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Dryland river regime shifts in Iran: Drivers and feedbacks

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Abstract

In the Anthropocene, human activities have created unprecedented changes and nonlinear relationships between humans and nature. These changes can be much faster and more intense in arid and semiarid areas that have been affected by intense human activities. Iran has climates from very humid to very dry, but arid and semiarid climates cover the country's largest area. Many of these arid areas have undergone severe changes in their surface and groundwater ecosystems in recent years, which have caused severe damage to humans and the environment in the area and surrounding areas. Therefore, in this study, using the theory of regime shifts, the time series of the Zayandeh-Rud River Basin in the center of Iran were analyzed. First, the data of the desired time series in the period of 1986–2018 was arranged seasonally. Then, using the sequential *t*-test method, regime shifts in these time series were identified, and then, causal loop diagrams of these shifts and their drivers and feedbacks were interpreted. The results showed that in the time series of quantity and quality of surface water and groundwater level in the studied stations and aquifers, regime shifts can be identified. Regime shifts were also identified in the time series of agricultural land area. These shifts have occurred with the increase in human activities since the early 1950s in the metropolis of Isfahan, the increase in agricultural and industrial exploitation, and consequently, the increase in population. When this reinforcing feedback loop becomes dominant, the Zayandeh-Rud River system has shifted from a regime of rich water resources to a regime of poor water resources. However, by recognizing and systematically analyzing these shifts, the Zayandeh-Rud River system can be directed toward a sustainable system through structural reform, negotiation, and redefining goals.

KEYWORDS

causal loop diagrams, social–ecological systems, system dynamics, tipping points, Zayandeh-Rud River Basin

1 | INTRODUCTION

Unprecedented changes in the Anthropocene, especially in social–ecological systems (SESs), arguably have caused the Earth to enter a new geological time interval, and consequently, these systems show novel states and characteristics (Bennett et al., 2016). These changes have been more severe since World War II and have had devastating effects on human livelihoods and environmental security (Biggs et al., 2021). Factors affecting these sudden changes in the Anthropocene include an exponential increase in the human population, technological advancement, and consequently, an increase in consumption and utilization of available natural resources (Steffen et al., 2015).

These changes can be thought of as an intertwined system that can be identified as a human–environmental system on different temporal and spatial scales (Folke et al., 2016; Nyström et al., 2019). These changes and the resulting problems are in line with climate change and other environmental changes, and as a result, they become more intense over time (Biggs et al., 2021). Many global researchers (e.g., Biggs et al., 2018; Reid et al., 2016; Rocha et al., 2015a) have used the system dynamics approach to identify and analyze these changes in different human–environmental or coupled SESs (Gohari et al., 2013; Rebs et al., 2019).

A system can be defined as a set of two or more elements that meet a specific goal in effective interaction and communication with each other (Naderi et al., 2021). These elements have two conditions; first, each element affects the behavior or characteristics of the whole system, and second, there is interdependence between the elements in terms of behavior and the type of impact on the whole system (Meadows, 2008). The interaction of two or more elements with each other and their mutual feedbacks creates balancing or reinforcing feedback loops (Newman et al., 2005). Balancing feedback loops usually cause self-correction and balancing in the system, but reinforcing feedback loops will cause growth or deterioration in the system (Meadows, 2008; Preiser et al., 2018). Therefore, by recognizing a SES in the form of a dynamic system and then recognizing the elements, relationships, and loops of interaction, the occurrence of sudden changes in the Anthropocene can be analyzed.

These sudden changes in systems are known as "regime shifts" (Biggs et al., 2018). These shifts can affect various variables such as economy, security, human health, and general ecosystem services necessary for human societies (Crépin et al., 2012; Meng et al., 2021; Millennium Ecosystem Assessment, 2005). From the point of view of systems thinking, regime shift occurs when one dominant feedback loop in one system is weakened and another feedback loop prevails, which causes a rapid nonlinear change throughout the system and shifts the system state from one regime to another (Rocha et al., 2014; Rocha et al., 2018). This shift in the dominance of the feedback loop can occur suddenly due to a large shock (external factor) or gradually due to a decrease in resilience until it reaches a critical threshold or tipping point. The drivers of a regime shift, both gradual changes (internal or intrinsic variables) and shocks (external variables), can directly or indirectly affect the dynamics of the system (Biggs et al., 2018; Rocha et al., 2015a).

These regime shifts in SESs have occurred in many systems of the Earth on different temporal and spatial scales (Rocha et al., 2015b). These shifts have been observed in Iran, especially during the last decade (Azareh et al., 2021; Mohajeri & Horlemann, 2017; Saemian et al., 2020). Examples of these shifts include regime shifts in ecosystems such as rivers, lakes, and groundwater.

In Iran, several studies have been conducted regarding the monitoring of shifts in natural ecosystems. Also, several researchers in Iran have researched the dynamics analysis of these ecosystems (Gohari et al., 2013; Ravar et al., 2020). In addition, in global studies such as Chust et al. (2022), climate regime shifts in the Bay of Biscay have been researched, and the incidence of these regime shifts has been investigated by analyzing the time series of temperature, salinity, and some human-made variables. Also, Osuch et al. (2022) have analyzed the shifts in the identified flow regimes in the analysis of the water flow regime shift in the upper watersheds of the North Pole with the application of the system dynamics approach. Therefore, the use of system dynamics analysis along with the theory of regime shift in ecosystems can well indicate management strategies and scenarios to manage these regime shifts (Biggs et al., 2021).

Therefore, due to the location of a large part of Iran in arid and semiarid climates and also due to climate change in recent years and increasing water stress due to severe and intermittent droughts, along with increasing population and increasing resource utilization in existing water, shifts in system states have occurred faster and more intensely (Gohari et al., 2013; Ravar et al., 2020). One of the most important and stressful areas with these rapid and drastic shifts is the Zayandeh-Rud River Basin in the center of Iran (Zayandeh-Rud River literally means "Life-giving river"). In the 1950s, due to the increase in technology in the province of Isfahan and consequently the increase in population, the need for water increased, and as a result, the managers of the time implemented water transfer projects from upstream and adjacent basins to this area. Then, due to the increase in water resources, industrial and agricultural centers in this area have also developed and this trend has continued to date with the implementation of new water transfer projects (Gohari et al., 2013; Zamani et al., 2019; Zolfagharpour et al., 2021). As a result of these gradual changes and with the increase of stresses affected by climate change in this area, in recent years, drastic shifts have taken place in the ecosystem of the Zayandeh-Rud River Basin. Therefore, the overall aim of this research is as follows:

1. Determination of the occurrence or nonoccurrence of regime shifts in the studied area;

And the supporting objectives include the following:

2. System dynamics analysis of these identified regime shifts;
3. Identification and analysis of drivers and feedbacks in these systems.

2 | MATERIALS AND METHODS

2.1 | Study area

The Zayandeh-Rud River Basin, with an area of 41,500 km^2, is situated in central Iran, with longitude and latitude of 52°24′ E to 53° 24′ E and 31° 11 ′ N to 33° 42 ′ N, respectively. This basin includes mountainous areas with a maximum height of 3974 m.a.s.l. and plain areas with a minimum height of 1466 m.a.s.l. (Figure 1). Additionally, it has an arid climate in the river basin's lower regions and a semiarid climate upstream, with an average annual rainfall of 140 mm for the entire basin. Also, the average long-term temperature of the basin is 14.5°C, and the annual potential evapotranspiration in this area is equal to 1900 mm (Azad et al., 2019).

