The dynamic of groundwater level in the lower reaches of Tarim River affected by transported water from upper reaches

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Abstract: Using the grey system theory and the observed data from the monitoring section of Yingsu, the paper studied the dynamics of groundwater level in the lower reaches of Tarim River affected by transported water from upper reaches. The main findings are as follows: 1) the groundwater level has revealed an upward trend versus time since 2000, but downward trend versus the distance from the river centre at the same time; 2) the discharging volume, running days of water diversion and discharging water per day, are the three main parameters that markedly affect the groundwater level; 3) transported water from upper reaches not only markedly raised the groundwater level near river bank, and caused the groundwater level rising within the range of 1,050 m from the river centre.

Keywords: dynamics; groundwater level; Tarim River; water diversion; grey system.

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1 Introduction

Groundwater is a complex dynamic system. Generally, groundwater levels are dynamic responses of a groundwater system to its input (i.e., recharge) and output (i.e., base flow or groundwater discharge to rivers and streams). The recharge process is affected by various hydrological processes (i.e., precipitation, evaporation, transpiration, runoff, infiltration, and soil moisture that in turn depend on atmospheric temperature and pressure, solar radiation, wind speed, topography, land use and land cover, etc.) and by the hydraulic properties of soils and aquifers (i.e., hydraulic conductivity and porosity). These natural processes and properties vary at different spatial and temporal scales and their variations affect fluctuations of groundwater levels and base flow directly or indirectly. As a result, groundwater levels and base flow may vary over multiple spatial and temporal scales with no single characteristic spatial and temporal scale (Li and Zhang, 2007). From this, it can be seen that modelling the dynamic of groundwater and surface water interactions is a complex problem that requires detailed understanding of the hydrological processes involved (Ritter and Muñoz-Carpena, 2006).

Many studies have been carried out in arid and semi-arid areas around the world. Farah et al. (1997) assessed the groundwater resources in a semi-arid area by comparing and classifying lithological, hydrogeological, and hydrochemical characteristics. Urbano et al. (2000) studied groundwater – lake interactions in semi-arid environments. Demarsily (2003) analysed the interaction between groundwater and surface water and the behaviour of temporary ponds in arid climates. Oren et al. (2004) investigated groundwater processes in an arid area and drilled several wells to compare natural groundwater with contaminated groundwater. Navarro et al. (2005) calculated the flow geometry by integrating several types of data and developed an effective approach for understanding groundwater dynamics in a semi-arid basin. Berendrecht et al. (2003) used a numerical simulation to investigate the movement and distribution of groundwater, while distributed hydrological models have been used to understand the macro-scale movement mechanism of groundwater (Bogena et al., 2005). Time-series models (Box and Jenkins, 1976) and transfer function-noise (TFN) models (Hipel and Mcleod, 1994; Berendrecht et al., 2003) have both been extensively applied in analysing groundwater dynamics. Liu et al. (2007) conducted a simulation using a coupled MIKE SHE/MIKE 11 model over 112 days of the flood season and calculated the average water balance.

Based on the pioneer study, we think the dynamic of groundwater level in the lower reaches of Tarim River is even more complicated system, which is controlled and affected by not only various nature process but also various human activities. Especially, water diversion project from upper reaches of Tarim River has been an assignable cause since 2000, which controlled and affected the groundwater in lower reaches (Chen et al., 2006; Xu et al., 2004).

In order to prevent desertification, protect and rehabilitate the ecosystem in the lower reaches of Tarim River, which is the most important water source of semi-arid Xinjiang, China central government launched an emergency water diversion programme in 2000. So far, there have been 11 times[1] human water diversion project from Daxihaizi reservoir to lower reaches of Tarim River since May 2000. On 2 November 2001, 4th water diversion made water flowing into Taitema Lake which is in lower reaches of Tarim River, which was the first time for water moistening the dried land on the bottom of the lake since it had dried for 30 years. Results show that groundwater level in lower reaches of Tarim River went up obviously under the effect of water diversion (Xu et al., 2004), but modelling studies on dynamic of the groundwater level affected by transported water from upper reaches are insufficient (Xu et al., 2008).

