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Application of Hydrological Balance Approach in the Study of Surface Water-Groundwater Exchange (Case Study: Zayandehrood River)

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ABSTRACT

Introduction: Studying the changes in surface water storage and exchanges with groundwater in the hydrological system of rivers is a prerequisite for water resources management in the basin. In this paper, Zayandehrood River has been studied and the historical series of flow has been used in six hydrographic stations located downstream the Zayandehrood Dam.
Materials and Methods: Based on the surface water balance and considering monthly inflows and outflows in each river reach, a general equation for water outflow was extracted for each month, in which the net interaction of surface water with the water in the air and groundwater are in the form of a polynomial of the inflows and a constant.
Results: The obtained equations showed that in two reaches, surface water was increased by groundwater and in the other three reaches, surface water fed the groundwater. The results showed that in normal conditions, 1613 million cubic meters of surface water resources were consumed in the reaches under study. In the event of severe drought, except for the first three reaches (from the sadtanzimi to Lenj), the remaining reaches (downstream Lenj) faced water shortage. The results showed that increasing surface water by groundwater is very important for water supply in drought condition.
Conclusion: Based on the results, the proposed method is an appropriate tool for investigating the exchange of surface water with groundwater.

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Introduction

With prevailing methods, surface water and groundwater systems as the main parts of hydrological systems are often studied and managed separately, while these systems are widely interrelated climatically, topographically, and geographically. Accordingly, water can continuously move between surface and groundwater systems, so the method of exploitation and the quality of one resource can affect the other [1, 2]. Since these waters are not distinguishable in a hydrological system, understanding their relationship is of great importance to the evaluation of a surface water system, such as Zayandehrood. The evaluation of this relationship is complicate, so researchers have proposed different methods. According to Mencio et al., these methods can be categorized as follows: (a) direct measurement of water flux; (b) thermal tracking techniques; techniques based on Darcy equation; (d) mass balance approaches; and (e) modeling approaches [3]. The mass balance approach assumes that any increase or decrease in surface water, or any change in its characteristics, may be related to a particular water source [4], groundwater can be determined in this way. For example, groundwater leakage into the river bed can be calculated from the difference in flow at successive stations along the river. This technique has been used by researchers such as Harvey and Wagner, Farnsworth and Mencio et al., [3, 5, 6]. Another method for estimating the contribution of groundwater in the surface flow is the hydrograph separation of stream flow data. In this method, the base flow is assumed to be the discharge of groundwater into the river [7]. Among mass balance methods, chemical and environmental tracers have been widely used [8, 9]. In this study, a method has been used to investigate water exchange, in which, by consideration a hydrological balance in a river reach, an equation is obtained for outflow that results in the achievement of net exchange between surface water and groundwater. This method is a subcategory of mass balance approaches and a modified version of the method presented by Liu and Sheng. The researchers implemented the method on eight reaches from the Rio Grande River, California, and stated that this method is an appropriate tool for understanding the relationship between surface water and groundwater in dry and semi-dry regions [10]. In the proposed method extractions related to drinking water and industry, return flow and water transfer between river reaches were not considered, and implementation of this method to the complex system of Zayandehrood River will not yield accurate results. Therefore, in this study, there were some corrections in this method and it was used to study the relation between surface water and groundwater in six reaches of downstream Zayandehrood River.

Study site

Zayandehrood River, the most important river in the central region of Iran, originates from ZardkouhBakhtiari heights and after a distance of 350 km to the east it ends up in Gavkhuni swamp. The total reach of Zayandehrood basin is about 26917 km2 in which mainly the downstream dam is influential in providing water flow. Downstream of the dam, which accounts for the largest portion of water consumption in the reach, is a semi-dry, high tension zone in which chronic water shortages threaten agricultural production and limit economic development [11, 12, 13].In this reach, water distribution is carried out through five new irrigation and drainage networks. More than 60% of irrigation water is supplied through groundwater extraction [14]. The reach of the plains downstream the dam is 10698 square kilometers, of which 7350 square kilometers are aquifers and the rest are hard formations. The average rainfall in the Zayandehrood basin varies from 100 to 1400 mm per year and with decrease in height it decreases from west to the east of the basin. The maximum potential evapotranspiration in the study reach is East of Isfahan and about 2000 mm per year. The long-term average of Zayandehrood annual flow is 1440 million cubic meters per year at Sadtanzimi. During the drought of 1998-1999, the annual amount of Zayandehrood flow at the aforementioned site decreased to 562 million cubic meters. A schematic of the study reach is presented in Figure 1.

Surface water and groundwater in the Zayandehrood River basin are actively interconnected through various hydrological processes. In this study, a series of historical flow at 6 hydrometric stations (Table 1), is the basis for the study of this relationship. The location of the stations is presented in Figure 1.