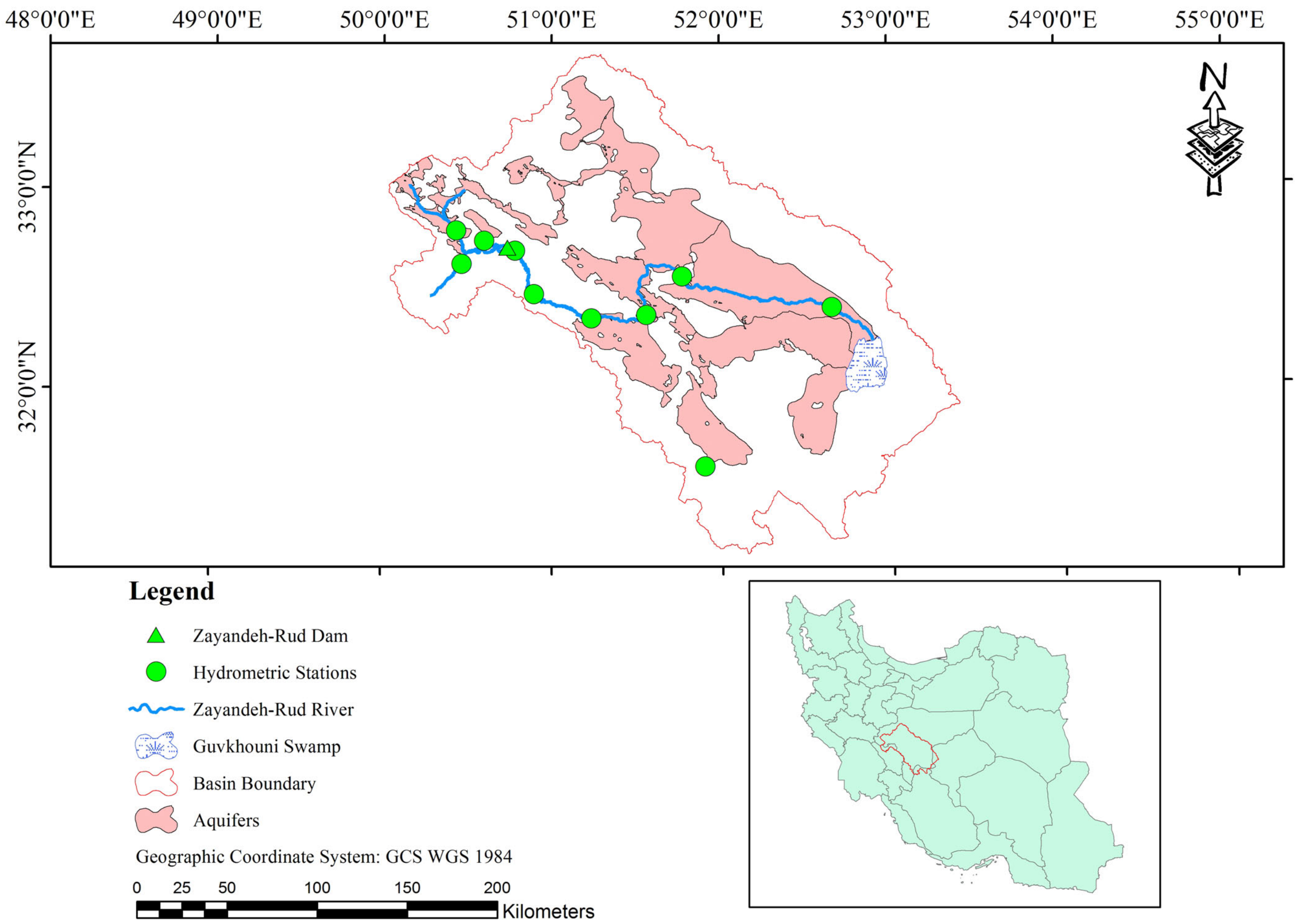

FIGURE 1 Location of the study area in Iran. [Color figure can be viewed at wileyonlinelibrary.com]

The upper sub-basins of this river basin are mostly used for irrigated farmland and are situated in Chaharmahal-va-Bakhtiari Province. In addition, on the main river of this basin, the Zayandeh-Rud River, the Zayandeh-Rud dam was established in 1970. In the past, this river, along with 16 large aquifers, fed the lower reaches of the basin in various irrigation networks for agriculture. Large industrial centers such as steel and petrochemical industries near the metropolis of Isfahan also use the water of this river. Also, the Guvkhouni swamp, which is a suitable place for wildlife, especially migratory birds, is located at the end of this river basin (Nabiafjadi et al., 2021; Zolfagharpour et al., 2021).

2.2 | Data collection

In order to analyze possible regime shifts in water resources of the Zayandeh-Rud River Basin, decadal-scale seasonal (1986–2018) quantitative and qualitative data (flow rate, total dissolved solids [TDS]) of 10 hydrometric stations located on the Zayandeh-Rud River and the groundwater level of 16 large exploited aquifers, including observation wells in this area, were collected from relevant organizations. To analyze the variation of the water area of Guvkhouni swamp (seasonal), the Normalized Difference Water Index (calculating the area of swamp water cover in the period 1986–2018) was used. Also, to analyze the status of agricultural areas (seasonal), the Normalized Difference Vegetation Index (calculating the area of agricultural cover in the period 1986–2018) from Landsat 5 and 7 satellite imageries was used in three sections including upstream of Zayandeh-Rud dam, downstream of Zayandeh-Rud dam to Isfahan city, and east of Isfahan (Kouhpaye-Segzi sub-basin). Also, the rainfall data of seven synoptic stations located in this area were also received and arranged seasonally.

2.3 | Data analysis

The sequential *t*-test technique (Xie et al., 2021) and the add-in Regime Shift Detection in Excel software (http://www.beringclimate.noaa.gov/regimes) were used in this research to statistically analyze the current time series and find potential regime shifts in each time series. In this test, with the entry of small data, a specific and purposeful output (determining the occurrence or nonoccurrence of regime shifts and determining the number of these events) will be presented. Therefore, this test was selected to analyze regime shifts in this study.

When a new observation is made in this technique, if $x_1, x_2, \ldots, x_i$ is a time series, an investigation is conducted to determine whether there is a statistically significant deviation from the regime's mean value. If the difference is substantial, that year is designated as the potential shift point c, and future observations are used to support or refute this theory. The regime shift index (RSI) is used to evaluate this hypothesis which is computed for each c as follows:

$$RSI_c = \sum_{i=c}^{c+m} \frac{x_i^*}{l\sigma_l} \quad (1)$$

where m denotes the number of years since the commencement of the new regime ($m = 0, \ldots, l - 1$), l denotes the test regime cut-off duration, and σ_l denotes the average standard deviation for all 1-year periods in the time series.

The minimal length of the regimes for which the amplitude of the shifts remains constant is determined by the cut-off length l (Rodionov, 2004). The RSI is the total of the normalized deviations 〚x_i〛^* from the new regime's imagined mean level, where the difference from the present regime's mean level is statistically significant according to the Student's t-test (Reid et al., 2016; Xie et al., 2021). Thus, in the time series, the RSI index was calculated and the presence or absence of a shift point in them was examined. In a time series, zero, one, or more tipping points may be detected (Damalas et al., 2021). After identifying the tipping points that caused the regime shift in the relevant time series by calculating the moving average of eight seasons to 32 seasons (depending on the series studied and the intensity of the regime shift, the number of seasons changes for the moving average), and putting the numbers as trial and error to calculate the threshold point number, these points were identified for each regime. This logical phrase can be defined as follows (with the condition of shifting the regime in a decreasing way):

- If the moving average of $x_i, x_{i+1}, \ldots, x_{i+n}$ is upper than T, then regime 1 is dominated.
- Else if the moving average of $x_i, x_{i+1}, \ldots, x_{i+n}$ is lower than T, then regime 2 is dominated.

where x is the corresponding time series number and T is the threshold point identified by trial and error. If the moving average of several seasons of the time series is less than or greater than the value of T, a regime shift has occurred in that time series. It is very important to know this threshold point in the implementation of various management actions and scenarios to evaluate the system performance and determine the possibility of shifting to another regime (ideal regime; Rocha et al., 2018).

The possible regimes in the surface water system of Zayandeh-Rud were considered, including the regime of high river flow and the regime of low river flow. Also, the possible regimes of surface water quality were considered, including the regime of good water quality and the regime of poor water quality. In the groundwater level system, two regimes of high water level and low water level of groundwater; in the water area system of Guvkhouni swamp, two regimes of waterlogged swamp and dry saltmarsh swamp; and also in the agricultural land area system, two regimes of large cultivation area and low cultivation area were considered. The existence of these assumed regimes is considered based on the high or low status of the main component of each system, such as the amount of water flow in the river. Shifts in precipitation data were also analyzed using this method.