In fact, from the point of view of grey system theory (Deng, 1982, 1985, 1989), the dynamic of groundwater level in the lower reaches of Tarim River affected by water diversion from upper reaches is typical grey system, which maybe provides us one of methods to attempt the problem. As an attempt in this paper, we use the grey system theory to study the dynamic of groundwater level in the lower reaches of Tarim River affected by water diversion from upper reaches.

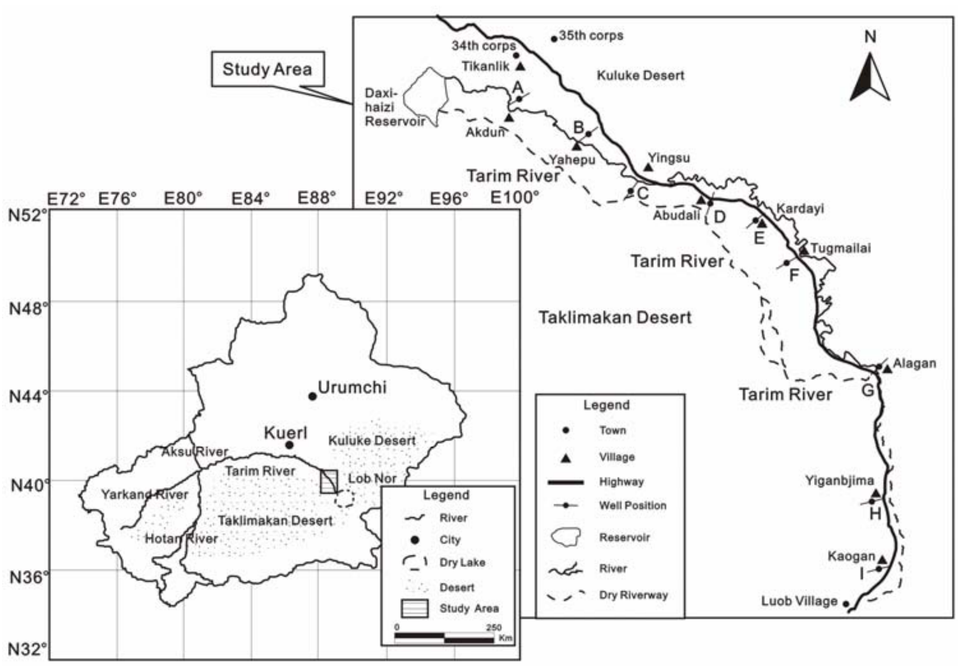
Maybe to figure down the dynamic of groundwater level in all lower reaches of Tarim River based on limited observed data is difficult, this study only looks at the section at Yingsu, which is 45 km away from Daxihaizi reservoir along Tarim River and the running water for every times water diversion crossed here, as focal to reveal the groundwater level dynamic in the lower reaches of Tarim River affected by the water diversion from upper reaches.

2 Study area and data

2.1 Study area

The 1,321 kilometre Tarim River runs west to east along the northern edge of the Taklimakan Desert, China's largest, and flows into Taitema Lake. With a full length of 428 km, the lower reaches of Tarim River are located between Daxihaizi reservoir and Taitema Lake in the lower reaches of the Tarim River (39° 38' ~ 41° 45'N, 85° 42' ~ 89° 17'E). The channel bed stretches from east to south on alluvial fans along the Taklimakan Desert and the Kuluk Desert. The ground-surface is remarkably flat, the elevation decreasing from north to south. Water seeps from streams into the alluvial fans, which can recharge shallow aquifers. The region is classified as an extremely acid warm temperate zone. The annual precipitation varies in the range 17.4 ~ 42.0 mm, and the total annual potential evaporation is approximately 2,500 ~ 3,000 mm. Strong winds blow frequently in the region. The construction of the Daxihaizi reservoir in 1972 reduced the water flow into the Tarim River and dried up a length of 321 km in its lower reaches. The groundwater level fell greatly to a depth of 8~12 m as a result of the lack of recharging through surface runoff for 30 years.

