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Research Article

Temporal Stability and Periodicity of Groundwater Electrical Conductivity in Luohuiqu Irrigation District, China

Soil salinization is currently a constraint on agriculture development in irrigated areas throughout the world. This study was conducted to examine the temporal stability and periodicity of groundwater electrical conductivity (EC) in irrigation districts. To accomplish this, 51 observation wells were selected for analysis of groundwater EC. Relative difference analysis and the non-parametric Spearman rank correlation test were used to check EC temporal stability, while the Morlet wavelet analysis was applied to measure the periodic variation of groundwater EC and groundwater level of high and low salinity wells. The mean groundwater EC of the 51 wells did not show an increasing trend over the entire measurement period, but demonstrated a moderate spatial variability, with coefficient of variation values ranging from 61 to 72%. The groundwater EC exhibited a strong temporal stability with Spearman correlation coefficients ranging from 0.81 to 0.98. The mean EC representative location in the study area was well 2, showing a good relationship between groundwater EC and groundwater level. Changes in groundwater EC were mainly affected by lateral groundwater recharge sources in small time scales. However, the groundwater EC and groundwater level always showed an obviously inverse phase with a large time scale due to precipitation effects. In conclusion, the groundwater EC, lateral recharge sources, and irrigation time should be fully considered in irrigation to avoid soil salinization.

Keywords: Arid soils; Irrigation; Morlet wavelet analysis; Semi-arid soils; Soil salinization

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1 Introduction

Soil salinization is an important environmental problem caused by natural or human activities in China and throughout the world, especially in arid and semi-arid regions [1]. Currently, irrigated agriculture accounts for about one-third of the worldwide production of food and fiber and it will have to produce nearly 50% by 2040 to meet demands [2]. Globally, about 10 million ha of irrigated land is abandoned every year because of soil salinization [3–5]; accordingly, soil salinization is currently a constraint on agricultural development throughout the world. In China, 17 million ha of irrigated land is undergoing salinization [6]. Soil salinization reduces soil quality, limits crop growth, constrains agricultural productivity, and in severe cases, leads to abandonment of agricultural soils [7]; accordingly, it has long attracted a great deal of attention worldwide. Soil salinity also induces a reduction in the mineralization of organic carbon, resulting in the release of CO_2 in levels inversely proportional to the salinity of the water supplied [8]. A variety of new techniques have been applied for identifying and monitoring salt affected areas with varying degrees of success [9, 10].

The Luohuiqu Irrigation District is an important agricultural production base on the Guanzhong Plain. In this area, soil salinization is always a potential threat to the development of local agricultural production. Owing to over-exploitation and utilization of human activities, the area of soil salinization and irrigation-induced soil secondary salinization has expanded, threatening sustainable production, land protection, and food security [11]. Exploited land increases groundwater recharge and brings soil-stored soluble salts to the surface [12]. Groundwater salinity and depth are two major factors impacting the dynamic changes in salt content in soil water [6]. Soil salinity can be reduced by leaching soluble salts out of soil with excess irrigation water. Understanding variations in groundwater electrical conductivity (EC) is of great importance to the management of soil salinization in the Luohuiqu Irrigation District.

The concept of temporal stability has been defined as the time-invariant association between spatial location and statistical

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Abbreviations: **CV**, coefficient of variation; **EC**, electrical conductivity; **MRD**, mean relative difference; **SDRD**, standard deviation; **WL**, water level

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parameters of soil properties [13]. This concept was first introduced by Vachaud [14], who assumed that specific locations could represent the mean values of a study site over a period of time. Other scientists later supported this assumption [15–19]. The concept of temporal stability can greatly reduce the number of samples needed to characterize soil water content in a field. Castrignanò studied the temporal stability of EC, Na content, and sodium adsorption ratio of soil salinity [20]. Douaik analyzed the temporal stability of spatial patterns of soil salinity determined from laboratory and field EC and found that low saline conditions were more time-stable, while high saline locations were the least time-stable [13].