After identifying the regime shifts in the studied time series, using the method of reviewing the available resources in the Zayandeh-Rud River Basin (including Farsi et al., 2020, Gohari et al., 2013; Malmir et al., 2022; Mohajeri & Horlemann, 2017; Nabiafjadi et al., 2021; Ravar et al., 2020; Safavi et al., 2016; Zamani et al., 2019; Zolfagharpour et al., 2021), causal loop diagrams (CLDs) for any detected regime shift in Vensim PLE software 7.3.5, the drivers, their feedbacks to each other, and the dominant feedback loops were identified. In one CLD, there are elements including variables, the relationships between them, the polarity of each relationship (positive or negative feedback), loops, and delays (Rocha et al., 2014; Shackleton et al., 2018). Thus, according to the review of resources, the drivers related to any type of regime shift in the study area and their relationships and feedback were identified, and according to these relationships, feedback loops including balancing feedback loops and reinforcing feedback loops were defined; the delays were also identified in these loops.

3 | RESULTS

According to the results, out of 10 hydrometric stations studied, regime shift was identified in 8 stations and no shift was identified in only two upstream stations of the area (Eskandari and Qale-Shahrokh stations). At the stations of Pol-e-Choum, Pol-e-Zamankhan, Tang-e-Esferjan, Zayandeh-Rud regulation dam, and Lenj-Nekouabad, only one shift was identified in 2008, all of which had changed from a higher flow regime to a lower flow regime. At the Pol-e-Kaleh station, two shifts in the river flow regime were identified in 1997 and 2008, both of which were toward lower flow regimes (Figure 2). Also, in two stations of Mandarjan and Varzaneh, regime shift was identified three times; in Mandarjan station in 1994, first, the water flow regime was shifted from a high flow regime to a low flow regime, then, in 2004, it returned to a high flow regime, but again in 2008, it was shifted to a low flow regime, and until the end of the study, time series remains in this regime. This pattern has also happened for Varzaneh station, but considering that this station is the last station studied on the Zayandeh-Rud River, these shifts are more intense and in shorter periods of time (shift to the low flow regime in 1989, then back to the high flow regime in 1992, and from 1994 to the end of the time series in the low flow regime; Table 1).

The findings of regime changes in the surface water flow of the investigated stations in the Zayandeh-Rud River basin are given in Table 1.

For each studied station, the quantity of these shifts in the time series, the date they occurred, and the sort of regime transition are

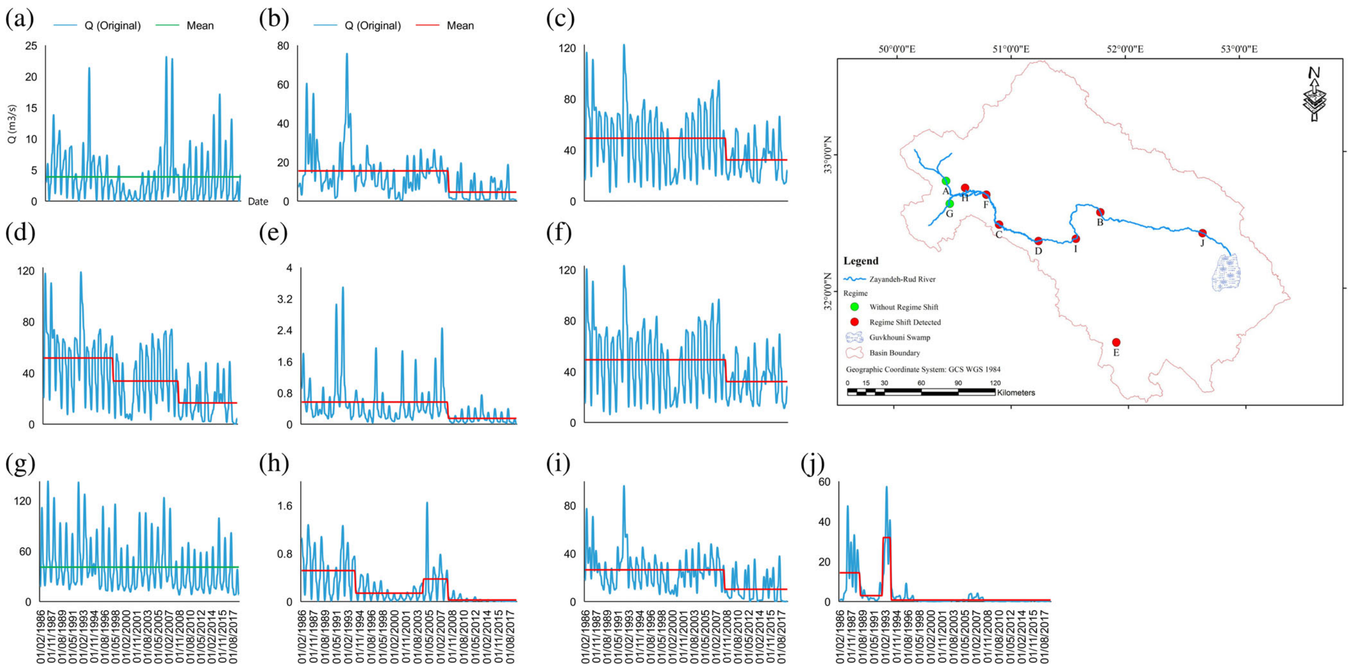

FIGURE 2 Surface stream flow time series and regime shifts detected (1986–2018): (a) Eskandari St., (b) Pol-e-Choum St., (c) Pol-e-Zamankhan St., (d) Pol-e-Kaleh St., (e) Tang-e-Esferjan St., (f) Zayandeh-Rud Reg. Dam St., (g) Qale-Shahrokh St., (h) Mandarjan St., (i) Lenj-Nekouabad St., (j) Varzaneh St. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Regime shifts detected in surface stream flows.

Station	Regime shift's date (month/year) $^{(-)}$: Negative RS, $^{(+)}$: Positive RS	Thresholds of regimes (MA[a]; m^3/s)		
		R1	R2	R3
Eskandari	–	–	–	–
Pol-e-Choum	08/2008$^{(-)}$	$T > 6.48$	$T < 6.48$	–
Pol-e-Zamankhan	11/2008$^{(-)}$	$T > 35.68$	$T < 35.68$	–
Pol-e-Kaleh	11/1997$^{(-)}$–11/2008$^{(-)}$	$T > 44.02$	$20.30 < T < 44.02$	$T < 20.30$
Tang-e-Esferjan	05/2008$^{(-)}$	$T > 0.20$	$T < 0.20$	–
Zayandeh-Rud Reg. Dam	11/2008$^{(-)}$	$T > 35.92$	$T < 35.92$	–
Qale-Shahrokh	–	–	–	–
Mandarjan	05/1994$^{(-)}$–08/2004$^{(+)}$–05/2008$^{(-)}$	$T > 0.33$	$0.05 < T < 0.33$	$T < 0.05$
Lenj-Nekouabad	08/2008$^{(-)}$	$T > 13.47$	$T < 13.47$	–
Varzaneh	02/1989$^{(-)}$–11/1992$^{(+)}$–02/1994$^{(-)}$	$T > 5.73$	$T < 5.73$	–

[a]Moving average (8–32 Seasons).

listed individually. Also, the threshold values of the identified regimes (high flow regime and low flow regime) are given based on the moving average of 8–32 seasons. These threshold values of the detected regimes indicate that, for example, if the moving average of eight seasons exceeds 6.48 m^3/s in the coming years at Pol-e-Choum station, it will indicate a shift from the current regime (low flow rate) to another regime (high flow rate).

In order to investigate the presence or absence of a regime shift in surface water quality, TDS time series data (mg/L) of 10 studied stations were arranged with a common time base of 1986–2018, and then they were adjusted seasonally. The results of the regime shift detection test in these data showed that in four stations of Eskandari, Qale-Shahrokh, Mandarjan, and Zayandeh-Rud regulation dam, which are located in the upper part of the basin, no regime shift could be detected, but in 6 other stations, in 2008, 2009, or 2012, the regime shifted from a good water quality regime to a regime with poorer water quality (Figure 3). Also, according to Table 2, the date of occurrence of these regime shifts for each station and the values of river water quality threshold for both regimes of good water quality and poor water quality are mentioned.