Figure 1 Locations of nine monitoring section along Tarim River in the lower reaches



Because of the intensive exploitation and utilisation of water resources in the Tarim River watershed in the past five decades, the flow in a 320 km section in the lower reaches has been cut off for a long time, causing a consecutive drying-up of lakes at the tail of the river and a severe drop in groundwater levels. The problem has led to the degradation of environment as well as a heavy reduction in biodiversity and an impairment of the ecosystem structure and functions. Subsequently, many plant communities gradually diminish or completely die away in a turn of grass, shrub and woodland (Li and Yang, 2001), the situation of desertification of this region becomes more and more aggravated (Chen et al., 2003). To save the 'Green Corridor' (the middle and lower sections of the lower reaches of the Tarim River are located in the zone between the Taklimakan Desert and the Kuluk Desert, the vegetation was profuse here previously and National Highway 218 and the planned Xinjiang-Qinghai Railway pass through this corridor), which is of a strategic significance for the lower reaches of Tarim River, the programme to convey flowing water from Daxihaizi reservoir to lower reaches was started in 2000. The objective is to increase the groundwater level and save the increasingly deteriorating natural vegetation and the seriously damaged ecosystems.

2.2 Data

Under support from China central government and the Government of Xinjiang autonomous region, there have been 11 water diversions from Daxihaizi reservoir to lower reaches of Tarim River since May 2000. Table 1 shows the related information about the water delivery.

Table 1 Water diversion from Daxihaizi reservoir to lower reaches of Tarim River

Times for water diversion	*Running days for water delivery*	*Discharging volume of water ($10^8 m^3$)*	*Discharging water from the mainstream of Tarim River ($10^8 m^3$)*	*Discharging water from Bosten Lake ($10^8 m^3$)*	*Flowing distance (km)*
1	2000-05-14~2000-07-12	0.98	0	0.98	106
2	2000-11-03~2001-02-05	2.25	0	2.25	216
3	2001-04-01~2001-07-06	1.84	0	1.84	310
4	2001-09-12~2001-11-18	1.98	0.35	1.63	357
5	2002-07-20~2002-11-10	3.31	0.86	2.45	357
6	2003-03-03~2003-07-11	3.40	0.97	2.43	357
7	2003-08-04~2003-11-03	2.85	2.85	0	357
8	2004-03-01~2004-07-06	1.02	0.28	0.74	357
9	2005-03-01~2005-07-06	0.52	0	0.52	215
10	2005-08-30~2005-11-02	2.3	2.3	0	357
11	2006-09-25~2006-11-21	2.33	2.07	0.26	357

Notes: The data in the table were sorted out from following sources:

1 Deng Mingjiang. Water rights of Tarim River reflect performance of system and intending wish (in Chinese). http://www.hwcc.com.cn/newsdisplay/newsdisplay.asp?Id=149957.

2 Zhu Xiangmin. The situation about five time's emergency water diversion to the lower reaches from upper reaches of Tarim River (in Chinese). http://www.mwr.gov.cn/ztbd/tlmhjdh/20040403/31471.asp.

3 http://www.tahe.gov.cn/main/ZhiLi_3.asp?id=2278; id=943; id=293.

In order to survey the dynamic of groundwater level in the lower reaches of Tarim River, nine monitoring sections along Tarim River were set up, which are Akdun (section A), Yahepu (section B), Yingsu (section C), Abudali (section D), Kardayi (section E), Tugmailai (section F), Alagan (section G), Yganbjima (section H) and Kaogan (section I), the locations of which are showed in Figure 1. There are several monitoring wells at each section, and there have been 40 to 65 periodical observationsfor groundwater level data in each well since May 2000.

The section C, i.e., Yingsu is the third monitoring section that is 45 km away from Daxihaizi reservoir and the running water for every times water diversion crossed here. So, this paper chose section C as a focal section, where the groundwater level dynamic affected by the delivering water from the upper reaches of Tarim River was studied.

As shown in Table 2, we have observed the groundwater level in eight monitoring wells at section C for seven years since 2000, and obtained hundreds of data. Because of lower elevation, monitoring wells C_1 and C_2 used to overflowed during water diversion, and the groundwater in C_2 is also too sensitive to the channel water because it is too near to the channel, so many observed data from C_1 and C_2 were distorted. In addition, the cover of well C_3 often was locked because of some reason and we had no record for observed data after 2003. So, this paper mainly used the observed data for the depth of groundwater in well C_4, C_5, C_6, C_7 and C_8.