Table 1: List and specifications of hydrometric stations located on the Zayandehrood River

Gauge station	Longitude	Latitude	Height (meter)	Available Data
Sadtanzimi	50˚ 47'	32˚ 43'	1970	1968-2013
Polzamankhan	50˚ 53'	32˚ 29'	1880	1948-2013
Polkale	51˚ 13'	32˚ 32'	1715	1948-2013
Lenj	51˚ 33'	32˚ 23'	1446	1980-2013
Polchoum	51˚ 46'	32˚ 35'	1551	1985-2013
Varzaneh	52˚ 39'	32˚ 25'	1469	1948-2013

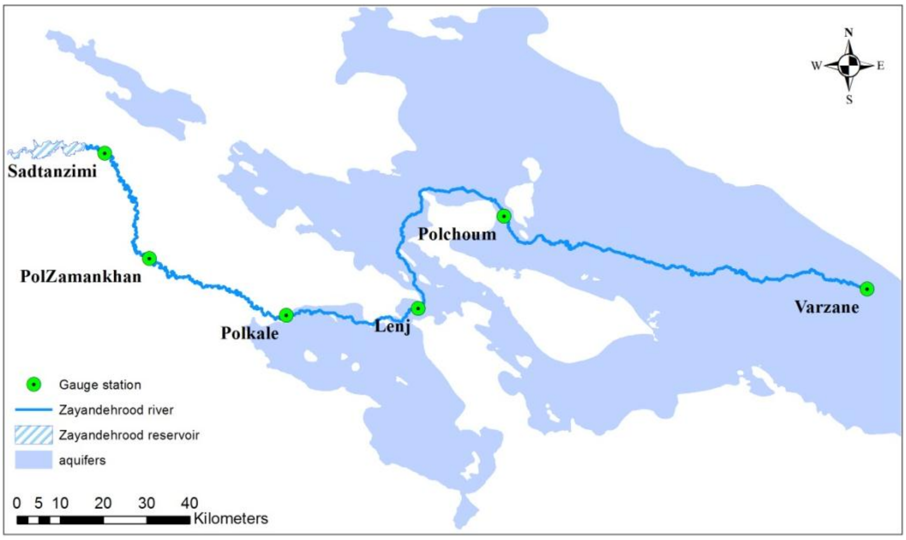

Figure 1: Schematic of the studied stations

Materials and Methods

A common method for investigating the relationship between the river and its bottom aquifer is to measure river flow at specific points. These points divide the river into reaches that by examining the water balance in these reaches, and through the difference in inflows and outflows, the exchange between surface water and groundwater can be obtained. This method depends on accurate measurements of river flow as well as estimation methods of water balance components. [15]. In this study, based on the statistics of inflow and outflow flows from a river basin, a net relation between surface and groundwater is obtained. In Zayanehrood, the resources of surface water include runoff caused by rainfall (including surface and under-the-surface flow) and water released from dam. Each river reach receives an inflow from its upstream reach and collects rainwater from surrounding and upstream reaches and streams. Then the water in this reach is discharged into the upstream reach or it enters the atmosphere through evaporation from the surface of the river, canals and drains and evaporation from irrigated lands, or by leakage losses from the River, canals and drains and deep penetration of irrigated lands into groundwater. In this study, based on the surface water balance in each reach of the river, an equation is obtained that the sum of the outflows of each reach is obtained as a function of the river inflows in that reach. The parameters of this equation indicate the mode and extent of water exchanges at that reach. In the reach under study, in addition to the river route, water exchange between the reaches through extraction channels and drainage of irrigation networks is also carried out, which should be entered into the equation. For this purpose, in addition to the flow data of the studied stations (Table 1), the historical series of water extraction and transfer data was also used.

The source of this data is Isfahan Regional Water Company. The amount of small pumping, extractions fordrinking water and industry and return flow are also the components of the surface water balance in each reach. In this study, the average annual values of these variables reported in previous studies of Salemi et al. were used [16].To test the proposed method, the historical series of data from the water years of 1986 to 2006 were used. In the next section, the application of this data and generation of outflow function reaches presented.

Simulated outflow equation

Groundwater system in this study includes aquifers located on Ben - Saman plains, Lenjanat, Najafabad, Borkhar-Isfahan and Kohpayeh-Segzi. The aquifers are unconfined and the plains are fed with Zayandehrood river. In this research, the relationship between surface water and groundwater is considered based on the relation between the surface water system of Zayandehrood and groundwater in the floodplains at downstream Zayandehrood. According to Liu and Sheng (2011) and the water balance, the outflow water of each reach can be written as follows [10]:

$$Q_{so} = Q_{si} - \Delta S_s + (Q_p - Q_e) + (Q_{gg} - Q_{gl}) + (Q_{ig} - Q_{il} - Q_{ET}) \quad \text{Equation (1)}$$

In which Q_{so} is the surface water outflow from each reach to downstream reach, Q_{si} is the inflow from the upstream reach, ΔS_s is the change in surface water storage, Q_p is the increase of surface water by the atmosphere (raining and snow melting), Q_{gl} is the losses of surface water through leakage into groundwater, Q_{ig} is surface water increase due to agricultural drainage, Q_{il} is deep percolation of irrigation water and Q_{ET} is losses due to evapotranspiration from irrigation water. The dimensions of all the variables listed are L^3T^{-1}. In the above equation, there is no mention of extraction for drinking water and industry from the surface water and their return flow to the river as well as the displacement of water between the reaches water outside the main river route, while in the complex system of Zayandehrood surface water there are numerous and significant cases of such flows. In this study, with the inclusion of extractions for drinking water and industry and transfer between the river reaches, corrections were made in equation (1) and the equation was corrected as in equation (2).

$$\begin{aligned} Q'_{so} &= Q_{so} + Q_{to} + Q_{di} - Q_r - Q_{ti} \\ &= Q_{si} - \Delta S_s + (Q_p - Q_e - Q_{ET}) \\ &+ (Q_{gg} - Q_{gl} - Q_{il}) \end{aligned} \quad \text{Equation (2)}$$