Then, in order to analyze the occurrence or nonoccurrence of regime shifts in groundwater resources, 16 large aquifers in the

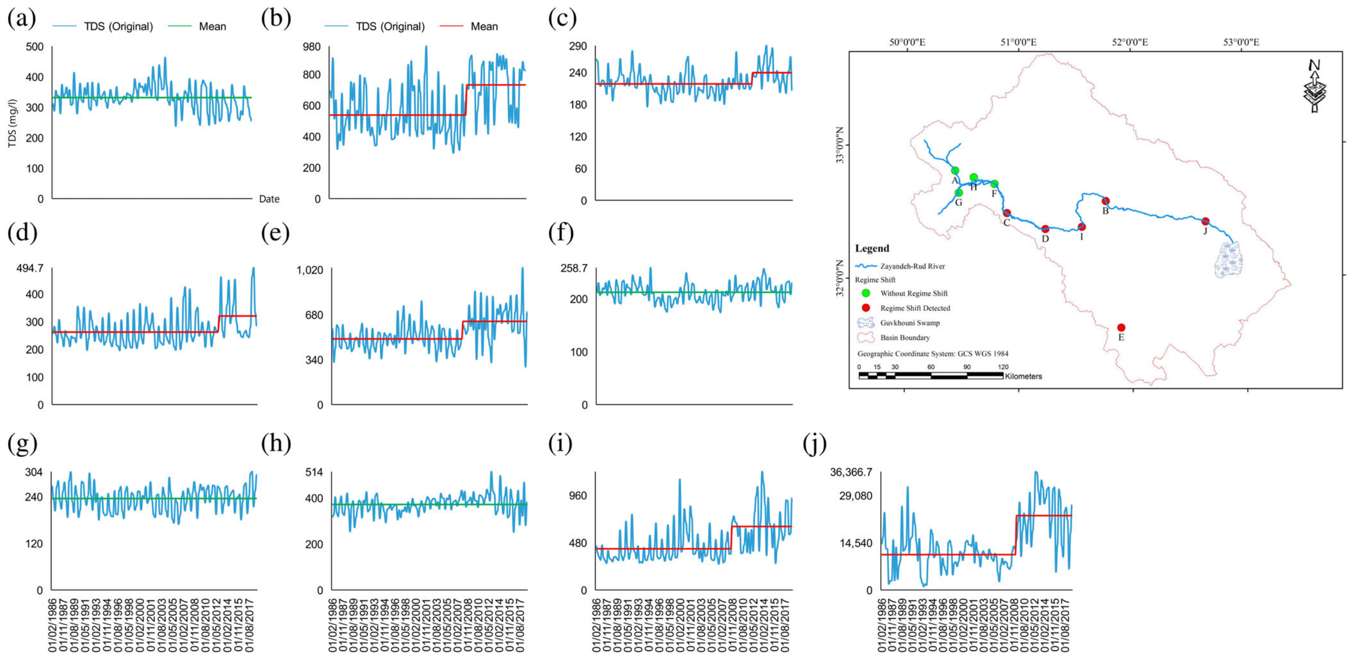

FIGURE 3 Surface flow quality time series and regime shifts detected (1986–2018): (a) Eskandari St., (b) Pol-e-Choum St., (c) Pol-e-Zamankhan St., (d) Pol-e-Kaleh St., (e) Tang-e-Esferjan St., (f) Zayandeh-Rud Reg. Dam St., (g) Qale-Shahrokh St., (h) Mandarjan St., (i) Lenj-Nekouabad St., (j) Varzaneh St. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Regime shifts detected in surface stream quality.

Station	Regime shift's date (month/year) $^{(-)}$: Negative RS, $^{(+)}$: Positive RS	Thresholds of regimes (MA) (mg/l)	
		R1	R2
Eskandari	–	–	–
Pol-e-Choum	11/2008$^{(-)}$	T < 670.80	T > 670.80
Pol-e-Zamankhan	02/2012$^{(-)}$	T < 223.26	T > 223.26
Pol-e-Kaleh	11/2012$^{(-)}$	T < 299.61	T > 299.61
Tang-e-Esferjan	02/2008$^{(-)}$	T < 584.22	T > 584.22
Zayandeh-Rud Reg. Dam	–	–	–
Qale-Shahrokh	–	–	–
Mandarjan	–	–	–
Lenj-Nekouabad	11/2008$^{(-)}$	T < 562.12	T > 562.12
Varzaneh	05/2009$^{(-)}$	T < 13,434.88	T > 13,434.88

Zayandeh-Rud River Basin were selected, and after receiving the data from observation wells, the groundwater level for each aquifer was calculated and adjusted. Then, by applying a sequential t-test, the occurrence or non-occurrence of a regime shift was identified (Figure 4). The results showed that in all studied aquifers, regime shifts occurred at the groundwater level, and only the severity and number of occurrences of these shifts varied between two and four events. Also, the date of occurrence and threshold values of each identified regime are given in Table 3 based on the moving average of several seasons.

In order to analyze the regime shifts in the water level of Gavkhouni swamp and the level of agricultural lands in three parts of the river basin, after receiving data from satellite images and measuring the mentioned indicators, the relevant time series was prepared and the results of the regime shift test showed that in the time series of the water cover of Guvkhouni swamp, there were three cases of regime shift. The first shift was in 1989 when it changed from a waterlogged swamp regime to a dry, saltmarsh swamp regime. In 1993, the state of this aquatic ecosystem returned to its previous regime, the regime of waterlogged swamp, and then in 1995, another shift in regime occurred and remained until the end of the study period. These shifts in the Guvkhouni swamp have a direct relationship with the inflow of the Zayandeh-Rud River in Varzaneh station (Figure 5a).