Table 2 Elevation, latitude, longitude, and distance from river centre of monitoring wells

Monitoring well	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Elevation	841	839	845	845	852	850	849	850
Latitude	N40° 26.123’	N40° 25.921’	N40° 25.918’	N40° 25.869’	N40° 25.817’	N40° 25.766’	N40° 25.646’	N40° 25.532’
Longitude	E87° 56.535’	E87° 56.459’	E87° 56.458’	E87° 56.437’	E87° 56.418’	E87° 56.398’	E87° 56.354’	E87° 56.315’
Distance apart from river centre	230	50	150	250	350	450	750	1,050

3 Methods

Grey system theory is a multidisciplinary theory dealing with those systems for which we lack information, which uses a black-grey-white colour spectrum to describe a complex system whose characteristics are only partially known or known with uncertainty (Deng, 1982, 1989; Wen, 2004; Guo, 2005). There are three kinds of information, in which the white information we already know well, the grey information we now know partly, and the black information we do not know at all about it.

The dynamic of groundwater level in the lower reaches of Tarim River affected by water diversion from upper reaches is controlled and related by many factors, which is a very complicated and lots of them are not known well. From the point of grey system theory, the dynamic of groundwater in the lower reaches of Tarim River is typical grey system (Xu, 2002). As an attempt, the grey system theory maybe provides us one of methods to approach the problem. Therefore, this paper uses the grey relational analysis and grey modelling methods to study the dynamic of groundwater level in the lower reaches of Tarim River affected by water diversion from upper reaches.

3.1 The grey relational analysis

It is impossible to build models for all uncertain factors with grey system method. Therefore, grey relation analysis is involved in selecting most important factors such as the objects for study. In grey relation analysis, influencing factors are represented by time series. Grey relation is the indefinite relationship among the time series. The aim of grey relational analysis is to study the affecting degree of comparative series to reference series. A parameter called grey relation degree is used to represent propinquity of two series. If the relation degree of one series is higher than that of other, it places greater influence on reference series, and will be chosen for modelling (Deng, 1985; Wong and Lai, 2000).

For reference series $\{X_1^{(0)}(t) \mid t = 1, 2, ..., n\}$ and influence series $\{X_i^{(0)}(t) \mid i = 2, 3, ..., m; t = 1, 2, ..., n\}$, the following formula is used to calculate relation parameters of two series:

$$\xi_{1i}(t) = \frac{\min_i \min_t \left| X_1^{(0)}(t) - X_i^{(0)}(t) \right| + k \max_i \max_t \left| X_1^{(0)}(t) - X_i^{(0)}(t) \right|}{\left| X_1^{(0)}(t) - X_i^{(0)}(t) \right| + k \max_i \max_t \left| X_1^{(0)}(t) - X_i^{(0)}(t) \right|} \tag{1}$$

where k is a grey parameter is between 0 and 1, which is often assigned a value as 0.5 for calculation.

With relation parameters, we can calculate grey relation degree of each influence series to reference series:

$$\gamma_{1i} = \frac{1}{n} \sum_{t=1}^{n} \xi_{1i}(t) \tag{2}$$

It is necessary to point out that the data of each series should be normalised before doing the grey relational analysis. There are several methods for normalising the data, and one of methods for data normalised by mean value is as following:

$$x_i^{(0)}(t) = X_i^{(0)}(t) / \bar{X}_i^{(0)} \quad i = 1, 2, \ldots, m \tag{3}$$

where $\bar{X}_i^{(0)}$ is the average value of $X_i^{(0)}(t)$.

3.2 The GM (1, m) model

The grey relational analysis reveals the propinquity relationship for the reference factor $X_1^{(0)}(t)$ among its related factor $X_2^{(0)}(t), ..., X_m^{(0)}(t)$, but cannot mathematically describe the dynamic relationship among of them. The GM (1, m) model can mathematically describe the dynamic relationship between the characteristic variable and its related factors.