In which, Q_{ti} and Q_{to} are the transferred flow into and out from the reach, respectively, Q_{di} is extractions for drinking water and industry, and Q_r is the total return flow. By presenting simplifying assumptions of Liu and Sheng, the simulated outflow (Figure 2, Q^T_{so}) can be presented as Equation (3). These assumptions include: (1) simulated outflow, is a continuous monthly flow for a certain amount of continuous inflow;(2) changes in surface water depth are overlooked within the month; (3) groundwater level is assumed to be constant. Over the past decade, the Zayandehrood River in several months has dried out. Therefore, the study period in this study (years 1986 to 2006) was chosen so that the assumption of the continuous inflow flow would not be distorted. In Equation 3, Q^T_{so} is the simulation of the left-hand side phrase in equation 2 is [10].

$$Q^T_{so} = Q_{si} + \Delta Q_a + C_g \quad \text{Equation (3)}$$

In the above equation, $\Delta Q_a = Q_p - Q_e - Q_{ET}$,and it shows the relation between surface water and atmospheric water in river reach. $C_g = Q_{gg} - Q_{gl} - Q_{il}$ indicates the exchange of surface water with groundwater in that reach. Changes in Q_p, Q_e and Q_{ET} depends on changes in climate and irrigation management within the range of each reach. Also, the inflow into the reach of (Q_{si}) is necessarily influenced by the climatic conditions and water management in the upstream. So, we can assume that ΔQ_a is a function of Q_{si} . McLaren extension of this function can be written as follows:

$$f(Q_{si}) = f(0) + \sum_{n=1}^{\infty} \alpha_n Q_{si}^n \qquad \text{Equation (4)}$$

In which α_n represents the constant values. Due to the similarity of the climate in the two reaches, especially in dry and semi-dry reaches such as the Zayandehrood basin, Q_{si} equals zero, the value of $f(0)$ is expected to be zero. Now you can use polynomial functions to estimate ΔQ_a . Therefore, a general equation as follow be extracted from equation 3 for simulated outflow.

$$Q_{so}^T = \sum_{j=2}^{n} \alpha_j Q_{si}^j + (1+\alpha_1) Q_{si} + C_g \qquad \text{Equation (5)}$$

As shown in Figure 2, in this study, a linear form is suitable to express the simulated outflow in a reach. Accordingly, in the linear form of the equation, when α_1 and C_g equal zero, surface water has no interaction with the groundwater and the atmosphere. If C_g is larger than zero, the groundwater feeds on surface water, otherwise the surface water system will leak into groundwater.

When α_1 is larger than zero, the surface water system has a net gain from atmospheric water, and whenever it is less than zero, it has net loss to atmosphere.

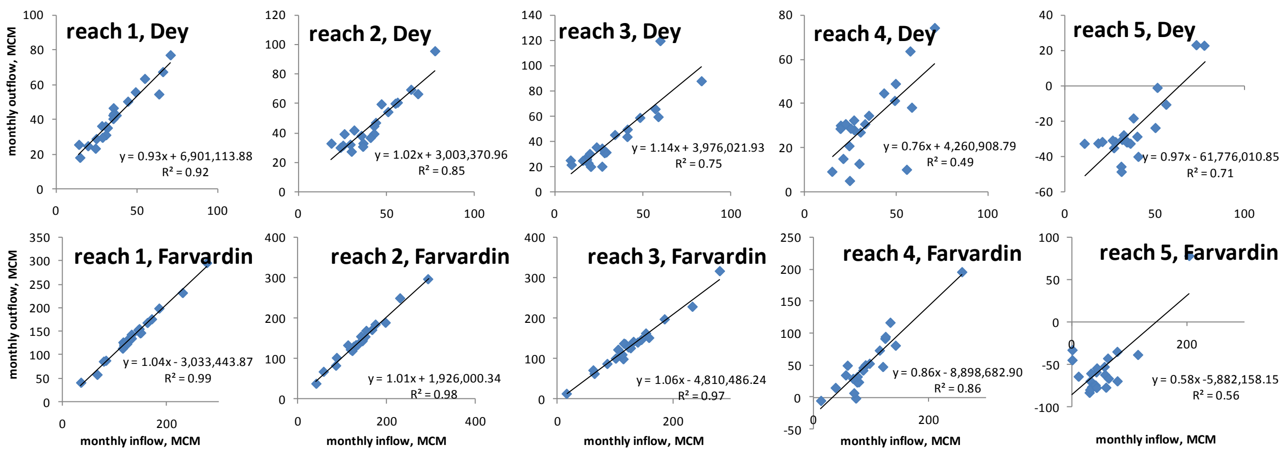

Figure 2: Simulated monthly outflow of surface water at the studied reaches in two months of Dey, Farvardin.

Change in storage and its ratio in a hydrologic period

In equation 3, it was assumed that the changes in surface water storage equal zero.

Now, from the difference between the actual outflow and the simulated outflow we can obtain changes in the surface water storage by subtractingequation 3 from equation 2 as follows:

$$\Delta Q_{so} = -\Delta S_s + \Delta Q_g + \Delta Q_i = Q'_{so} - Q_{so}^T \qquad \text{Equation (6)}$$

In which ΔQ_{so} is the difference in simulated outflow and inflow in the surface water system, ΔQ_g is the change in the groundwater flow, which is related to the net exchange of surface water and groundwater (Note: in equation (1), $Q_{gg} - Q_{gl} - Q_{il}$, has been equal to $C_g + \Delta Q_g$, with the assumption that the static level of ΔQ_g was set to zero.) It should be noted that ΔQ_g in equation 6 indicates the change in storage in groundwater (ΔS_g). If ΔS is the total change of storage in a reach, the equation 6 can be rewritten as follows:

$$\Delta S = \Delta S_s + \Delta S_g = -\Delta Q_{so} = Q_{so}^T - Q'_{so} \qquad \text{Equation (7)}$$

The above equation states that the total change in storage within river reach is a combination of changes in surface water storage and changes in groundwater storage. A positive or negative storage change indicates that a reach stores a larger amount of water or would discharge it to its downstream reach in that month. In a hydrological year, changes in annual storage (i.e., ΔS_a^+ is the total positive storage, and ΔS_a^- is the total negative storage) can be obtained from changes in monthly storage in that hydrological year by equation 7.

