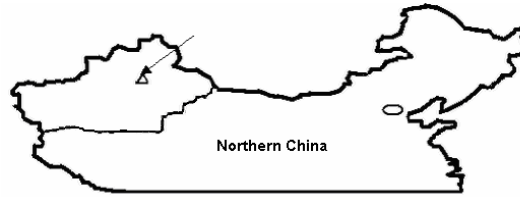
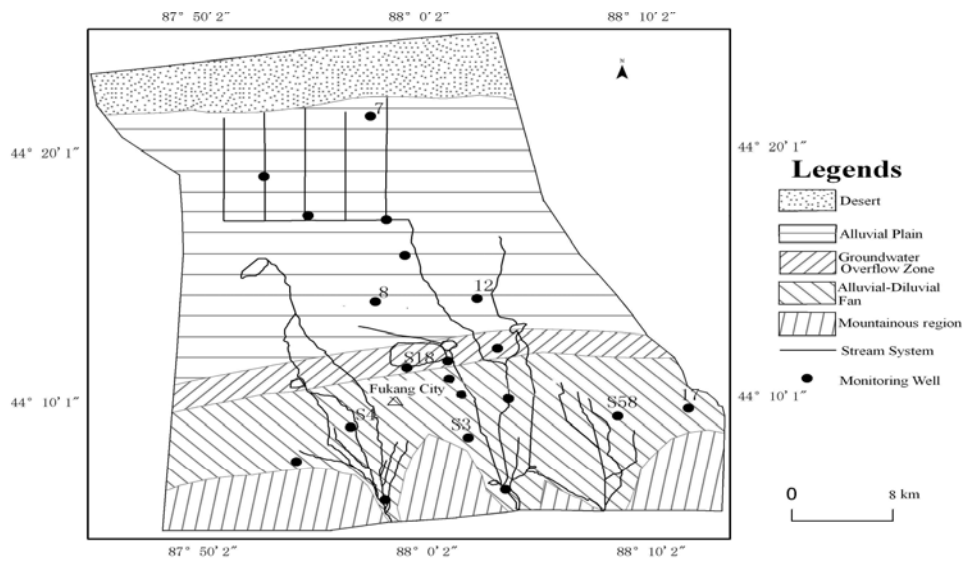


Fig. 2. The SanGong Oasis Region ‘



Total area of the region is 1 670 km²; the oasis covers 870 km². The region is typically arid with an average annual temperature of 6.9°C, the annual precipitation and evaporation are 216 mm and 1840 mm, respectively. A hydrogeological overview of this area is (Luo 2002): (1) in alluvial-diluvial-fan zone, thick and loose Quaternary sediments are found due to deposition, storage of groundwater and groundwater quality are good, and the groundwater table depth is usually more than 10 m. Groundwater is mainly recharged by surface runoff; (2) in groundwater overflow zone, coarse and fine grains are found alternately along the strata, where there are both unconfined and multi-layer confined aquifers. The lateral recharge is dominant and the hydraulic gradient is small. Also, shallow groundwater is connected with springs or swamp in many locations; (3) in the alluvial plain, shallow unconfined aquifer is distributed extensively and its water table is 1~3 m under the surface. Groundwater moves slowly in the horizontal direction, with drainage controlled by evaporation.

Data collection and analysis

The data used in the study involve RS imagery and hydrologic data. It includes 65 aerial

photographs (1:35 000) of the SanGong Oasis Region taken in 1978, a LANDSAT Thematic Mapper (TM) image acquired in 1987, and a LANDSAT Enhanced Thematic Mapper (ETM) image obtained in 1998 (bands 4, 3 and 2). The photographs and images were processed by ERDAS IMAGE software and the topographic map (1:50 000) to generate the composite images of 1978, 1987 and 1998, respectively, with identical projection coordinates (Transverse Mercator Projection) and scale (1:50 000).

The hydrologic information was derived from monitoring stations in the SanGong Oasis Region, which include water table data in the oasis during 1978~2003, groundwater quality data in the period of 1983~2002, groundwater discharge data in the Yuergou water source field from 1970 to 1990, and groundwater discharge data in Fukang City in the period of 1982~1990.

RS-GIS analysis

Combined localized information and field visits, the LUCC patterns in the SanGong Oasis Region in recent 20 years were determined from interpretation of the rectified images of 1978, 1987 and 1998. A number of tools were used during the RS imagery processing and spatial analysis including ERDAS IMAGINE 8.5 and ArcGIS 8.3 packages. The classification of land use was conducted according to the classification guidelines in the National Guide of Survey of Land Use in China. Following the guidelines, LUCC categories in the study area were classified into irrigated lands, shrubbery lands, natural grasslands, cities, towns, rural residential areas (including industrial/mineral lands), desert grasslands, saline and alkaline lands, swamp lands. ERDAS IMAGINE 8.5 and ArcGIS 8.3 were used extensively to obtain a LUCC distribution through the following steps:

- (1) land use/ cover categories were input into ERDAS IMAGINE 8.5 software to obtain the classification vector maps of LUCC of 1978, 1987 and 1998;
- (2) vector maps of LUCC were analyzed using GIS spatial analysis; and
- (3) temporal and spatial LUCC was quantified and used for further analysis in this study.