According to the principle of grey modelling (Deng, 1982, 1985, 1989), the first order accumulated generating series $X_2^{(1)}(t)$, $X_3^{(1)}(t)$, ..., $X_m^{(1)}(t)$, is defined as following:

$$\begin{aligned} X_2^{(1)}(t) &= \sum_{i=1}^{t} X_2^{(0)}(i), t = 1, 2, \ldots, n \\ X_3^{(1)}(t) &= \sum_{i=1}^{t} X_3^{(0)}(i), t = 1, 2, \ldots, n \\ &\cdots\cdots \\ X_m^{(1)}(t) &= \sum_{i=1}^{t} X_m^{(0)}(i), t = 1, 2, \ldots, n \end{aligned} \tag{4}$$

According to the principle of GM (1, m) model (Deng, 1982; Guo, 2005), the relationship between $X_1^{(1)}$, $X_2^{(1)}$, ..., and $X_m^{(1)}$ can be described by the following differential equation:

$$\frac{dX_1^{(1)}}{dt} + a_1 X_1^{(1)} = \sum_{i=2}^{m} a_i X_i^{(1)} \tag{5}$$

where $a = [a_1, a_2, a_3]^T$ can be obtained by the least squares estimation as

$$a = \left([B(n-1,m)]^T B(n-1,m)]\right)^{-1} [B(n-1,m)]^T Y \tag{6}$$

in which

$$[B(n-1,m)] = \begin{pmatrix} -\frac{1}{2}[\sum_{i=1}^{2} X_1^{(0)}(i) + \sum_{i=1}^{1} X_1^{(0)}(i)] & \sum_{i=1}^{2} X_2^{(0)}(i) & \dots & \sum_{i=1}^{2} X_m^{(0)}(i) \\ -\frac{1}{2}[\sum_{i=1}^{3} X_1^{(0)}(i) + \sum_{i=1}^{2} X_1^{(0)}(i)] & \sum_{i=1}^{3} X_2^{(0)}(i) & \dots & \sum_{i=1}^{3} X_m^{(0)}(i) \\ \dots & \dots & & \dots \\ -\frac{1}{2}[\sum_{i=1}^{n} X_1^{(0)}(i) + \sum_{i=1}^{n-1} X_1^{(0)}(i)] & \sum_{i=1}^{n} X_2^{(0)}(i) & \dots & \sum_{i=1}^{n} X_m^{(0)}(i) \end{pmatrix}$$

$$Y = [X_1^{(0)}(2), X_1^{(0)}(3), \dots, X_1^{(0)}(n)]^T$$

The approximate time response function is as following:

$$X_1^{(1)}(k+1) = \left[X_1^{(0)}(1) - \frac{1}{a_1}\sum_{j=2}^{3} a_j X_j^{(1)}(k+1) \right] \exp\left(-a_1 k\right) + \frac{1}{a_1}\sum_{j=2}^{3} a_j X_j^{(1)}(k+1) \tag{7}$$