The total annual storage change can be written as $\Delta S_a^T = \Delta S_a^+ - \Delta S_a^-$ (note that the ΔS_a^- value is negative). The remainder of the annual change in storage or the net storage change can also be written as $\Delta S_a^R = \Delta S_a^+ + \Delta S_a^-$. Now, the ratio of annual change in storage (R) is defined as follows.

$$R = \Delta S_a^R / \Delta S_a^T = (\Delta S_a^+ + \Delta S_a^-)/(\Delta S_a^+ - \Delta S_a^-) \qquad \text{Equation (8)}$$

According to equation 8, three types of storage changes can be defined [10]: (1) balanced, when -15%≤R≤15% (2) positive (increasing), when 15%≤R≤100% (3) negative (decreasing), When -100%≤R≤-15%. The normal state means that net change in water in a reach in one year is insignificant [10].

Results

According to the presented method in the previous section, the simulated outflow equations, the storage changes and the relationship between surface water and groundwater in five reaches, were studied and the pattern of relationship between them in normal and drought periods was also evaluated.

Simulated outflow equations

To extract simulated outflow equations downstream the Zayandehrood Dam, river flow data in hydrometric stations of Sadtanzimi, Polzamankhan, Polkale, Lenj, Polchoum and Verzaneh, as well as data related to drinking water and industry and return water were used. The equations were obtained by Excel software using monthly inflows and outflows for five river reaches. A sample of extracted relations for the studied reaches in two months of the year is shown in Figure 2. The values of the simulated equation parameters are also presented in Table 2. In this study, by using inflows and outflows of each reach per month, an equation was extracted. As shown in Figure 2 and Table 2, all reaches have linear simulated outflows.

Table 2: Simulated outflow parameters in the studied reaches.

Reach	Simulated outflow parameters	Mhr	Abn	Azr	Dey	Bah	Esf	Far	Ord	Khr	Tir	Mor	Shr	Absolute error
Sadtanzimi - Polzamankhan	α_1	-0.11	-0.04	-0.04	-0.07	0.05	0.05	0.04	-0.07	-0.05	-0.11	-0.13	-0.11	0.07
	Cg	8.65	4.47	3.82	6.90	3.64	1.44	-3.03	10.51	4.42	11.31	12.32	8.42	
	r^2	0.98	0.98	0.97	0.92	0.85	0.94	0.99	0.99	0.97	0.97	0.96	0.96	
Polzamankhan - Polkale	α_1	0.12	0.06	0.02	0.02	-0.04	0.02	0.01	0.06	0.07	0.00	0.02	0.12	0.09
	Cg	-10.88	-3.04	6.92	3.00	6.55	3.30	1.93	-8.34	-14.21	-3.18	-3.01	-17.89	
	r^2	0.97	0.95	0.95	0.85	0.91	0.97	0.98	0.99	0.96	0.93	0.94	0.98	
Polkale - Lenj	α_1	-0.01	0.01	0.00	0.14	0.15	0.03	0.06	-0.04	-0.05	-0.01	-0.07	-0.10	0.14
	Cg	1.65	0.47	7.31	3.98	1.23	-1.71	-4.81	3.03	-0.13	-8.60	-0.18	9.75	
	r^2	0.97	0.98	0.97	0.75	0.93	0.98	0.97	0.97	0.93	0.86	0.86	0.90	
Lenj - Polchoum	α_1	-0.31	-0.20	-0.23	-0.24	-0.45	-0.02	-0.14	-0.13	-0.42	-0.34	-0.35	-0.22	1.98
	Cg	-24.40	-24.36	-14.18	4.26	4.15	-12.99	-28.90	-56.31	-39.02	-72.26	-70.65	-68.73	
	r^2	0.73	0.92	0.89	0.49	0.31	0.81	0.86	0.93	0.43	0.51	0.37	0.49	
Polchoum - Varzaneh	α_1	-0.66	-0.37	-0.17	-0.03	-0.31	-0.48	-0.42	-0.22	-0.51	-1.00	-0.95	-0.80	0.41
	Cg	-64.44	-71.91	-75.65	-61.78	-43.08	-46.58	-85.88	-109.31	-88.16	-65.04	-68.77	-69.92	
	r^2	0.17	0.61	0.74	0.71	0.73	0.71	0.56	0.85	0.28	0.00	0.00	0.06	

Storage change

As previously mentioned, the annual storage change can be divided into three increasing, decreasing, and balanced modes. In this section, based on equation (7), monthly storage changes in reaches, Polzamankhan to the Varzaneh, were measured, and then the annual storage change ratio index (R) was calculated by Equation (8) and the results were presented in Figure 3, this index shows that in a water year, storage changes in a reach have been rising or falling, or whether or not these changes are insignificant. The average of positive and negative storagechanges in the studied reaches in years when they were increasing, decreasing, and normal conditions are calculated and presented in Table 3. As seen in Figure 3, the reach from the Lenj to the Polchoum is more balanced than the rest of the reaches. In other reaches, a balanced situation has been observed, too. Storage change in the reach between Polzamankhan and Polkale before 1996 has been almost falling, but after that, it has been rising.