Spatial interpolation analysis

The spatial interpolation analysis is usually used to transform the discrete data to the sequential data so as to compare with the distribution patterns of other spatial objects. This technique was utilized to address the spatial distribution of mineral content in groundwater. Specifically, an inverse distance weighted (IDW) interpolation method was proposed to process discrete mineralization data of groundwater systems (Lam, 1983):

$$F(x, y) = \frac{\left[\sum_{i=1}^n W(L_i) Z_i \right]}{\left[\sum_{i=1}^n W(L_i) \right]} \quad (1)$$

where $W(L_i)$ is the weighting function; L_i is the distance between point i and point (x, y) ; Z_i is the measured value at point i ; $F(x, y)$ is the interpolated value at the point (x, y) .

Groundwater mineral content and mineralization rate were selected in this study to show the changes of local groundwater quality with time and location and the possible impacts from LUCC. Specifically, historical data of groundwater mineral content in different wells were processed using the spatial analysis module of ArcGIS 8.3. An IDW interpolation method was used to interpolate the measured data and obtain the spatial condition of groundwater mineralization in 1987 and 1998, respectively.

Similarly, groundwater storage was analyzed based on the changes of water table observed in a number of monitoring wells from 1978 to 1998. Outputs from the geospatial analysis include both tabulated database and GIS maps. Subsequently, both statistical and GIS spatial analyses were used to study the impacts of LUCC on groundwater resources.

Results and discussions

Results

Temporal and spatial analysis of LUCC

Table 1 shows the results of LUCC analysis for the SanGong Oasis Region using the RS-GIS method. It indicates that the area of cities, rural residential areas, irrigated lands, and shrubbery lands increased significantly in the study period. Especially, the area of cities changed by twelve times from 1.42 km² in 1978 to 17.19 km² in 1998. This is mainly because of the growth and expansion of Fukang City and the development of petroleum industry in the SanGong Region. Also, the areas of desert grasslands and saline and alkaline lands reduced by 42.85 km² and 29.72 km² during the period of 1978~1998, respectively.

A multi-temporal analysis was further conducted to examine the details of LUCC for the study area. It showed that irrigated land, cities, towns, rural residential areas increased continuously during the period of 1978-1998. However, the shrubbery lands and swamp lands expanded from 1978 to 1987 but decreased from 1987 to 1998. Desert grasslands decreased by 25% in the period of 1978-1987 and increased by 8% in the period of 1987-1998. Saline and alkaline lands kept decreasing from 65.75 km² in 1978 to 55.82 km² in 1987 and to 36.03 km² in 1998. According to Figure 2, the expanded irrigated lands were mainly in the alluvial-diluvial-fan and the upper part of the alluvial plain; the enlarged cities and rural residential areas were in the alluvial-diluvial-fan. The reduced area of desert grasslands and saline or alkaline lands was transferred into the regions of cities, rural residential areas, irrigated lands and shrubbery lands. The shifted regions were principally located in the upper part of the oasis; the alluvial-diluvial-fan, groundwater overflow zone and upper part of the alluvial plain.

Table 1. Land use and land cover change in the SanGong Oasis Region (km²)

Categories	Area in 1978	Area in 1987	Area in 1998	1978-1987 area changes	1987-1998 area changes	1978-1998 area changes
Irrigated lands	221.92	240.90	250.89	18.98	9.99	28.97
Shrubbery lands	137.80	162.73	146.54	24.92	-16.18	8.74
Natural grasslands	130.06	129.25	128.03	-0.80	-1.22	-2.03
Cities	1.42	6.56	17.19	5.14	10.63	15.77
Towns	1.00	2.10	2.87	1.10	0.77	1.87
Rural residential areas	16.86	28.58	32.28	11.72	3.70	15.42
Desert grasslands	232.29	174.07	189.45	-58.23	15.38	-42.85
Saline and alkaline lands	65.75	55.82	36.03	-9.93	-19.78	-29.72
Swamp lands	5.91	16.94	10.32	11.03	-6.62	4.41

Variation of groundwater level

The temporal and spatial change of groundwater level were assessed from 8 monitoring wells, which are located in the alluvial-diluvial-fan (i.e., wells labeled S3, S58, S4 and 17 in Fig. 2), the groundwater overflow zone (i.e., wells labeled S18 in Fig. 2), the upper part of alluvial plain (i.e., wells labeled 8, 7 in Fig. 2) and the oasis-desert ecotone (i.e., wells labeled 12 in Fig. 2). The results of groundwater level changes in the recent 25 years are shown in Figure 3 and Figure 4.