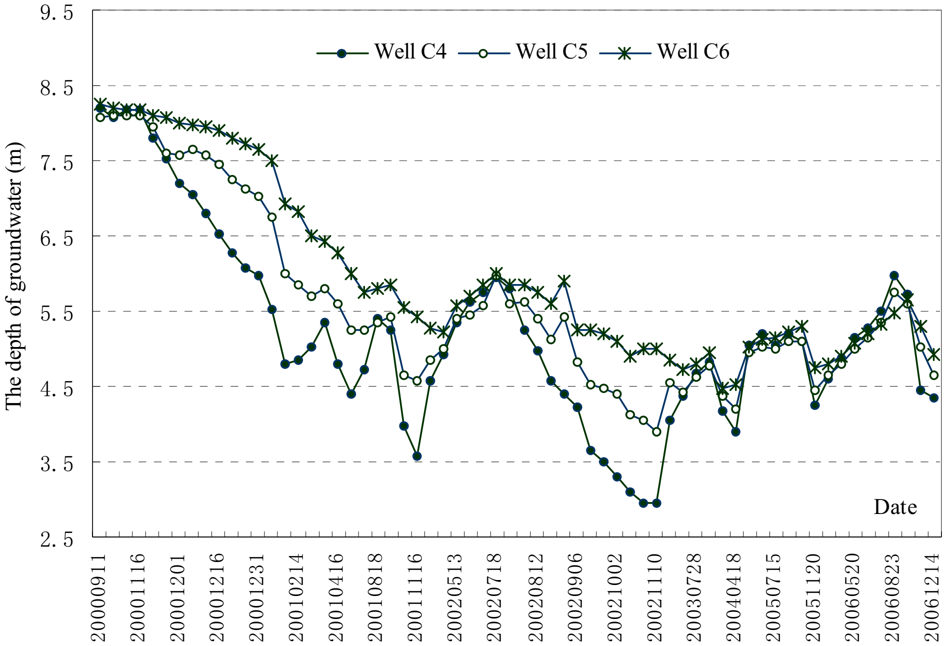
4 Results and discussion

4.1 The groundwater level and its change trend

Analysing the observed data from each monitoring well at Yingsu section, we arrive at a basic fact that the depth of groundwater in all wells has diminished as a whole since May 2000 when the project of water diversion from Daxihaizi reservoir to lower reaches of Tarim River was started.

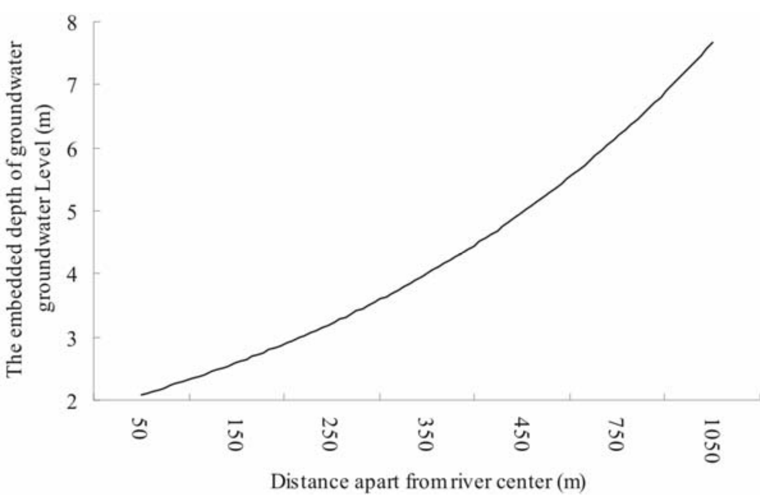
Figure 2 shows the trend of groundwater level in wells C4, C5 and C6 at Yingsu (section C), it tells us the groundwater level has markedly ascended in the wake of water delivery, but the response of groundwater level in each monitoring well to water diversion is different. It is evident the depth of groundwater in each well becomes more and more shallow since the first time water diversion in May 2000, and that in well C4 is always lower than in well C5, that in well C5 is always lower than that in well C6. The results are corresponding to Chen et al. (2004). The results imply laws in two aspects: the depth of groundwater is diminishing trend versus time since the first time water diversion, but at the same time, the groundwater level is falling trend versus the distance from river centre.

Figure 2 The depth of groundwater for monitoring well C4, C5, and C6 at section C, Yingsu (see online version for colours)



Using the observed data of groundwater level in each monitoring well at the end day of fifth water delivery 2002-11-10 when the depth of groundwater became relatively stable, we have fitted a curve in Figure 3, which shows the depth of groundwater versus the distance apart from river centre at section C, Yingsu. It is evident that the groundwater level becomes lower versus the distance from river centre.

Figure 3 The depth of groundwater versus the distance from river centre at the monitoring section C, Yingsu



Using the monitoring data of the depth of groundwater in each well at the end day of fifth water delivery, we also calculated the following regression equation:

$$X_1^{(0)} = 1.6797e^{0.217D} \qquad R^2 = 0.9888 \tag{8}$$

where $X_1^{(0)}$ is the depth of groundwater, and D is the distance from river centre.