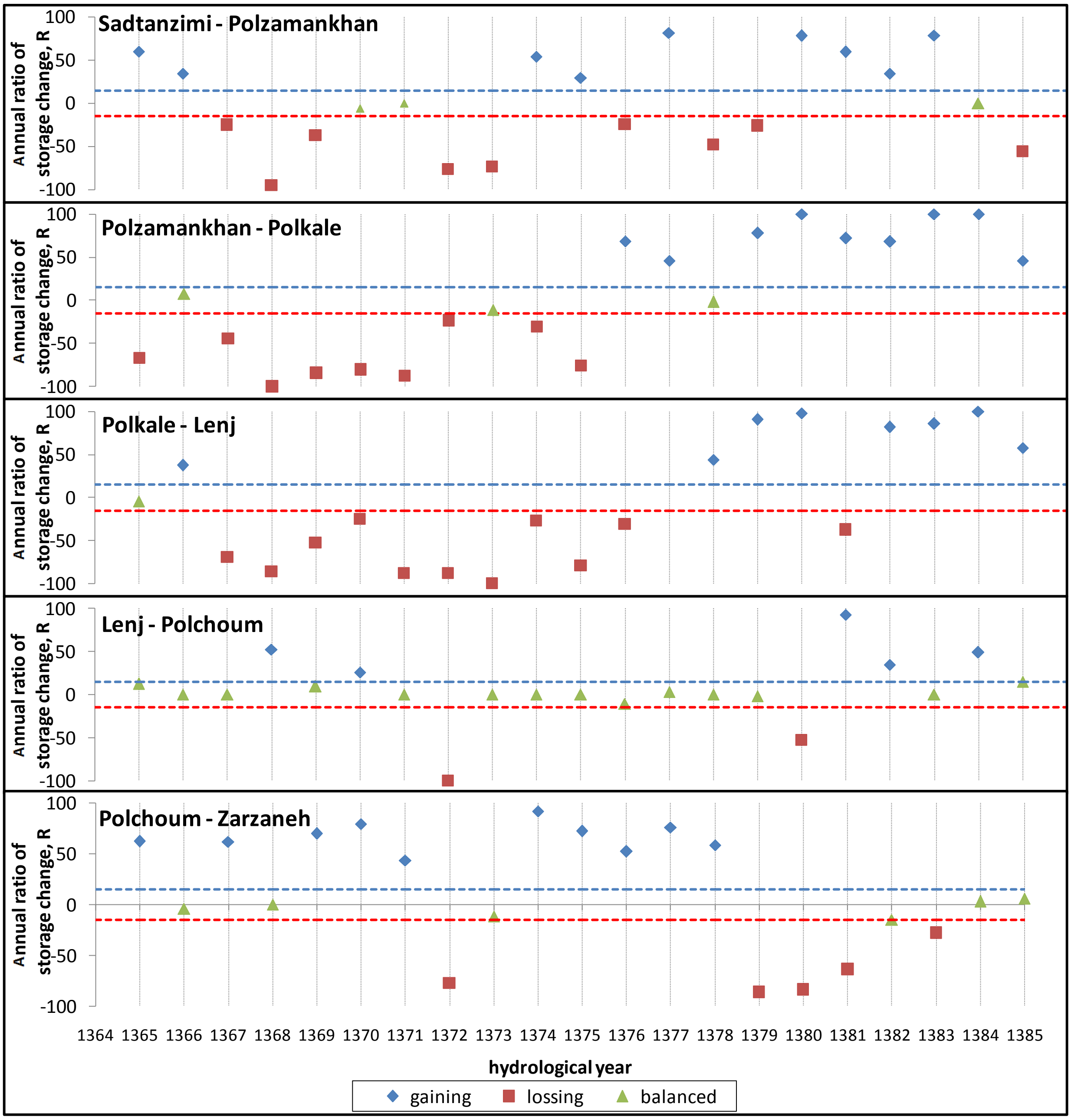

Figure 3: The annual ratio of storage change in the studied reaches.

All studied reaches have had positive changes for some years. According to Table 3 and Figure 3, the reach between Polzamankhan and Sadtanzimi had a positive storage change in 9 years with an average of 45 million cubic meters per year. Since 1995, changes in the annual storage in this reach have been positive for most years. Storage changes in the reach leading to the Polkale station has also been rising in 9 years with an average of 76.8 million cubic meters per year. The storage change around the Polkale and the Lenj has been positive for 8 years with an average of 139 million cubic meters per year.

In the reach between Lenj to Polchoum range, positive storage changes over a five-year period reached an average of 129 million cubic meters per year. It was observed that changes in the annual storage of this reach were more balanced. Based on the results, the storage changes in the last are have increased over the years. The average annual storage change in this reach was estimated 123 million cubic meters per year.

Based on Figure 3, the first three reaches from the mid-1980s to the following decades have encountered increasing storage change and somehow increasing water extraction. As can be seen from Table 3 and Figure 3, all studied reaches also have negative storage changes at some points.

Table 3: Average change of annual storage for the six reaches under study.