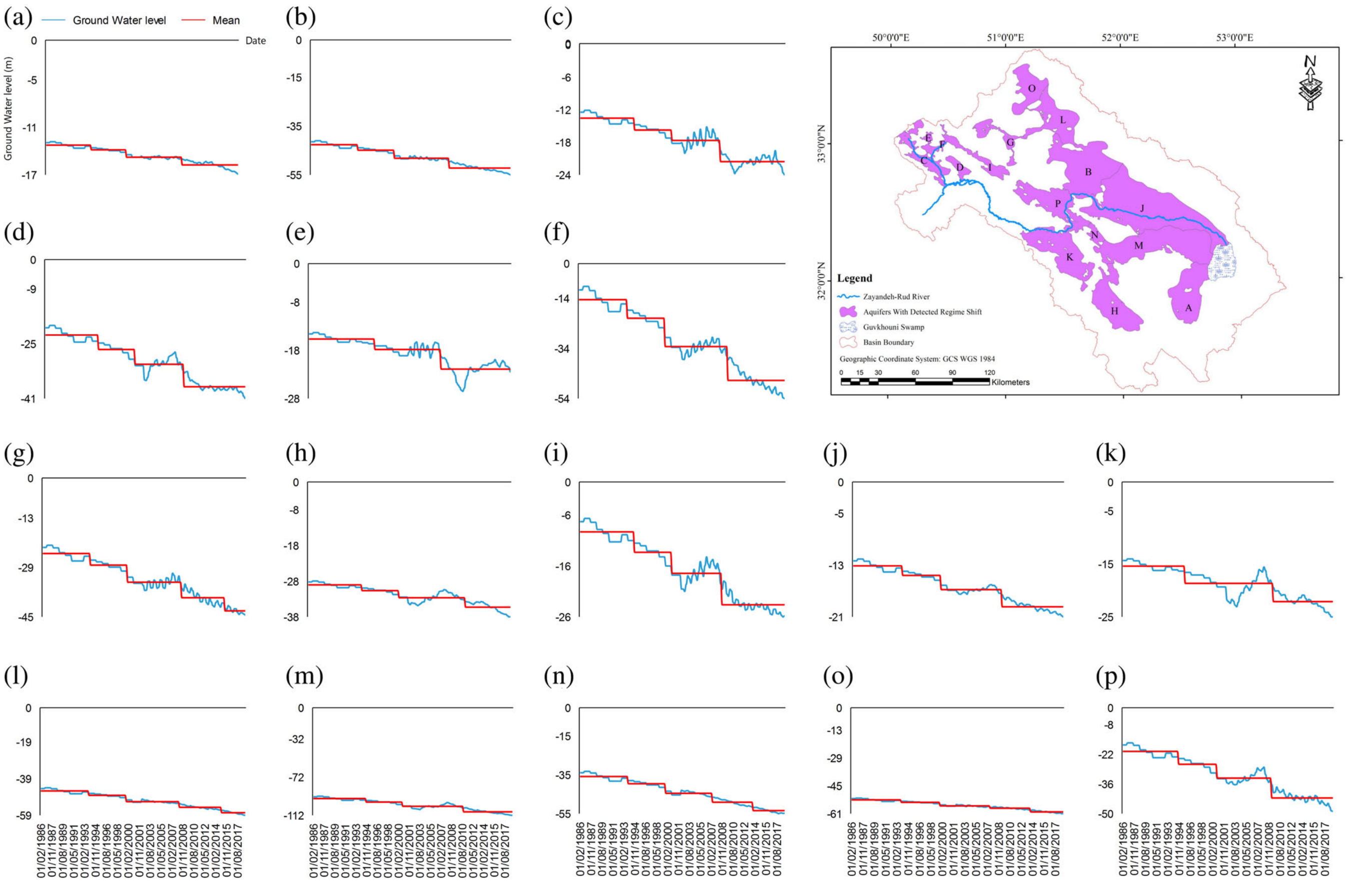

FIGURE 4 Aquifer water level time series and regime shifts detected (1986–2018); (a) Esfandaran, (b) Isfahan-Barkhar, (c) Boien-Miandasht, (d) Chadegan, (e) Chehelkhaneh, (f) Damaneh-Daran, (g) Alvicheh-Dehagh, (h) Ghomsheh, (i) Kroun, (j) Kouhpayeh-Segzi, (k) Lenjanat, (l) Mourcheh-Khourt, (m) Mahyar-e-Jonoubi, (n) Mahyar-e-Shomali, (o) Meimeh, and (p) Najafabad. [Color figure can be viewed at wileyonlinelibrary.com]

Also, according to Figure 5b, the level of agricultural areas upstream of the Zayandeh-Rud dam has shifted from low cultivation areas to large cultivation areas in 2001. Figure 5c shows the time series of agricultural areas downstream of the Zayandeh-Rud dam to Isfahan City. In 1999, in this time series, a regime shift from a large cultivation area to a low cultivation area has occurred. Also, this shift in the time series of agricultural areas in the east of Isfahan occurred with more intensity in 2000 and 2010 (Figure 5D). The results for the thresholds of each regime identified in these time series are given in Table 4.

The study plotted the CLDs of each regime shift after identifying shifts in time series relating to the quantity and quality of surface water, groundwater level, water level in the Guvkhouni swamp, and agricultural land areas in three significant regions of the Zayandeh-Rud River basin. Thus, based on Figure 6a, the drivers affecting the production and amount of surface flow in the Zayandeh-Rud River and the feedbacks between them are drawn in the form of the river surface flow dynamics system. In the past, despite natural factors and drivers such as climatic and terrestrial drivers, the water cycle in the river has been balanced; also human exploitation of this resource with the introduction of traditional agriculture did not cause a drastic shift in the river regime. However, since the 1950s, with the increase in technology, higher agricultural production, and, consequently, the increased utilization of public water supplies, water transfer projects have been implemented from upstream and adjacent basins to the Zayandeh-Rud River. Therefore, with the increase in water flow, the amount of agricultural and industrial activities and consequently the human population in this area increased again. As a result, this reinforcing feedback loop prevailed in the surface water flow system of the Zayandeh-Rud River and weakened the balancing feedback loops in the system. As a result, based on the results of identifying regime shifts in the time series of Zayandeh-Rud River hydrometric stations, except in the two stations upstream of the basin, in other stations, a regime shift from a high water flow regime to a low water flow regime was identified. So that the value of the investigated thresholds in this type of regime shift showed that from upstream to downstream, respectively, in stations of Mandarjan (0.33, 0.05), Zayandeh-Rud Reg. Dam (35.92), Pol-e-Zamankhan (35.68), Pol-e-Kaleh (44.02, 20.30), Lenj-Nekouabad (13.47), Pol-e-Choum (6.48), and Varzaneh (5.73) had a decreasing trend.

Also, in Figure 6b, a CLD of the surface water quality of the Zayandeh-Rud River Basin is drawn. Thus, as the regime shifts

TABLE 3 Regime shifts detected in groundwater level.

Aquifer	Regime shift's date (month/year) $^{(-)}$: Negative RS, $^{(+)}$: Positive RS	Thresholds of regimes (MA) (m)				
		R1	R2	R3	R4	R5
Esfandaran	11/1993$^{(-)}$–11/1999$^{(-)}$–05/2009$^{(-)}$	$T > -13.84$	$-14.70 < T < -13.84$	$-15.40 < T < -14.70$	$T < -15.40$	–
Isfahan-Barkhar	11/1993$^{(-)}$–11/1999$^{(-)}$–11/2008$^{(-)}$	$T > -45.11$	$-48.20 < T < -45.11$	$-51-42 < T < -48.20$	$T < -51.42$	–
Boien-Miandasht	11/1994$^{(-)}$–11/2000$^{(-)}$–08/2008$^{(-)}$	$T > -16.46$	$-17.65 < T < -16.46$	$-21.40 < T < -17.65$	$T < -21.40$	–
Chadegan	11/1994$^{(-)}$–11/2000$^{(-)}$–11/2008$^{(-)}$	$T > -25.21$	$-29.26 < T < -25.21$	$-35.66 < T < -29.26$	$T < -35.66$	–
Chehelkhaneh	11/1996$^{(-)}$–08/2007$^{(-)}$	$T > -17.37$	$-20.66 < T < -17.37$	$T < -20.66$	–	–
Damaneh-Daran	11/1993$^{(-)}$–11/1999$^{(-)}$–11/2009$^{(-)}$	$T > -20.30$	$-31.93 < T < -20.30$	$-41.77 < T < -31.93$	$T < -41.77$	–
Alvicheh-Dehagh	11/1993$^{(-)}$–11/1999$^{(-)}$–08/2008$^{(-)}$–08/2015$^{(-)}$	$T > -27.44$	$-33.31 < T < -27.44$	$-37.38 < T < -33.31$	$-42.80 < T < -37.38$	$T < -42.80$
Ghomsheh	11/1994$^{(-)}$–11/2000$^{(-)}$–08/2011$^{(-)}$	$T > -30.66$	$-31.87 < T < -30.66$	$-34.78 < T < -31.87$	$T < -34.78$	–
Kroun	11/1994$^{(-)}$–11/2000$^{(-)}$–11/2008$^{(-)}$	$T > -12.85$	$-16.42 < T < -12.85$	$-22.41 < T < -16.42$	$T < -22.41$	–
Kouhpayeh-Segzi	11/1993$^{(-)}$–11/1999$^{(-)}$–05/2009$^{(-)}$	$T > -14.14$	$-16.37 < T < -14.14$	$-18.43 < T < -16.37$	$T < -18.43$	–
Lenjanat	11/1995$^{(-)}$–08/2009$^{(-)}$	$T > -17.53$	$-21.64 < T < -17.53$	$T < -21.64$	–	–
Mourcheh-Khourt	11/1993$^{(-)}$–11/1999$^{(-)}$–05/2007$^{(-)}$–11/2013$^{(-)}$	$T > -38.37$	$-43.53 < T < -38.37$	$-47.62 < T < -43.53$	$-52.46 < T < -47.62$	$T < -52.46$
Mahyar-e-Jonoubi	11/1993$^{(-)}$–11/1999$^{(-)}$–05/2008$^{(-)}$–02/2015$^{(-)}$	$T > -47.24$	$-50.69 < T < -47.24$	$-53.54 < T < -50.69$	$-57.14 < T < -53.54$	$T < -57.14$
Mahyar-e-Shomali	11/1994$^{(-)}$–11/2000$^{(-)}$–11/2010$^{(-)}$	$T > -97.75$	$-101.44 < T < -97.75$	$-106.62 < T < -101.44$	$T < -106.62$	–
Meimeh	11/1993$^{(-)}$–11/1999$^{(-)}$–08/2007$^{(-)}$–11/2013$^{(-)}$	$T > -54.12$	$-56.17 < T < -54.12$	$-57.42 < T < -56.17$	$-59.56 < T < -57.42$	$T < -59.56$
Najafabad	11/1994$^{(-)}$–11/2000$^{(-)}$–05/2009$^{(-)}$	$T > -25.17$	$-31.15 < T < -25.17$	$-40.20 < T < -31.15$	$T < -40.20$	–