According to the study result from Chen et al. (2004), the response range of groundwater level to water delivery is about 1000 m from the river channel, so the upper empirical formula (8) should be used in the range. In fact, because the distance apart from river centre of all monitoring wells at Yingsu section does not exceed 1,050 m, not only formula (8) but also all the results and conclusion of this paper should be restricted to a range of less than 1,050 m from river centre.

4.2 The main factors of water delivery affecting groundwater level dynamic

In order to reveal the effect of related factors of water delivery from upper reaches of Tarim River to groundwater level at Yingsu section, we supposed X_1 represent the depth of groundwater, X_2 represent discharging volume of water, X_3 represent running days for water delivery, X_4 represent discharging water per day, X_5 represent discharging water from the mainstream of Tarim River, and X_6 represent discharging water from Bosten Lake, and calculated grey relation degree of each related factors to groundwater level. The calculated results for grey relation analysis are shown in Table 3.

Table 3 Grey relation degree of each related factors to groundwater level

Well	γ_{12}	γ_{13}	γ_{14}	γ_{15}	γ_{16}
C4	0.7430	0.8553	0.7124	0.5693	0.6054
C5	0.7537	0.8387	0.7190	0.5723	0.6297
C6	0.7541	0.8329	0.7274	0.5806	0.6505
C7	0.8326	0.9181	0.8501	0.6637	0.7839
C8	0.8396	0.8997	0.8569	0.6733	0.8334

From Table 3, we found that the descending order for grey relation degree in wells C4, C5 and C6 is as $\gamma_{13} > \gamma_{12} > \gamma_{14} > \gamma_{16} > \gamma_{15}$, and that in wells C7 and C8 is as $\gamma_{13} > \gamma_{14} > \gamma_{12} > \gamma_{16} > \gamma_{15}$. The results of grey relational analysis show that main three factors related with water delivery from upper reaches of Tarim River, which affect the depth of groundwater, are discharging volume of water X_2, running days for water delivery X_3 and discharging water per day X_4.

4.3 Groundwater level dynamic affected by water diversion

From the point of view of logical relation, it is evident that discharging water per day X_4 is correlated with discharging volume of water X_2 and running days for water delivery X_3, so we should eliminate X_4 for modelling the dynamic relationship mathematically between groundwater level and its affected factors.

In order to study the effect of water diversion on groundwater level dynamic and reveal the relationship between groundwater level and discharging volume of water and enduring days for water diversion, by using $X_1^{(0)}(t)$ to represent the highest-level of groundwater that caused by t^{th} water delivery, $X_2^{(0)}(t)$ to represent discharging volume for t^{th} water delivery, and $X_3^{(0)}(t)$ to represent the running days for t^{th} water delivery, we set up the GM (1, 3) model for monitoring wells C4, C5, C6, C7 and C8 at section C, Yingsu. The model and the fitting parameters of it $a = [a_1, a_2, a_3]$ are shown in Table 4.

Table 4 The GM (1, 3) model and its fitting parameters

Well	*Distance apart from river centre (m)*	*Modelling parameters*			*Equation*
		a_1	a_2	a_3	
C4	250	0.2554	0.3711	0.0076	$\frac{dX_1^{(1)}}{dt} + 0.2554X_1^{(1)} = 0.3711X_2^{(1)} + 0.0076X_3^{(1)}$
C5	350	0.5235	0.668	0.0133	$\frac{dX_1^{(1)}}{dt} + 0.5235X_1^{(1)} = 0.668X_2^{(1)} + 0.0133X_3^{(1)}$
C6	450	0.8281	1.129	0.0235	$\frac{dX_1^{(1)}}{dt} + 0.8281X_1^{(1)} = 1.129X_2^{(1)} + 0.0235X_3^{(1)}$
C7	750	1.044	1.7317	0.0345	$\frac{dX_1^{(1)}}{dt} + 1.044X_1^{(1)} = 1.7317X_2^{(1)} + 0.0345X_3^{(1)}$
C8	1,050	1.7544	2.9757	0.0655	$\frac{dX_1^{(1)}}{dt} + 1.7544X_1^{(1)} = 2.9757X_2^{(1)} + 0.0655X_3^{(1)}$

Table 4 shows that all the modelling parameters a_2 and a_3, i.e., the coefficients of $X_2^{(1)}$ and $X_3^{(1)}$ in each equation are positive, which indicate that the discharging volume and running days for water delivery from upper reaches of Tarim River are two main factors that markedly control and affect the groundwater level.