Salt-affected soils often occur on irrigated lands, especially in arid and semi-arid regions, where the annual precipitation is insufficient to meet evaporation and the needs of plants [21]. Irrigation water quality is an important factor affecting soil salinization. EC is one of the main indicators to determine whether irrigation water will cause soil salinization. EC also reflects the salt content of water or soil solution. When compared with salinity measurements, EC measurement is reliable, economical and fast; accordingly, EC is a common international standard to evaluate irrigation water quality. However, few studies have investigated the temporal stability of groundwater EC to date. Therefore, the objectives of this study were (1) to assess the temporal stability of groundwater EC, (2) to identify representative locations of groundwater EC, and (3) to analyze periodic variations in groundwater level and EC.

2 Materials and methods

2.1 Description of study area

The Luohuiqu Irrigation District (109°43′–110°19′E, 34°36′–35°02′N) is located in the Wei and Luo River terraces of Guanzhong Plain in Dali County, Weinan City, Shaanxi Province. The study area has an altitude ranging between 329 and 533 m a.s.l. and covers an area of 750 km^2. The area is located within the temperate continental semi-arid climate zone with an average annual temperature of 13.5°C. The mean annual precipitation is 484 mm, the mean annual evaporation is 1690 mm and the mean shallow groundwater table is 4–12 m. The main source of groundwater recharge is rainfall and diversion irrigation and the primary crops are fruit trees and cotton. The entire groundwater flow, which is consistent with the ground slope, is from northwest to southeast.

2.2 Groundwater sampling and analysis

A total of 51 observation wells was selected for analysis of the EC characteristics of groundwater from 2004 to 2010. The distribution of observation wells is shown in Fig. 1. Water samples were collected from 2 m below the well water surface to measure EC and temperature at each site. Based on the EC characteristics of the observed wells, wells 36 (high EC) and 43 (low EC) were selected for long-term observation. A CTD-Diver (Schlumberger Water Services, USA) groundwater level data logger was adopted for measurement and recording of the groundwater level, temperature and EC. The vertical distances of the CTD-Divers to the ground of wells 36 and 43 were 13.5 and 38.2 m, respectively. Morlet wavelet analysis was used to investigate periodic variations in groundwater level and EC.

2.3 Data analysis

Two approaches were used to check for the existence of EC temporal stability in this study: relative difference analysis and a non-parametric Spearman rank correlation test [14].

For the relative differences analysis, EC_{ij} was assumed to be at location i ($i = 1, \ldots, 51$) and time j ($j = 1, \ldots, 18$), and the relative

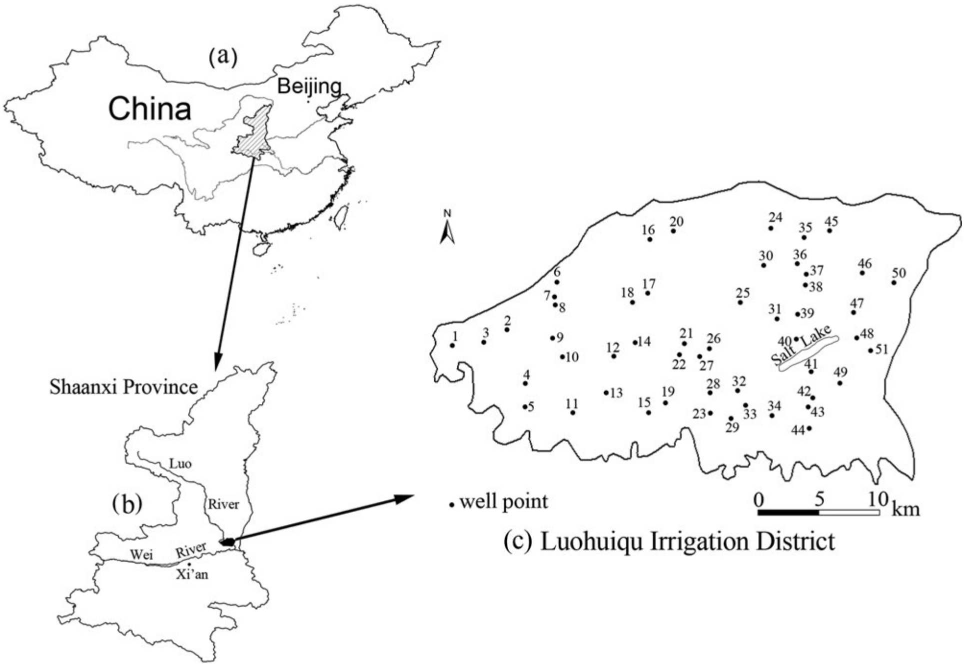


Figure 1. (a, b) Location of the study area in Shaanxi Province, China; and (c) the spatial locations of 51 observation wells in the Luohuiqu Irrigation District.

