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Determination of water requirements of the Gavkhuni wetland, Iran: A hydrological approach

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ABSTRACT

This study compared three hydrological methods – low flow frequency analysis, flow duration curve (FDC), and concentration-discharge (C-D) modeling – to determine the water requirement of the Gavkhuni wetland located in an arid region of Iran. Due to the effects of water impounding upstream on the hydrological regime of the Gavkhuni's inflow after construction of the Zayandehrud dam, none of the methods produced satisfactory results.

Consequent modification of the hydrological regime of the wetland's inflow using a scaling process allowed all the methods except low flow frequency analysis to dependably estimate the base flow for the wetland. The results of the C–D method revealed that this method can provide a minimum health condition from the water quality point of view, while the results of the FDC demonstrated that not only the inflow estimated using this method can supply minimum conditions in terms of water quality parameters, but it also covers most areas of the wetland, based on the results of hydraulic modeling.

The results reveal that the hydrological methods implemented in this study can dependably estimate environmental water allocation for wetlands in arid and semi-arid regions when there is no detailed knowledge about the biological requirements of the wetlands' biota.

1. Introduction

As unique and highly productive and biologically diverse ecosystems, wetlands provide many advantages to the planet. These natural treasures covering 6% of the world's land surface also provide many critical benefits to human society: water storage and flood attenuation, water quality improvement and maintenance of biodiversity and resilience to the stresses of development (Cui et al., 2009). But in recent decades, the effects of rapid population growth and the abstraction of surface water for public water supplies, industry and agriculture has led to reduced water availability for wetlands and has threatened the survival and health of these natural ecosystems, especially in arid and semi-arid regions (Acreman et al., 2007; Jia and Luo, 2009).

Since wetlands are dynamic systems, vulnerable and particularly susceptible to quantity and quality changes of inflow (Erwin, 2009), the altering the water regime of many wetlands due to the combined pressures of climate change and increasing water demands arising from population growth illustrates the importance of effective long-term strategies for ensuring stable and healthy conditions for these ecosystems.

In arid and semi-arid regions during severe drought conditions, the interruption of a wetland's inflow not only affects its hydrological regime, but also destroys its ecological functions. As the environmental and ecological value of the wetlands in arid and semi-arid regions is being increasingly realized, protecting and restoring them with regards to the variability and uncertainty of their future climate conditions are now crucial parts of regional water resources management and planning (Jia and Luo, 2009). Therefore, acknowledging wetlands' services requires an understanding of the hydrological conditions of wetlands so that sufficient water can be supplied to them to produce desired ecological effects and meet environmental demands. Thus, determining an accurate quantity of inflow distribution to maintain an adequate level of wetness can help these ecosystems better perform their biological functions in continual water deficit periods.

Generally, approaches to determining water requirements of terminal wetlands can be divided into two main methodologies: hydrology driven and ecology driven (Gippel, 1996). As a significant advantage of the ecology-based approaches is addressing wetland

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water requirements based on the existing or preferred biota's water needs, the lack information regarding species' requirements is considered the main disadvantage of these methods (Davis et al., 2001). On the other hand, water regimes of wetlands may be determined through the use of hydrological data or by modeling (Zhang and Mitsch, 2005). Although the lack of information of the current ecological values is considered a limitation of the hydrological approaches (Davis et al., 2001), the low cost of these methods is advantageous when there is no detailed knowledge about the water requirements of the wetlands' biota.

In arid and semi-arid regions, due to long-term droughts, wetlands experience prolonged water shortages. During these periods, the interruption of the inflow mostly leads to the extinction of the wetlands' biota. Under such conditions, due to lack information on ecological indicators, determination of the water requirement of wetlands is not possible using ecological approaches. Therefore, to restore the ecosystem, hydrological-based approaches that use historical hydro-climatic data are the best alternatives for determining water requirements of wetlands in terms of quantity and quality.