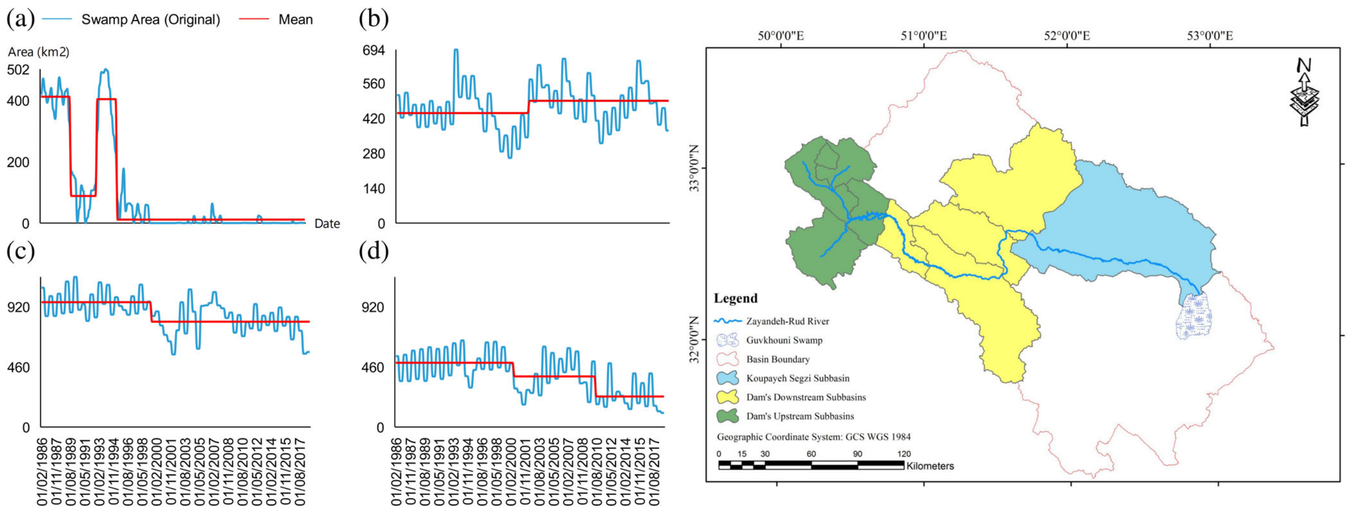

FIGURE 5 (a) Normalized Difference Water Index time series and regime shifts detected in the Guvkhouni swamp (1986–2018). (b, c, d) Normalized Difference Vegetation Index time series for agricultural use and regime shifts detected upstream of Zayandeh-Rud dam, downstream of Zayandeh-Rud dam to Isfahan city, and in Kouhpayeh-Segzi watershed, respectively (1986–2018). [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Regime shifts detected in Guvkhouni Swamp and agricultural areas.

Index	Regime shift's date (month/year) $^{(-)}$: Negative RS, $^{(+)}$: Positive RS	Thresholds of regimes (MA; km^2) R1	R2	R3
Guvkhouni swamp water cover area	11/1989$^{(-)}$–02/1993$^{(+)}$–08/1995$^{(-)}$	$T > 150.48$	$T < 150.48$	–
Area of agricultural lands upstream of Zayandeh-Rud dam	11/2001$^{(+)}$	$T < 459.77$	$T > 459.77$	–
Area of agricultural lands downstream of Zayandeh-Rud Dam to Isfahan city	08/1999$^{(-)}$	$T > 910.25$	$T < 910.25$	–
Area of agricultural lands east of Isfahan city	08/2000$^{(-)}$–08/2010$^{(-)}$	$T > 396.25$	$257.78 < T < 396.25$	$T < 257.78$

continuously in the quantity of surface water flow in the basin, the concentration of contaminants in the flowed water has increased. Moreover, increasing human activities such as the use of chemical fertilizers and pesticides in agriculture, industrial activities, as well as the disposal of municipal wastewater into the flowing water, caused a drastic shift in the quality of river flow in the studied hydrometric stations (except in four upstream stations); so, the river water quality regime has shifted from a good water quality regime to a poor water quality regime based on the TDS index. In the surface water quality regime shift, the trend of the thresholds from upstream to downstream of the river has been increasing, so that the amount of thresholds in the studied stations of Pol-e-Zamankhan (223.26), Pol-e-Kaleh (299.61), Lenj-Nekouabad (562.12), Pol-e-Choum (670.80), and Varzaneh (13,434.88) has been calculated, respectively.

The reduction of surface water flow along the Zayandeh-Rud River has reduced the supply of environmental water downstream of the basin and reduced the water level of the Guvkhouni swamp. Therefore, according to the findings of the analysis of the regime shift in the time series of the Guvkhouni swamp, a regime shift in this swamp has occurred due to the reduction of incoming water flow to the swamp. In Figure 6c, this regime shift can be seen in the form of a swamp surface water dynamics system and the drivers, feedbacks, and dominant feedback loops that caused this regime shift.

The increase of the mentioned human activities in the Zayandeh-Rud River Basin and the decrease of surface water available for exploitation and consumption in agricultural, industrial, and drinking activities also increased the exploitation of groundwater resources. According to Figure 6d, the increase in these activities reduced the groundwater resources in the aquifer of the Zayandeh-Rud River Basin, and as a result, with the dominance of the reinforcing feedback loop, increasing the population, increasing production, and increasing inter-basin water transfer projects, the resilience of the system in the face of water scarcity has decreased, and as a result, the entire aquifer system in the basin has shifted from a rich aquifer regime to a poor aquifer regime. In this type of regime shift, the number of shifts has increased from the upstream to the downstream, So that the regime shift occurred three times in Chehelkhaneh aquifer and the Mahyar-E-Jonoubi aquifer has been identified five times of regime shift.

The time series study of agricultural lands in three important agricultural sections of the Zayandeh-Rud River Basin (Figure 7) showed

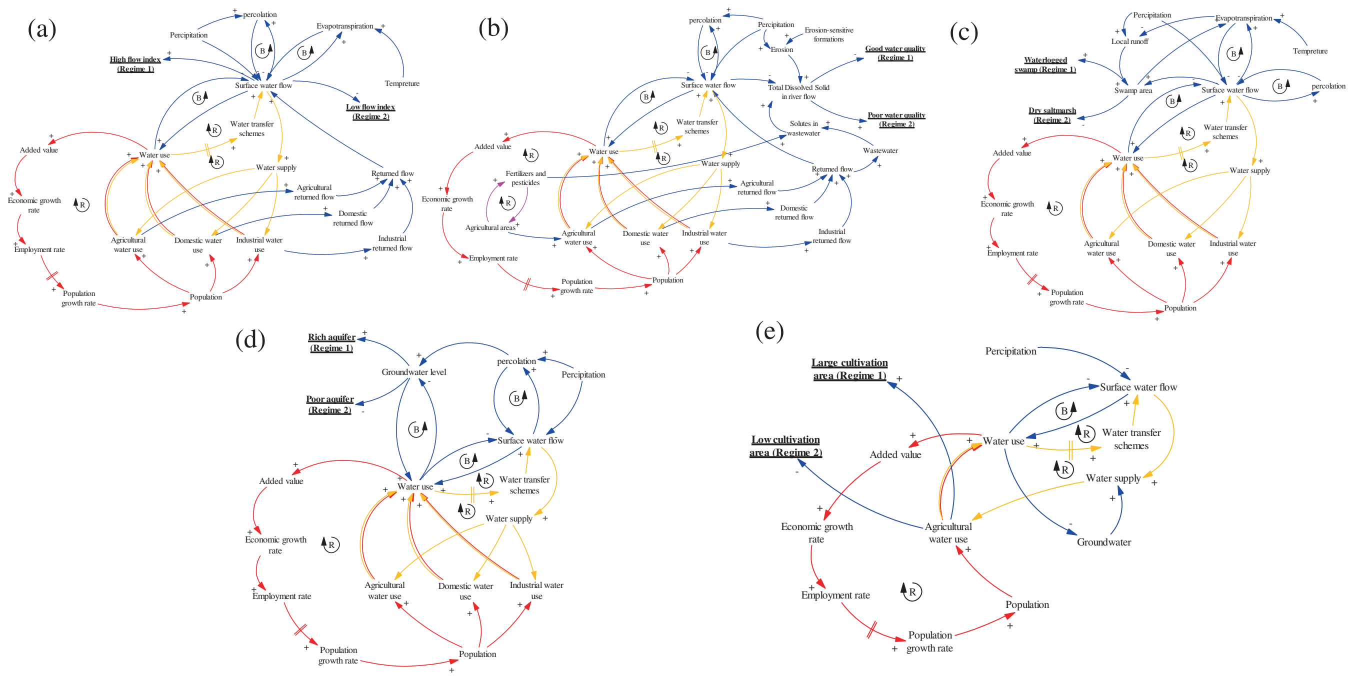

FIGURE 6 Causal loop diagrams of (a) Surface water flow regime shift, (b) River flow quality regime shift, (c) Swamp regime shift, (d) Groundwater regime shift, (e) Agricultural lands regime shift. The drivers and feedbacks between them and the reinforcing feedback loops are marked in yellow and red. [Color figure can be viewed at wileyonlinelibrary.com]