difference δ_{ij} was defined as:

$$\partial_{\mathrm{ij}} = \mathrm{EC}_{\mathrm{ij}} - \frac{\overline{\mathrm{EC}_{\mathrm{j}}}}{\overline{\mathrm{EC}_{\mathrm{j}}}} \tag{1}$$

where $\overline{\mathrm{EC}_{\mathrm{j}}}$ was the spatial mean value for the time j with n locations:

$$\overline{\mathrm{EC}_{\mathrm{j}}} = \frac{1}{n}\sum\nolimits_{\mathrm{i}=1}^{\mathrm{n}} \overline{\mathrm{EC}_{\mathrm{ij}}} \tag{2}$$

The temporal mean relative difference (MRD) and its standard deviation (SDRD) were defined by:

$$\overline{\partial_{\mathrm{i}}} = \frac{1}{m}\sum_{\mathrm{j}=1}^{m} \partial_{\mathrm{ij}} \tag{3}$$

and:

$$\sigma(\bar{\partial}_{\mathrm{i}}) = \sqrt{\frac{1}{m-1}\sum_{\mathrm{j}=1}^{m}(\partial_{\mathrm{ij}} - \bar{\partial}_{\mathrm{i}})^2} \tag{4}$$

where m is the number of time instants.

The MRD can be plotted against their ranks with the corresponding temporal standard deviations. A small MRD value indicates a time-stable location, while a large value indicates a site with values that are strongly time-variable [13]. The temporally stable locations should be those with the MRD closest to 0 and the minimum associated standard deviations. The locations with MRD values within ± 0.05 were considered to be close to 0 [19, 22]. Another condition for temporally stable locations that must be fulfilled is to have low SDRD values [19].

The second method is based on the non-parametric Spearman rank order correlation (r_{s}):

$$r_{\mathrm{s}} = 1 - \frac{6\sum_{i=1}^{n}\left(R_{\mathrm{ij}} - R_{\mathrm{ik}}\right)^2}{n(n^2-1)} \tag{5}$$

where R_{ij} is the rank of the EC at location i and time j and R_{ik} is the rank of the EC at the same location but for a different time, k ($k \neq j$). This correlation is computed for all possible pairs of measurement times. A perfect temporal stability between time instants j and k is indicated by $r_{\mathrm{s}} = 1$, and a lack of temporal stability implies that $r_{\mathrm{s}} = 0$ [13].

The Spearman rank correlation coefficient is used to describe the similarity among different spatial patterns of groundwater EC at different measuring times, and SDRD reflects the time stability characteristics of specific wells. The Morlet wavelet analysis can be used to determine scale and time series changes of water levels and EC [23]. The Morlet wavelet is defined as [24]:

$$g(t) = \mathrm{e}^{\mathrm{j}2\pi \mathrm{f}_0|\mathrm{t}|}\mathrm{e}^{-|\mathrm{t}|/2} \tag{6}$$

where j is the imaginary unit, f_0 is the wavelet function center frequency, and t is the time.

The Fourier spectrum of the Morlet wavelet is given by the translated Gauss function [25]:

$$G(f) = \sqrt{2}\pi\mathrm{e}^{-2\pi^2}(f - f_0)^2 \tag{7}$$

The EC temporal stability analysis was determined using Microsoft Excel 2003 (Microsoft), SPSS 16.0 (IBM, New York, USA), and OriginPro 8.0 (OriginLab, Northampton, USA). The Morlet wavelet analysis was based on MATLAB.