Reach	Storage change $\Delta S = Q_{so}^{T} - Q'_{so}$ (MCM/y)				
	Positive (+)	Negative (-)	Residue	Residue Rate (%)	Type
Sadtanzimi - Polzamankhan	45.4	-22.3	23.1	34.1	Positive
	17.0	-44.7	-27.7	-45.0	Negative
	26.3	-41.4	-15.1	-22.3	Balanced
Polzamankhan - Polkale	76.9	-10.0	66.9	77.0	Positive
	14.7	-87.9	-73.2	-71.3	Negative
	50.4	-29.1	21.3	26.7	Balanced
Polkale - Lenj	139.4	-24.0	115.4	70.6	Positive
	21.1	-103.5	-82.4	-66.1	Negative
	34.2	-56.2	-22.0	-24.3	Balanced
Lenj - Polchoum	129.0	-50.3	78.7	43.9	Positive
	41.1	-128.6	-87.5	-51.6	Negative
	73.0	-48.8	24.2	19.9	Balanced
Polchoum - Varzaneh	123.8	-36.2	87.7	54.8	Positive
	34.3	-236.5	-202.3	-74.7	Negative
	77.9	-76.8	1.0	0.7	Balanced

Interactions of surface water, groundwater and atmosphere

Interactions in a normal water year

In this study, in order to evaluate the water exchange in a normal water year, the long-term average (1981-2012) of the Zayandehrood River flow in the Sadtanzimi Station was used. The average flow of the river during this period was 1444 million cubic meters per year.According to the historical series of the river in this place, the amount of flow in the water years of 1374-1373 is 1446 million cubic meters, the closest number to theaverage. Therefore, by choosing this year as a normal water year, using the outflow equations (Figure 2), the outflow values of the studied reaches are calculated downstream the dam, and the results are presented in Table 4.

Table 4: Interactions calculated in a normal water year, million cubic meters.

Reach Name	Inflow (Q_{si})	Surface water exchange with atmospheric water ($\alpha_1 Q_{si}$)	Surface water exchange with groundwater (C_g)	Net surface water exchange ($\alpha_1 Q_{si} + C_g$)	Outflow	Net surface water exchange (%)
Sadtanzimi					1446 [a]	98.3
Sadtanzimi - Polzamankhan	1446	-100	73	-27 [b]	1431	-1.7
Polzamankhan - Polkale	1431	64	-39	26 [a]	1295	1.7
Polkale - Lenj	1295	-26	12	-14 [b]	702	-0.9
Lenj - Polchoum	702	-171	-403	-574 [b]	354	-35.6
Polchoum - Varzaneh	354	-147	-851	-997 [b]	186	-61.8
Lower Varzaneh	186					

+ Increased surface water through the atmosphere or groundwater, or both
- Surface water losses to the atmosphere or groundwater, or both
avalues used to calculate total surface water produced downstreamZayandehrood Dam (1471 million cubic meters).
bvalues used to calculate total net consumption of water in the downstream basins of the Zayandehrood Dam (1613 million cubic meters).

As seen from Table 4, almost all surface water released downstream, is from the dam, and only a small amount of 26 million cubic meters (1.7%) in the Polzamankhan-Polkale has been added to surface water. In surface water exchange with groundwater and atmosphere, 27 (1/2%), 14 (1/1%), 574 (41.7%) and 997 (56%) cubic meters of surface water respectively have been decreased in the reaches of the Sadtanzimi-Polzamankhan, Polkale - Lenj, the Lenj-Polchoum and Polchoum-Varzaneh.

According to Table 4, in the normal water year, 186 million cubic meters of surface water and goes out of Varzaneh Station and enters Gavkhoni swamp.

Interactions in a severe drought

According to the hydrograph of Zayandehrood River, annual flow at the set dam station, the most severe drought has occurred at hydrological period 2000-2001. This hydrological year was selected as a severe drought year and its flow data was used to examine water exchange. The inflows and outflows of each reach are presented in Table 5. The simulated outflow for each reach was calculated using the equations presented in the previous section and the values of the parameters in Table 2 were calculated.The values of flow in a normal water year are also given in Table 5 for comparison with the drought condition. In this section, it is assumed that in the normal water year, surface water of Zayandehrood River downstream the dam can meet all the needs of the studied reaches. Compared to the normal water year, significant changes are observed in surface water exchange with groundwater and the atmosphere under severe drought conditions. During a drought, the inflow water in the set dam can only meet the needs of the first three reaches and, as shown in Table 5, the other two reaches faced water shortage. In the first and third reaches, surface water is fed by groundwater. This increase in surface water is respectively 13% and 4% outflow of these reaches in drought conditions.

Table 5: Water exchange during normal and drought periods, million cubic meters.

Reach	Observed or calculated Inflow (MCM/y)	Observed or calculated Outflow (MCM/y)	Net supply (+) or use (-)[a] (MCM/y)	Simulated outflow[b] (MCM/y)	Storage change (MCM/y)	Water deficit[c] (MCM/y) (%[d])	Gain from Groundwater (MCM/y) (%[e])
Sadtanzimi -							
Normal	1446 [f]	1431 [g]	-27	1431	0		73 (5%)
Drought	563 [f]	564 [f]	34	609	44		73 (13%)
Differen	-883	-867	61	-822	44		
Polzamankhan - Polkale							
Normal	1431 [g]	1295 [g]	26	1295	0		
Drought	564 [f]	198 [f]	-13	369	171		
Differen	-867	-1097	-39	-926	171		
Polkale - Lenj							
Normal	1295 [g]	702 [g]	-14	702	0		12 (2%)
Drought	198 [f]	282 [f]	11	380	99		12 (4%)
Differen	-1097	-420	25	-321	99		
Lenj - Polchoum							
Normal	702 [g]	354 [g]	-574	354	0		
Drought	282 [f]	199 [f]	-507	97	-119	68	
Differen	-420	-298	68	-257	-119	(12%)	
Polchoum - Varzaneh							
Normal	354 [g]	186 [g]	-997	186	0		
Drought	199 [f]	1 [f]	-864	35	-356	133	
Differen	-298	-185	133	-151	-356	(13%)	

a Net supply (+) or use (-) = outflow–inflow.
b Simulated outflow
c Water deficit = Net use (-) in drought – net use (-) in normal.
d The percentage is the ratio of water deficit in the absolute value of its net use in normal year.
e The percentage is the ratio of gain from groundwater in outflow.
f Observed.
g Calculated