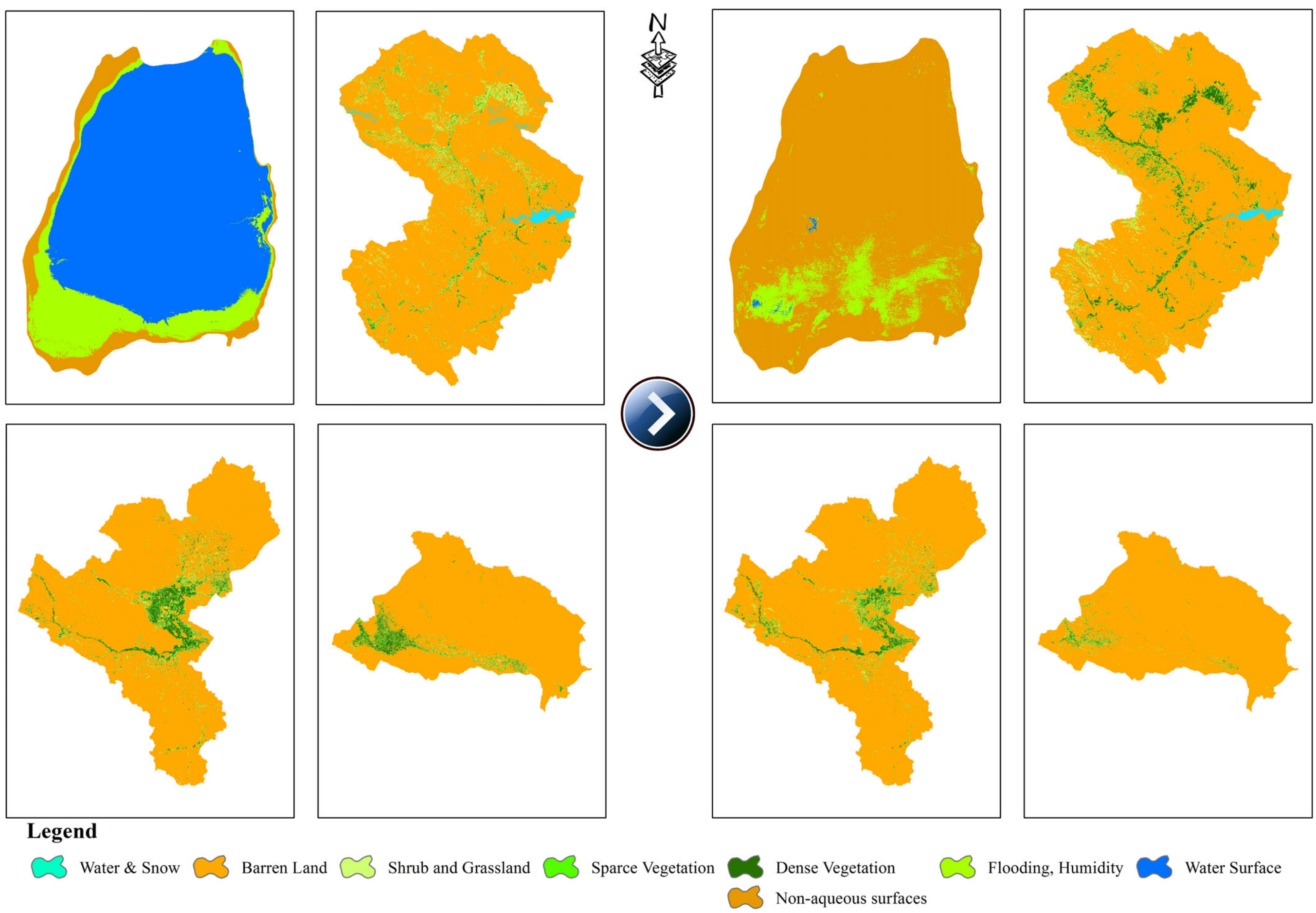

FIGURE 7 Regime shifts in Guvkhouni Swamp water area and basin agricultural areas (same seasons). [Color figure can be viewed at wileyonlinelibrary.com]

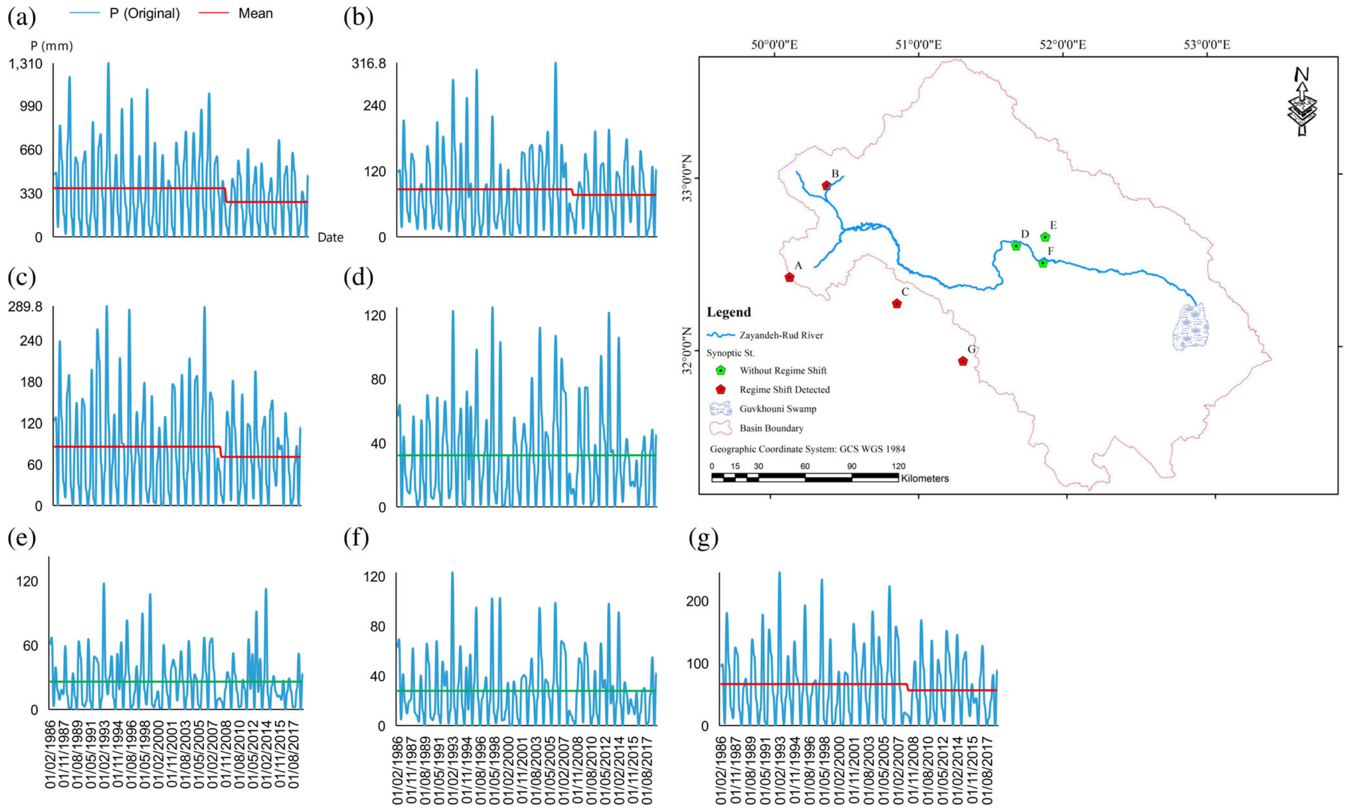

FIGURE 8 Regime shifts in precipitation data. [Color figure can be viewed at wileyonlinelibrary.com]

that the regime shift from a large cultivation area regime to a low cultivation area regime occurred downstream of the Zayandeh-Rud dam to Isfahan city and in the eastern sub-basin of Isfahan (Kouhpaye-Segzi) is due to the dominance of the reinforcing feedback loop drawn in Figure 6e. Accordingly, increasing the use of surface and groundwater over time, reducing existing water resources, and ultimately the inability to re-supply these resources (even with the implementation of water transfer projects) reduce the amount of agriculture and regime shift in the lower parts of the Zayandeh-Rud River Basin. The intensity of these shifts has been greater downstream. Also, a positive regime shift has occurred in the agricultural lands upstream of the Zayandeh-Rud dam, which indicates an increase in the utilization of water resources upstream of the dam.