Fig. 3. Changes of groundwater level of the alluvial- diluvial fan area

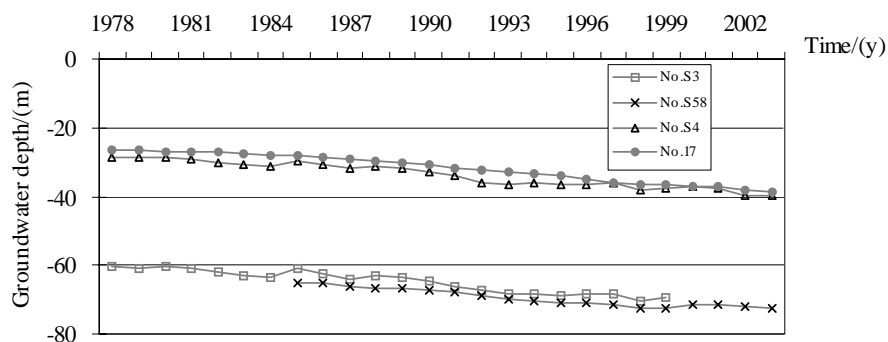
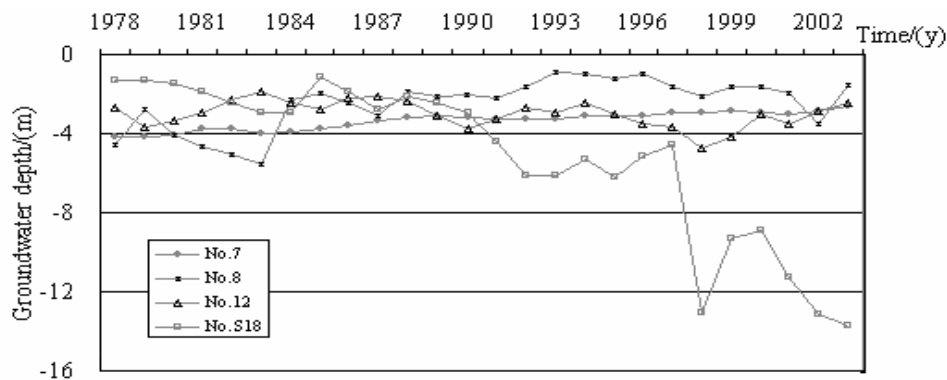


Fig. 4. Changes of groundwater level of the groundwater overflow zone and the alluvial plain