Discussion

In this study, the simulated outflow equations were extracted for the five reaches downstream Zayandehrood Dam and the results were presented in Table 2 and Figure 2. According to Table 2, the simulation of the outflow flow in the last two reaches has been less accurate. In such a way that the explanation coefficients in the two reaches leading to the Chum bridge and Varzaneh are less than other reaches. The absolute error value also confirms the decrease in the accuracy of the simulation in these two reaches. This low accuracy is due to the complexity of the surface water system and the lack of precise measurements of water extraction and water exchange between the last two reaches.

The only surface water inflow to reach 1 (Sadtanzimi - Polzamankhan) is the released water from the Zayandehrood dam. In this reach, there is no water transfer to the outside of the basin, and extraction from the river only includes small pumping and drinking water for local residents. The average annual extraction of water and rainfall in this reach has been reported to be 3 and 1.2 cubic meters per second, respectively [15].

Surface water gaining from groundwater in the Sadtanzimi - Polzamankhan can be as a result of hydraulic connections of the Zayandehrood reservoir with groundwater in this reach. Groundwater in this reach is discharged through 80 deep and semi-deep wells, 278 qanats and 589 springs. It is noted that groundwater extraction is more than springs and qanats, and nearly 85% of it is consumed in the agricultural sector [14]. With groundwater modeling, more accurate information can be obtained on the relationship between surface water and groundwater in this reach.

In the reach between Polzamankhan and Polkale in addition to the water outflow from Polkale station, upstream this station, drinking water is transferred to Isfahan and Yazd. Transfer of Isfahan's drinking water began in1988 and its transfer to Yazd began in 1999. The average annual transferred water from Isfahan during the study period (water years of 1986 to was 4.5 cubic meters per second and the transferred water to Yazd was 1.8 cubic meters per second. In Salemi et al. study, extraction of drinking water and pumping in this reach of the river was reported to be 1.7 cubic meters per second [16].

The distance between the Polkale Station and the Lenj station is the start of important water extractions from Zayandehrood. The only inflow to this reach is the main river flow from the Polkale station. Outflows of this reach in addition to the flow of the Zayandehrood River at Lenj station, include transferred water to Mahyar-Jarghouyeh network and water diversion into Nekoabad network. The average annual extraction of industrial water and pumping in this reach were reported to be 2.5 and 6.6 cubic meters per second, respectively [17]. According to the reports from the map, the groundwater level in the Zayandehrood Basin, around the Polkale-Lenj, the direction of flow is from the groundwater to the river and the outflow of the reach [14]. The results of this study also indicate the feeding of surface water by the aquifer in this reach and subsequently confirm the movement of groundwater towards the river. The presence of Shour river basin on the right bank of the river with a drainage surface of 1700 square kilometers, artificial feeding plans in the basin and deep penetration of agricultural lands within this reach can be the reasons for the increasing of net surface water by groundwater in this reach of the river.

In the reach between Lenj and Polchoum, surface water has losses to both atmosphere and groundwater. The existence of agricultural lands of Nekoabad and Borkhar water supply networks and the existence of more than 12,000 deep and semi-deep wells in this reach testify to the high consumption of water resources. The average annual discharge of 690 million cubic meters of water from the aquifer in this region has led to thedrop in static level and, as a result, the feeding of aquifers by the river [14]. It should be noted that Borkhar's water supply network from the Nokabad dam is at the upstream reach and off the main river. Since the Nekoabad irrigation network site is located upstream the Lenj Station, therefore, the historical series of water extractionfrom this network in the reach upstream the Lenj Station as transferred outflow and downstream reach as inflow transferred water entered the equation 2.The drinking and industrial extractions and pumping in this reach of the river were reported to be 1.77 and $4m^3$ per second, respectively [17]. The water extraction for waterfall network is also in this reach, where the historical series of this deviation entered equation (2) as outflow.

In the last reach between Polchoum and Varzaneh, on average, approximately 2,225 million cubic meters of surface water have been annually delivered to the two irrigation networks of waterfall and Roudasht. This reach has a surface water loss to the atmosphere. Approximately 700 million cubic meters of aquifers in Kouhpayeh-Segzi reach are often discharged for agricultural use annually [14]. Therefore, in this reach of the river, feeds the aquifer, and this confirms the results obtained in Table 2 and Figure 2. Since the water deviation for waterfall network is located upstream Polchom station, the historical series of this extraction was considered as the inflow of the fifth reach.