From Table 4, we also find all of the modelling parameter a_1 appears a gradually increasing trend versus distance from river centre. The result implies food for meditation that the response degree of groundwater level changing to itself was reduced versus the increase of the distance from river centre. In other words, the sensitivity of groundwater level changing respond to itself becomes more and more lower versus the distance from river centre, which is corresponding to the study conclusions of Chen et al. (2004) and Xu et al. (2004).

We also know that from Table 4 the modelling parameters a_2 and a_3 gradually increase versus the distance from river centre. The results imply that the effect of the discharging volume and running days for water delivery to groundwater level changing becomes more significant versus the distance from river centre.

5 Conclusions and recommendations

Through the demonstration study by grey relational analysis and grey modelling at the monitoring section of Yingsu, we think that the grey system theory is really one of the methods for approach to the dynamic of groundwater level in the lower reaches of Tarim River affected by transported water from upper reaches.

From above research results, we elicit the following conclusions:

1 The depth of groundwater as a whole is diminishing trend versus time since the first water diversion in 2000, but at the same time, the groundwater level is falling trend versus the distance from river centre.

2 The results of grey relational analysis show that the discharging volume, running days for water delivery and discharging water per day, which related with water delivery from upper reaches of Tarim River, are three main factors that markedly control and affect the groundwater level.

3 The modelling results based on the GM (1, 3) model show that the sensitivity of groundwater level changing respond to itself becomes more and more lower versus the distance from river centre, and the affection from the discharging volume and running days for water delivery to groundwater level changing becomes more significant versus the distance from river centre.

4 The water diversion from the upper reaches has played an active role in raising the groundwater level in lower reaches of Tarim River. It can clearly be seen that the ecological water conveyance is an effective measure to protect the downstream groundwater.

Based on the above results, some suggestions about the protection of the groundwater in lower reaches of the Tarim River could be put forward as following:

1 It is better to continue implementing the ecological water conveyance project. This study shows that the water from the upper reaches of the Tarim River has played an active role in raising the groundwater level in the lower reaches. Furthermore, groundwater levels near the river channel present an uplift process, and the latitudinal impact range is up to 1,000 m approximately. It can clearly be seen that the ecological water conveyance is an effective measure to protect the downstream groundwater. It is necessary to make full use of the high flow period in Kaidu River annually, by transferring a portion of water resources from the upper reaches to the lower reaches of Tarim River, in order to increasing ecological water there.

2 Water resources in the drainage area should be placed under unified management and scheduling, by centring on the rational allocation of water resources. Firstly, on the aspect of the development and utilisation of water resources in the upper reaches of Tarim River, it should lay equal stress on both surface water and groundwater, and use groundwater in spring mainly while surface water in summer and autumn. Secondly, in the plain of middle reaches, it is better to abandon surface reservoir and change into 'underground reservoir' storage, so as to decrease the unnecessary evaporation. Thirdly, it is necessary to increase the recharge of groundwater to ensure the ecological water in the lower reaches of Tarim River.

3 It is proposed to arrange rationally and make full use of monitoring sites for water environment, and meanwhile it should apply '3S', based on taking monitoring for the utilisation of water resources as the main line and combining with points, lines and planes, to implement monitoring which is focused on the water environmental change of the whole basin. Accordingly, a scientific basis could be provided for unified management and rational configuration of water resources throughout the basin, and protection of the ecology and environment.

4 It is important to implement laws and regulations and law enforcement supervision, and regulate the management behaviour of groundwater resources. Simultaneously, it should be well-considered about the conditions of water resources and carry out the economic restructuring actively and steadily, so as to realise the transformation of economic growth mode and coordinate the contradictions between the economic development and the protection of ecological system.

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Notes

1 Times of water diversion in this paper indicate the periods for continuously diverting of water. The division maybe is different from the division in other reference.