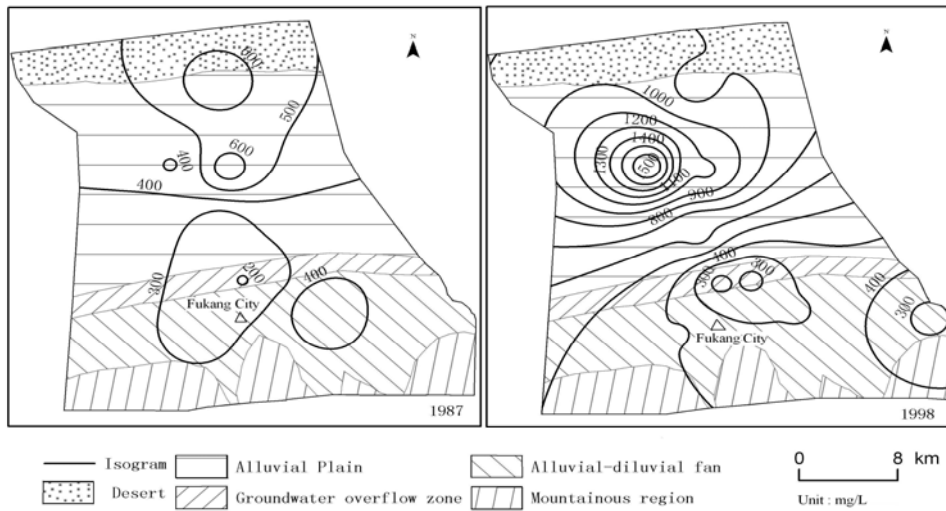


Spatial analysis of the changes shows: (1) water table in the central part of the alluvial-diluvial-fan (i.e., wells S3 and S58) descended from -60 m in 1978 to -72 m in 2003, a drop of 12 meters within 26 years, and declined from -26 m in 1978 to -40 m in 2003 in the lower part of the alluvial-diluvial-fan (i.e., wells S4 and 17) (Figure 3); (2) the largest decrease in water table occurred in the groundwater overflow zone (e.g., well S18). Multi-temporal analysis showed that groundwater level declined annually by 16 cm from 1978 to 1987, with an abrupt annual drop of 72 cm after 1990; (3) the groundwater depth in oasis-desert ecotone (e.g., well 12) fluctuated between -2 m and -5 m over 20 years, and was an average of -3 m lower (Figure 4); (4) in the alluvial plain, the groundwater changed little but had an increasing trend. For example, the groundwater level in the well 8 was -5.57 m in 1983 and increased to -0.86 m in 1993. The groundwater level in the well 7 was also raised by 7 cm annually (Figure 4).

Changes of groundwater quality

Groundwater quality represented by its mineral content has been measured since 1983 in the SanGong Region. The mineralization of groundwater was analyzed using a geospatial method to relate LUCC to the change of groundwater quality in 1987 and 1998. Figure 5 shows that mineral content of groundwater in the SanGong Oasis Region varied significantly during the period of 1987-1998. The degree of mineralization represented by CaCO_3 increased from 400 mg/L in 1987 to 900 mg/L in 1998 on average. The maximum increment was over 200%. In general, the mineral content is low in the southern part of the oasis but high in the northern area. For instance, groundwater mineral content in the alluvial-diluvial-fan changed from an average of 300 mg/L in 1987 to an average of 500 mg/L in 1998, and in the alluvial plain it varied from an average of 500 mg/L in 1987 to 1,100 mg/L in 1998. It is clear in Figure 5 that groundwater quality in the alluvial plain has deteriorated.

Fig. 5. Total mineral content of groundwater in 1987 and 1998



Discussion

Impacts of LUCC on groundwater level

Although annual recharge of groundwater in the SanGong Oasis Region does not change significantly for the recent 25 years, human activities in the oasis region have increased drastically in recent years (Luo 2002). It is seen that LUCC directly affected the groundwater level in the oasis by relating LUCC to the change of groundwater level based on a geospatial analysis. More details are as follows:

- In the alluvial-diluvial-fan part of the oasis, total area of cities enlarged 15 km² during the period of 1978-1998, thus resulting in an increase of the demand of groundwater. According to the statistics of hydrological data, annual withdrawal of groundwater in Fukang city has increased from $1.848 \times 10^7 \text{ m}^3$ in 1982 to $5.259 \times 10^7 \text{ m}^3$ in 1990. Thus, the water table in this part declined about 45 cm a year.
- In the groundwater overflow zone, groundwater level descended rapidly. This zone supplied a large quantity of water for agriculture in the alluvial plain and other land use development in the vicinity of this zone such as the enlarged irrigated lands, shrubby lands, towns and rural residential areas.
- In the alluvial plain, the irrigation of lands in the lower part of the oasis caused the water tables to rise gradually in the last decades.
- Human activities in the oasis-desert ecotone were maintained at similar levels and the groundwater level was relatively stable and fluctuated within in a small range.

Impacts of LUCC on groundwater quality

The LUCC has affected groundwater quality in the SanGong Oasis Region from urbanization and industrial development on the western side. The mineral content of the groundwater has

increased rapidly from incorporation of domestic sewage and wastewater. In the alluvial plain the mineral content increased 100% to over 200% as shown in Figure 5, because agricultural and irrigated lands have used chemical fertilizers and pesticides.

Topography influences the groundwater mineral content in the SanGong Oasis Region. The total area of cities in the upper part of the oasis had a growth of 10.63 km² and the irrigated lands enlarged by 9.99 km² in the period 1987-1998 (Table 1). The change of mineralization in the upper oasis was not significant. By comparison, the groundwater mineral content in the lower part of the alluvial plain increased as shown in Figure 5. Surface topography and hydrology indicate that groundwater moves from the alluvial-diluvial fan to alluvial plain, accumulating minerals in the lower part of the oasis.

Conclusions

In this study, a geospatial analysis approach based on RS-GIS technology has been applied to the SanGong Oasis Region in the Northwest China with the following conclusions:

- Recharge into groundwater did not change significantly during the period from 1978 to 1998 for the study area. However, both LUCC and groundwater level had remarkable variations in the SanGong Oasis Region, and their changes were correlated to each other spatially and temporally in the past two decades.
- Increases of urbanization and industrial activities are directly responsible for the decrease in the water table and deterioration of groundwater quality.
- The relation between the LUCC and the change of local groundwater resources has been examined for study region. The findings are helpful in understanding sustainability-related problems and identifying effective management options for the arid and semiarid areas in the Northwest China.

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