Based on Figure 3, there were rising and falling storage changes in all reaches. Positive storage change is one of the characteristics of the reaches with water shortages in these years and hydrological periods, and one of the characteristics of reaches with a negative storage change can be the presence of excess water in that reach. Storage changes in Polzamankhan-Polkale reach have been increasing since the mid-1980s before which was decreasing . Polkale station is located downstream the Chamaseman dam, the point where Isfahan's drinking water and transferred water to Yazd are extracted. With increasing capacity of Babashikhali's water treatment plant, extraction of Isfahan's drinking water increased since 1993. Also, Yazd water transfer tunnel opened in 1999. So, since the mid-seventies, less water has been discharged into the downstream reach. Hence, during this decade, the storage condition of this reach has been changed from negative to positive.

Investigating the interaction of surface water and groundwater under normal conditions showed that the studied reaches from Polzamankhan to Varzane received a net amount of about 64 million cubic meters (the sum of the positive values in the third column of Table 4) from the atmosphere every year. And also loses 444 million cubic meters (the sum of the negative values in the third column of Table 4) per year through evaporation, evapotranspiration. Salemi and Heidari in addition to evaluating the resources and uses of Zayandehrood basin, considered the third phase of water consumption (1986-2009) concurrent with the opening of Koohrang tunnel in 1365, followed by an increase in water consumption to 1500 million cubic meters in a year and proper flows in the basin outflow (550 million cubic meters per year).

The net increase in surface water through the atmosphere has occurred only in the reach leading to Polkale, while net water losses to the atmosphere are distributed among other reaches, in a way that the reaches of set dam-Polzamankhan, Polkale-Lenj, Lenj-Polchoum, and Polchoum-Varzaneh, respectively, account for 23, 6, 38 and 33 percent of the water discharge into the atmosphere (evaporation and evapotranspiration). Zayandehrood River downstream the dam is fed by a net amount of 85 million cubic meters per year (the total of positive valuesin the fourth column of Table 4) through groundwater and 1293 million cubic meters per year (the total of negative valuesin the fourth column of Table 4) is lost through leakage to the groundwater.

Table 5 shows that during the drought, the first three reaches did not suffer from shortage. extractions and water exchange have been such that the observed outflow of these three reaches were reduced to half the inflow. In contrast, the fourth and fifth reaches, respectively, faced shortages of 68 and 133 million cubic meters per year, and these shortages account for 12 and 13 percent of water use in normal conditions, respectively. In the first and third reaches surface water has net gain under drought conditions, while under normal conditions, these reaches extracted water. According to the results of Table 5, the rest of storage changes also showed that in drought conditions, the first three reaches had positive storage changes. This means that the maximum change in the increasing storage was related to the second reach with 171 million cubic meters per year, and the maximum change in decreasing storage in the last reach was 356 million cubic meters per year. The annual storage ratio of the first to fifth reaches in drought was 78, 100, 98, 53 and 84 percent, respectively.

Conclusion

Economic development and population growth over the past decades have overloaded the water resources of the Zayandehrood basin, and it has been difficult to allocate water, especially in water shortage conditions. Inter-basin water transfer and the lack of integrated, interconnected management of surface water and groundwater have increased the intensity of this tension. The relationship between surface water and groundwater has a great impact on the quantity and quality of water. One of the management strategies to increase the security and sustainability of water resources is reducing the water share of water carriers in the basin. While the relationship between river systems and groundwater in Zayandehrood basin remains unknown. Therefore, the consequences of reducing allocations in a complex basin, such as Zayandehrood, will be uncertain and controversial.

In this study, a method for assessing the exchange of surface water and groundwater was proposed. This method evaluates the exchange of surface water and groundwater using cumulative flow data at the inflow and outflow of each river reach, and the extraction for drinking water and industry and return water in each reach. Based on this, a general equation for the simulated outflow was obtained. This equation is a polynomial function of the inflow flow. Based on the balance of water in the studied reach, the constant value of the function indicates the relation between surface water and groundwater and the rest of the function statements indicate the relation between surface water and the water in the atmosphere. In this study, all reaches had linear simulated outflows. On the basis of the obtained equations, surface water in the first three reaches in some months of the year and in the last two reaches in all months, hadlosses in the atmosphere. The results showed that surface water in the reaches which end up to the Polzamankhan and Lenj stations, have net gain by groundwater, while in other reaches, surface water losses to groundwater.

The results of this study showed that in the normal state, 1471 million cubic meters of surface water are exchanged annually with groundwater and the atmosphere, almost all of which are supplied from the Zayandehrood dam, and a small amount in the Polzamankhan-Polkale is added to it which is from the net exchange of atmospheric and groundwater with surface water. In the net exchange of surface water with groundwater and the atmosphere, in a normal year, 1613 million cubic meters are used in downstream reaches of the dam. The reaches leading to the Polzamankhan, Lenj, Polchoum and Varzaneh use 1.7, 0.9, 35.6 and 61.8% of surface water, respectively. Similarly, the exchange of water in a water year with severe drought was also studied. The results showed that in these conditions, the first three reaches did not suffer from water shortage and supplied their own water, but other reaches faced water shortage. The net increase in surface water by groundwater in the first and third reaches compared to the outflow of these reaches was higher in the drought than in the normal water year, which indicates the importance of groundwater under drought conditions.

Due to the lack of detailed information on extractions and return water to the river, the components of the surface water balance of the reaches in this study entered into the equation in general, and some of the average annual data was used to discuss them. However, the results obtained in this study and their comparison with the data and information from previous studies showed that the proposed method is a suitable tool for assessing the exchange of surface water with groundwater. Therefore, it is suggested that in future studies this method be studied with more accurate data on extraction and return water. Comparing the results of this method in different time dimensions with various management and hydrological scenarios can be the basis of other studies in this regard.

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Conflict of interest

There are no conflicts of interest.

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