3 Results

3.1 Descriptive statistics of electrical conductivity

Descriptive statistics describing the EC calculated using 51 wells and 18 time instants are shown in Supporting Information Table S1. The EC of natural water, such as drinking or surface water, typically ranges from 0.01 to 0.1 S/m. The mean EC values over the entire 18 time instants ranged from 0.28 to 0.36 S/m, which was much larger than those of drinking water. The minimum and maximum EC over the entire 18 time instants ranged from 0.08 to 0.11 S/m and from 0.79 to 1.00 S/m, respectively. There was no big difference among the minimum EC values. The maximum and mean EC values also showed a similar situation. The minimum and maximum EC values appeared in well 34 and well 36, respectively. The minimum EC of well 34 showed only a slight difference to that of well 4 when the minimum EC appeared in well 4. The coefficient of variation (CV) can be used to qualitatively ascertain the magnitude of the spatial variability. Specifically, this value is considered weak when CV < 10%, moderate at 10% < CV < 100% and strong when CV > 100% [26]. Hence, the EC of the 51 wells over the entire 18 time intervals demonstrated moderate spatial variability, with CV values ranging from 61 to 72%. The CV values of the minimum, maximum, and mean EC values were 8, 7 and 6%, respectively, all showing weak spatial variability. Moreover, the CV and mean EC of the 51 wells did not show an increasing trend over the entire measurement period.

3.2 Temporal stability using Spearman correlation test

The Spearman rank order correlation is a nonparametric (free distribution) test that can indicate the strength and the direction of the same variable observed at different time instants [13]. The r_{s} values of the 51 wells for 18 time points are shown in Table 1, ranging from 0.81 to 0.98, which was close to 1, indicating that the EC of the 51 wells was of strong temporal stability. The lowest r_{s} values occurred in August 2004. With the exception of the r_{s} values observed in August 2004, no r_{s} values were <0.90. Moreover, the values of order correlation were all highly significant ($p < 0.01$). The Spearman correlation test indicated that the EC of the 51 wells presented strong spatial and temporal stability patterns across the entire measurement period.

3.3 Identification of representative locations based on relative difference analysis

Relative difference analysis was used to quantitatively identify the well that was consistently equal to the mean EC of the study area. Identification of these locations was one of the purposes of the EC temporal stability analysis. The rank ordered MRD and corresponding standard deviation for EC are presented in Fig. 2. The MRD and SDRD ranged from −0.65 to 1.89 and 0.04 to 0.25, respectively. The MRD showed relatively large changes. Specifically, locations 19, 26, and 36 and wells 4 and 34 showed larger and smaller MRD values, respectively, which is consistent with the maximum and minimum

Table 1. Spearman rank order correlation coefficients for EC at 18 time points

Time point	1[a]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1[a]	1.00																	
2	0.90																	
3	0.93	0.96																
4	0.84	0.87	0.87															
5	0.93	0.96	0.97	0.85														
6	0.94	0.95	0.97	0.88	0.96													
7	0.94	0.95	0.96	0.83	0.97	0.97												
8	0.93	0.94	0.95	0.89	0.93	0.95	0.97											
9	0.94	0.93	0.93	0.83	0.96	0.94	0.96	0.94										
10	0.95	0.91	0.93	0.81	0.94	0.95	0.98	0.94	0.96									
11	0.93	0.94	0.92	0.85	0.93	0.94	0.91	0.90	0.93	0.92								
12	0.94	0.92	0.94	0.83	0.95	0.95	0.96	0.94	0.97	0.96	0.95							
13	0.94	0.94	0.96	0.87	0.96	0.97	0.97	0.96	0.96	0.96	0.93	0.97						
14	0.93	0.94	0.95	0.87	0.96	0.96	0.95	0.95	0.96	0.94	0.95	0.97	0.98					
15	0.93	0.92	0.94	0.87	0.94	0.96	0.94	0.93	0.95	0.94	0.95	0.97	0.97	0.98				
16	0.92	0.92	0.93	0.89	0.93	0.94	0.93	0.92	0.95	0.93	0.97	0.98	0.95	0.98	0.98			
17	0.92	0.89	0.91	0.82	0.94	0.92	0.92	0.90	0.92	0.92	0.93	0.95	0.93	0.95	0.97	0.98		
18	0.94	0.89	0.92	0.84	0.94	0.94	0.94	0.91	0.94	0.94	0.95	0.95	0.94	0.94	0.96	0.96	0.95	1.00

Correlations are all significant at $p < 0.01$ (two-tailed).