Due to the widespread occurrence of regime shifts in the period of 2008 and 2009, rainfall data were also analyzed in order to investigate the triggering factor of drought occurrence in this region and the occurrence of a regime shift. The results showed that, in the seven investigated stations, four stations located upstream of the region had a regime shift in 2008. This case shows the existence of the regime shift trigger factor in the investigated water systems in the time frame of 2008 (Figure 8).

4 | DISCUSSION

Sudden changes could occur in arid and semiarid regions much faster and more severely than elsewhere, especially with increasing human activity. This is due to the vulnerability of ecosystems in arid and semiarid regions to the presence or absence of the minimum water required by nature living in them. On the other hand, these systems can have high resilience (Tooth, 2018). So that if in an ecosystem with arid climatic conditions, there is a slight change in the annual rainfall, due to the proximity of the thresholds, it can cause more drastic shifts in the ecosystem over time, because the ecosystem's resilience over time decreased and the action of external factors (trigger factors) strengthens and accelerates the occurrence of regime shift in the ecosystem. The most important reason for the decrease in the resilience of ecosystems in arid and semiarid regions to environmental and external changes is human activities and the gradual erosion of SES resilience. As a result, considering the system of a dry ecosystem, various human factors and drivers can cause reinforcing feedback loops in the system, and over time, as they prevail, cause shifts in the ecosystem regime.

In Iran, due to the existence of arid and semiarid climates, the observation of these regime shifts, especially in the Anthropocene, is not unexpected. As a result, in this study, we tried to identify and discuss the existence or absence of regime shifts by examining the available evidence on shifts in the time series of surface and groundwater resources in one of the most challenging river basins in Iran. Also, by systematic analysis and analysis of these sources, key drivers and feedbacks between them and as a result, the dominant and effective feedback loops in the occurrence of regime shift have been identified and discussed. Thus, according to the results of the analysis of regime shifts in the time series of surface water flow, surface water quality, groundwater level, and agricultural areas in the Zayandeh-Rud River Basin, it was determined that in all the time series, regime shifts can be identified. Similar results can be seen in the research of Farsi et al. (2020), Malmir et al. (2022), Nabiafjadi et al. (2021), and Safavi et al. (2016). According to them, the surface water flow in the study area has been decreasing. On the other hand, in this research, using the regime shift approach, the occurrence of shifts in the surface water flow time series was tested and confirmed.

Also, according to the study of the CLDs of this regime shift, the dominant feedback is related to the increase in water use around the metropolis of Isfahan since the early 1950s and consequently the increase in water transfer operations, and then the increase in agricultural, and industrial production and population growth, which then act as a reinforcing feedback loop in the system, gradually reducing the system's resilience to water scarcity due to climate change, and as a result, in 2008, caused a severe regime shift in eight hydrometric studied stations. The occurrence of intermittent droughts from 2008 to 2012 (Farsi et al., 2020; Nabiafjadi et al., 2021; Zolfagharpour et al., 2021) acted as a trigger factor, and along with the loss of resilience of the water systems due to the reasons mentioned, has caused severe regime shifts in surface water flow and consequently in other investigated systems. These results are consistent with the results of Gohari et al. (2013) and Ravar et al. (2020) regarding the dynamics of dominant feedback loops in the Zayandeh-Rud SES. The occurrence of intermittent droughts can trigger regime shifts in river basins; on the other hand, the occurrence of heavy rains in alternate years is not a sufficient reason to return to a stable and ideal state in a water system, and other system elements must also be considered (Peterson et al., 2009, 2021; Zipper et al., 2022).

The dominant feedback mentioned in the previous section has acted in all other forms of regime shifts. Therefore, increasing the use of surface and groundwater resources in the Zayandeh-Rud River Basin and increasing human activities, including agriculture and industry, reduces surface water quality, reduces the environmental flow into the Guvkhouni swamp in the downstream basin, reduces the groundwater level in the aquifers of the basin, and reduces the level of agricultural areas downstream of the basin. These shifts have been in a way that, statistically, has caused regime shifts in the state of each system. As a result, in general, in the Zayandeh-Rud River Basin system, there has been a drastic shift in the water resources of the basin. The most important reason from a systemic point of view is the dominance of the feedback loop (increased human activities, increased water demands, increased inter-basin water transfer projects, increase in water supply, increase in consumption, and consequently increase in production along with the advancement of technology and human activities in production and uncontrolled exploitation) without considering the capacity of water resources of the Zayandeh-Rud River Basin.

4.1 | Policy recommendations

The Zayandeh-Rud River Basin is trapped in the "Policy Resistance-Fixes that Fails" system. The trap of political resistance occurs when in a system, different actors pursue their individual goals and there is no comprehensiveness in these goals, so the main goal of the system becomes the individual interests of the actors and each actor or element pursues policies to achieve its own goals, which in most cases, are in conflict with the goals of other elements. So, in the Zayandeh-Rud River Basin, the main goal of the governance system of the basin is to fully exploit and produce the maximum resources in the river basin. Therefore, the political elements that are responsible for protecting these resources are inevitably the overall goal and follow the existing governance system and are incapable of implementing conservation plans to sustain the resources of the constituency.

Thus, in this area, the managerial view is only with a view to greater exploitation, and the only solution to meet the water shortage in the past decades from the 1950s to the present has been the implementation of water transfer projects from adjacent basins to this area, which have caused many tensions and challenges among the operators of the fields. As a result, it is suggested that the following measures be taken in the Zayandeh-Rud River Basin to get out of this systemic trap:

1. First mapping the system, its elements, relationships, and feedbacks in the existing system, and then identifying the anomalous structure and structural modification (redesigning) of it in the whole system.
2. Negotiating to achieve the goals of all actors with a focus on the main goal of the system with the presence of all actors and using their energy to achieve the main goal of the system.
3. Redefining the bigger or more important goals that all stakeholders can move toward together.

By implementing the policies above, by reforming the water governance system structure in the study area, and by changing the relevant goals and worldviews, effective steps can be taken to sustain the Zayandeh-Rud River Basin and improve its ecosystem services and the livelihood of people living in the basin and adjacent areas.

5 | CONCLUSIONS

In this study, regime shifts in the Zayandeh-Rud River Basin and key drivers and feedbacks effective in these regime shifts were identified. After knowing how the system works by examining the output events of each subsystem, we can understand the patterns in the system. As a result, by examining the output events resulting from the operation of the ecosystem of the Zayandeh-Rud River Basin, the patterns and dominant feedback loops of the regime shift from favorable to unfavorable to identify ecosystem services and human wellbeing were identified. By recognizing these patterns, various management scenarios can be presented to manage these regime shifts and the sustainability of the Zayandeh-Rud River Basin system, and as a result, the optimal scenario can be identified by providing relevant simulations to the basin managers.

In this study, the application of the theory of regime shifts in SESs with the support of system dynamics analysis was analyzed and discussed in a case study. In general, the results showed that the application of these two theories together with the analysis of human activities along with environmental changes such as climate change and their impact on the environment and available resources for environmental and human welfare in small systems (river basin systems) to large systems (cross-border and international systems) can be effective in making optimal decisions to manage these shifts. The most important outputs and points of this research for future research can be the application of this research method in examples and other types of regime shifts, and also in practice, cause changes in management decision-making methods.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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