[a] 1–18 refer to Jan, March, June, and August 2004; March, May, August, and September 2005; March and August 2006; March 2007; March and September 2008; March, September, and December 2009; March and September 2010.

EC results provided in Table 2. These findings indicated that the EC of wells 19, 26, and 36 was always larger than the mean EC of the 51 wells and the EC of wells 4 and 34 were always smaller than the mean EC of the 51 wells. Wells 2, 8, 29, and 40 had MRD values within ± 0.05 and SDRD values of 0.07, 0.11, 0.09 and 0.10, respectively. Therefore, well 2, which also had a small SDRD value, fulfilled necessary conditions for representative locations. Therefore, the mean EC representative location in Luohuiqu Irrigation District was well 2.

3.4 Periodicity of groundwater level and electrical conductivity

The periodicity of the groundwater level and EC was studied based on the wavelet transform. The Morlet wavelet transform of EC and groundwater level anomalies for wells 36 and 43 from March 2, 2008 (day 1) to September 4, 2009 (day 547) are shown in Fig. 3. The wavelet coefficients represent the signal strength. The lighter the contour color was, the higher the wavelet coefficient and EC were, and vice versa. For well 36, the groundwater EC vibrated obviously in the 120 days scale before 200 days. After 200 days, the groundwater EC vibrated obviously in the 200 days scale. The main vibration period of groundwater EC became larger over time. The vibration period was small and the EC changed quickly during March 2008 to September 2008. The vibration period was large and the EC changed relatively slowly during September 2008 to September 2009. The wavelet variance of the corresponding scale was calculated based on the wavelet coefficients of EC. There were three peak values that corresponded to time scales of 90, 200, and 310 days, respectively. The obvious vibration period in the water level (WL) was at about 250 days, while the peak value of wavelet variance corresponded to the time scale of 60 and 300 days. The groundwater EC vibrated

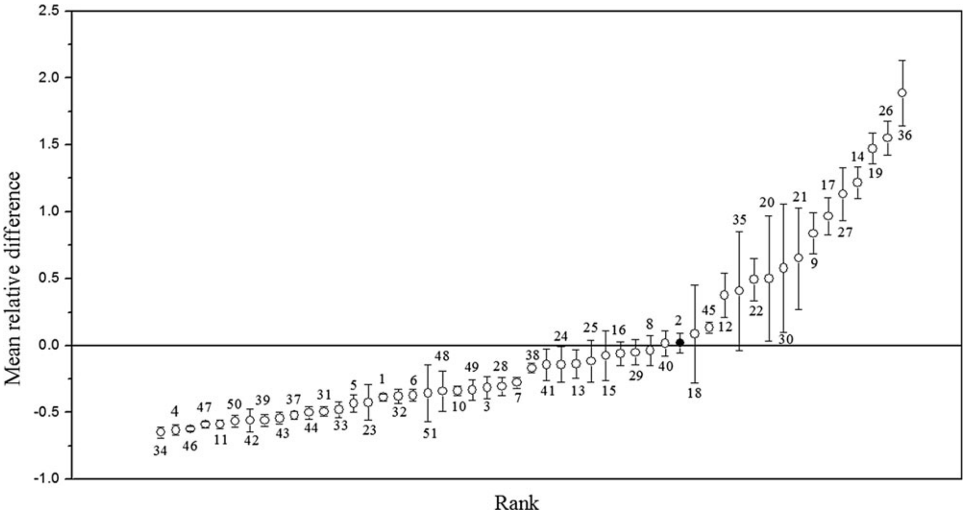


Figure 2. Plots of mean relative differences for EC. Vertical bars represent ±1 standard deviation. Representative locations are marked in black.

Table 2. Descriptive statistics for EC measured of 51 well locations at 18 time points

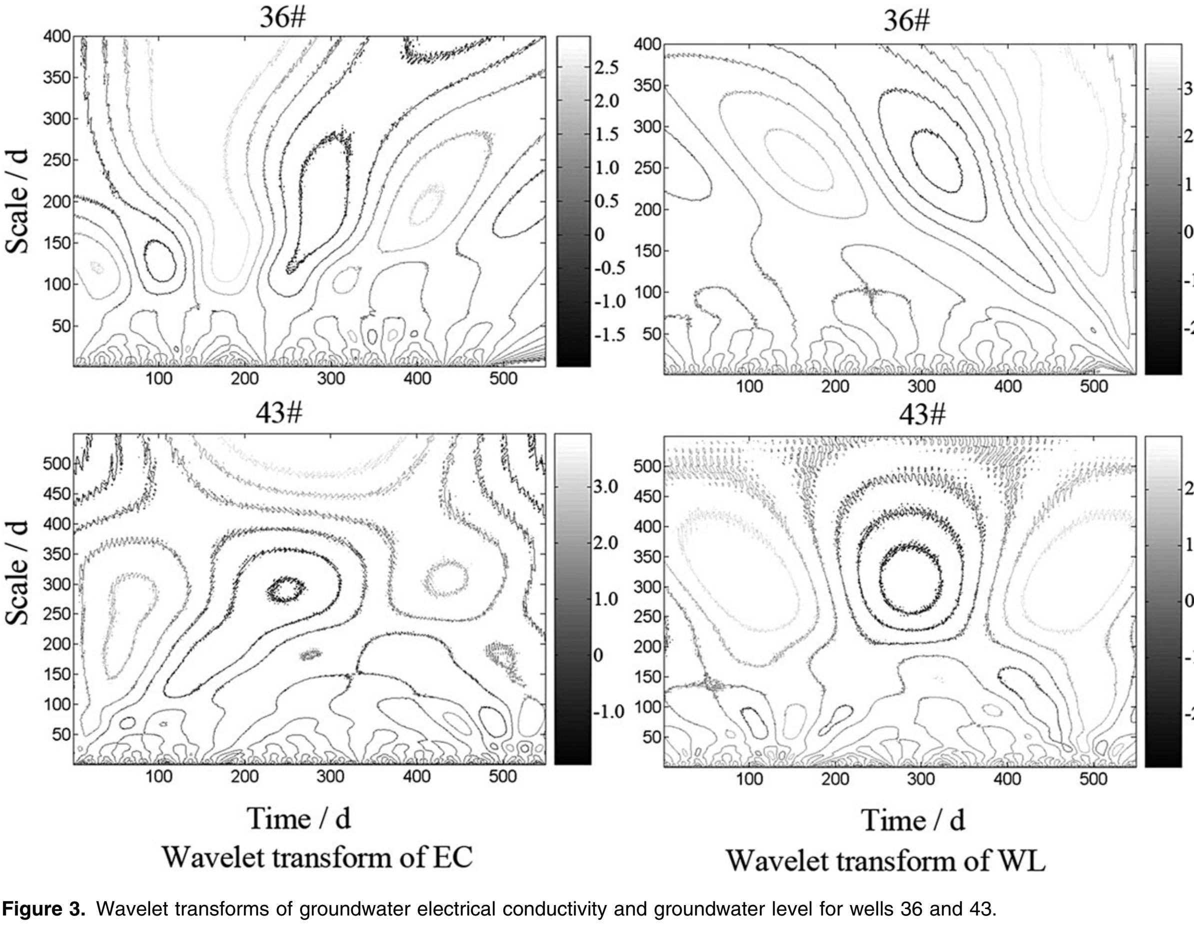
Date	EC minimum (S/m)	EC maximum (S/m)	EC mean (S/m)	CV (%)
01/2004	0.09 (well 34)	0.91 (well 36)	0.28	66
03/2004	0.10 (well 34)	0.92 (well 36)	0.30	64
06/2004	0.10 (well 34)	0.96 (well 36)	0.30	69
08/2004	0.10 (well 34)	0.99 (well 36)	0.30	72
03/2005	0.10 (well 34)	0.92 (well 36)	0.29	64
05/2005	0.10 (well 34)	0.91 (well 36)	0.31	63
08/2005	0.11 (well 34)	0.93 (well 29)	0.33	71
09/2005	0.10 (well 34)	0.94 (well 36)	0.32	68
03/2006	0.11 (well 4)	0.89 (well 36)	0.30	64
08/2006	0.11 (well 4)	0.90 (well 36)	0.32	65
03/2007	0.11 (well 34)	0.87 (well 36)	0.29	65
03/2008	0.11 (well 34)	0.87 (well 36)	0.30	62
09/2008	0.10 (well 34)	0.87 (well 36)	0.30	65
03/2009	0.11 (well 34)	0.82 (well 36)	0.30	62
09/2009	0.11 (well 4)	0.79 (well 19)	0.31	64
12/2009	0.11 (well 4)	0.79 (well 26)	0.30	64
03/2010	0.11 (well 34)	0.81 (well 26)	0.30	61
09/2010	0.08 (well 34)	1.00 (well 19)	0.36	66

obviously in the 300 days scale for well 43, and there were three peak values that corresponded to the time scales of 60, 90, and 280 days, respectively. The obvious vibration period in the water level was about 300 days and the peak value of wavelet variance corresponded to the time scale of 60, 90, and 360 days for well 43. Therefore, the EC and water level indicated different vibration periods in different time scales for wells 36 and 43.

3.5 Response relationship between groundwater level and electrical conductivity on different time scales

Three time scales were selected to analyze the relationship between EC and WL for wells 36 and 43 based on the vibration periods of EC and water level (Fig. 4). Specifically, time scales of 72, 200, and 310 days were chosen for well 36. The water level changed gently and the EC showed relatively large fluctuations on the 72 days scale. The EC and water level indicated a relatively consistent fluctuation, while they showed an opposite trend in the 200 and 310 days scale. On the large time scales, the EC and water level had a better corresponding relationship. Specifically, the EC and water level obviously showed an inverse phase, with the EC decreasing when the water level rose and vice versa.

Time scales of 60, 90, and 300 days were selected for well 43. The EC and water level indicated a consistent trend in the 60 and 90 days scale, with the EC increasing with rising water levels and decreasing with lowering water levels. However, the water level on the 90 days scale showed relatively larger fluctuation than that on the 60 days scale. The EC and water level obviously showed an inverse phase in the 300 days scale, with the EC decreasing with increasing water levels and vice versa.



Wavelet transform of EC

Wavelet transform of WL

Figure 3. Wavelet transforms of groundwater electrical conductivity and groundwater level for wells 36 and 43.

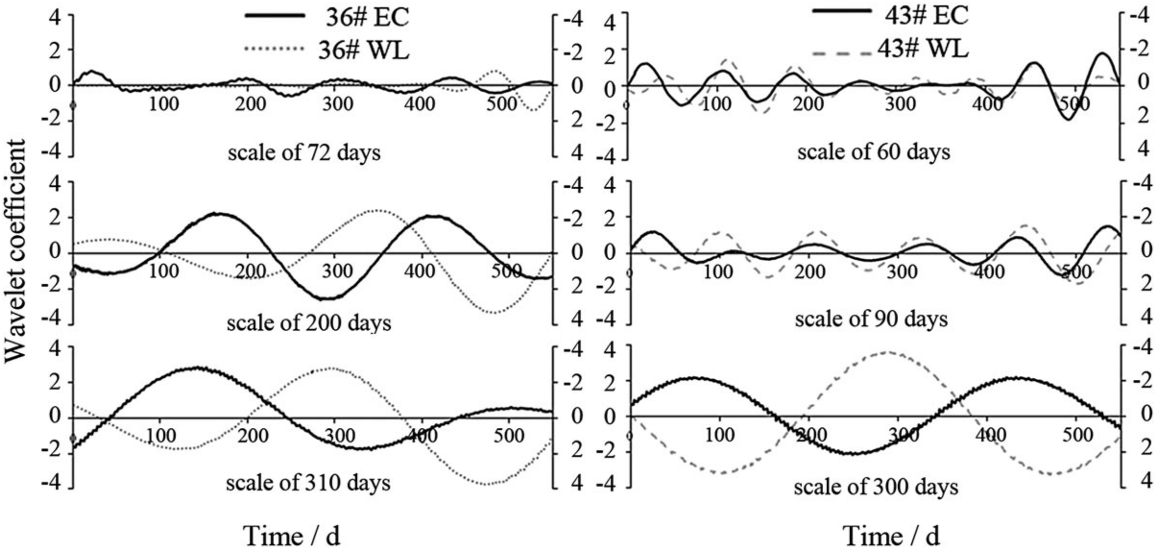


Figure 4. Trends in groundwater level and electrical conductivity at different time scales for wells 36 and 43.

4 Discussion

Based on the classification of salt water for the management of surface and groundwater, non-saline was defined by EC < 0.07 S/m, slightly saline as 0.07–0.2 S/m, moderately saline as 0.2–1.0 S/m, highly saline as 1.0–2.05 S/m, very highly saline as 2.0–4.5 S/m, and brine as EC > 4.5 S/m [27]. Based on the mean EC values of each well measured at the 18 time points, 21 wells were slightly saline and 30 wells were moderately saline (Table 2). These findings indicate that soil salinization was likely when certain wells were used for irrigation.

There was a strong temporal stability of the spatial pattern of groundwater EC across all wells and the entire study period. Well 2 was the mean EC representative location in the study area. This might be due to the fact that well 2 is located near the branch canal, pumped less water for irrigation, had various recharge sources, and the main recharge source was stable. Large EC MRD changes in wells were mainly due to irrigation, unsteady recharge sources, and large EC differences between well water and recharge water.

Based on the analysis of rainfall data, the groundwater level showed a good relationship with rainfall values [28]. The vibration period of EC in well 36 was small from March 2008 to September 2008. The EC in this period indicated rapid changes were related to irrigation and precipitation. The extent of changes in water level and EC for well 43 were relatively small from October 2008 to March 2009 because well 43 is an irrigation well and less water was pumped for irrigation during this period.

Many soluble salts were enriched in the sediments of an ancient lake in the Luohuiqu Irrigation District. The EC values show a ladder-like distribution in the groundwater, with the upper groundwater having low salinity and the lower groundwater high salinity [29]. On small time scales, the EC and water level indicated consistent changes in well 43, which were different from those in well 36. This was mainly due to the different lateral recharge sources for wells 36 and 43. Well 36 was mainly affected by the north lateral groundwater recharge, which was of good water quality and low salinity. When well 36 was recharged by lateral groundwater recharge, the water level rose and the EC decreased. When it was pumped for irrigation, the water level decreased and the EC increased relative to the EC of lateral groundwater. Well 43 was located on the south side of Salt Lake in an irrigation district and its recharge source was affected by the high salinity of the lake. When well 43 was recharged by lateral recharge, the water level rose and the EC showed a corresponding increase. When the well was pumped for irrigation, the water level decreased and the EC decreased compared to the salinity of the lateral recharge source. On large time scales, the relationship between EC and water level in well 43 was similar to that in well 36. The EC and water level showed an obvious inverse phase because the main recharge source of wells 36 and 43 was precipitation on large time scales.

5 Conclusions

In general, the groundwater was slightly or moderately saline in the Luohuiqu Irrigation District. The groundwater EC of the 51 wells demonstrated moderate spatial variability with CV values ranging from 61 to 72%. The groundwater EC of different wells exhibited strong temporal stability. Well 2 was time-stable and also represented the best mean EC. Well 2 has been subject to less pumping for irrigation, has various recharge sources, and a stable main recharge source. The EC and water level indicated different vibration periods on different time scales for both wells 36 and 43. The change in groundwater EC on small time scales was mainly affected by lateral recharge sources. The EC and WL showed an obviously inverse phase on large time scales. Consequently, the groundwater EC, lateral recharge sources, and irrigation time should be fully considered for irrigation to avoid soil salinization.

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