Some studies have applied hydrological approaches to determine water requirements, but most of them have focused on determining a river's water requirements, not specifically a wetland's (Gordon et al., 1992; Liu et al., 2002; Song et al., 2007). Existing research determining wetland water requirements is focused on calculation of the water requirement based on a water balance approach (Dunn and Roach, 2001), climatic models (Jia and Luo, 2009; Miralles-Wilhelm et al., 2005) and eco-hydrology methods (Wassen and Grootjans, 1996). The various inputs required for these methods limit their application in determining wetland water requirements. Information about these parameters needs to be obtained over long periods of observation, and unfortunately, in arid and semi-arid regions, this required information is rarely recorded and, where records are available, they are usually too short to act as a basis for reliable conclusions (McCosker, 1998). A few attempts have specifically been made to develop models to predict the water boundary extent of wetlands based on hydrologically-based approaches in arid and semi-arid regions. Gumbricht et al. (2004) developed a statistical model based on remote sensing satellite images and hydrological information to predict the area of flooding and spatial distribution, and also the extent of wetland loss, arising from water abstraction from the Okavango Delta wetland in southern Africa. Murray-Hudson et al. (2006) also studied the combined impact of up-stream developments (such as daming, water abstraction and deforestation) and climate change to flooding characteristics (floodplain water depth, inundation duration and frequency), and ecosystem services provided by the Okavango Delta. The results revealed that the combined effects of human abstraction and climate change may result in reduction in river flows and significant Delta drying, and consequently affect the Delta floodplain ecosystems. Jia and Luo (2009) presented a model simulation study based on the relationship of water supply, weather, and soil data to estimate the minimum requirement of wetland hydrology in arid and semi-arid regions. Since hydrological methods need less input information than other approaches, and as ecological and biological information on wetlands in arid and semi-arid regions is less plentiful than that on other regions, hydrological approaches could lead to a quantitative and qualitative understanding of a wetland's water requirement.

The objective of this study is to introduce simple hydrological methods for determining the threshold of water requirements for wetlands facing long-term impacts of drought and human manipulations. Hydrological-based approaches in this study use historical water quality parameters and inflow data to determine seasonal inflow volumes that are sufficient to maintain healthy and functional wetland ecosystems in terms of water quantity and quality in arid and semi-arid regions.

2. Study area

Located in the arid region of central Iran (52° 39′ E 32° 25′ N), the Gavkhuni wetland is one of the most important aquatic ecosystems of this region, registered in the international Ramsar convention in 1975 (http://www.ramsar.org). There are 1220 registered wetlands in this convention, of which 22 belong to Iran.

This natural ecosystem, with an area of 47,000 ha, is located at the end of the Zayanderud River in the Zayanderud basin. The Zayanderud river originates from the Zagros Mountains, which reach over 4500 m, and then bursts forth onto the plains at an altitude of some 1800 m. The total length of the river is about 350 km, and in the central 150 km of the floodplain to the east, the Zayanderud River passes through Isfahan, a major city with over four million inhabitants. The existence of deep and fertile soils, most of them silts and clay loams (Molle et al., 2009), has provided a basis for intensive agriculture along the river. The climate of the Zayandehrud basin varies remarkably. In the mountain parts situated at an elevation of almost 2300 m in the west of the basin, precipitation averages about 1500 mm, much of it in the form of snow that only melts when temperatures warm up from April onwards (Masih et al., 2011; Solatni and Sarhadi, 2011). In contrast, low parts, which lie just to the east of the basin, including the Gavkhuni wetland, receive only 110 mm rainfall each year, on average (Fig. 1).

The primary source of water in the basin is the Chadegan reservoir, completed in 1970, located just above the point where the Zayanderud enters the flatter parts of the basin (Fig. 1). The Chadegan reservoir, with a capacity of approximately 1500 million cubic meters, allows these natural flows to be regulated to supply drinking water to Isfahan and for industrial activities, and promotes more effective irrigation.

The Gavkhuni wetland has an important role in sustainable development of this region. From a conservation standpoint, it is one of the most valuable ecosystems in Iran, providing habitat for over 140 bird species and numerous other flora and fauna. Moreover, this ecosystem has an effective role in water refinement and stabilization of sand dunes located around the wetland. Unfortunately, recently population growth and bad water resources management have resulted in a depression of the quantity and quality of the wetland's incoming fresh water and destruction of this ecosystem has begun. Upstream diversions and unreasonable in-basin transmission of water resources and consequent reduced inflows downstream have also resulted in undesirable ecological effects on the wetland. On the other hand, the influx of excessive untreated industrial and domestic wastewater from Isfahan has influenced the wetland's water quality. All of these problems have been intensified by drought occurrences arising from climate change in recent years. These conditions have exerted adverse impacts on the wetland and have changed the hydrologic regime of the ecosystem, so that this natural ecosystem has been turned into a salt pan. Fig. 2 shows pictures of this natural ecosystem in the past and at present. As is apparent, no fauna and flora exist in this wetland.

Therefore, to restore this ecosystem and maintain it in a state of a good health, the requirement inflow of the wetland must be calculated and then supplied. Except for some halophytes, no fauna and flora are found in this salt pan. Consequently, there is no plan to define ecological water demand according to the biota's water requirements. However, this study uses hydrologically-based approaches that use quality parameters and a historical hydro-

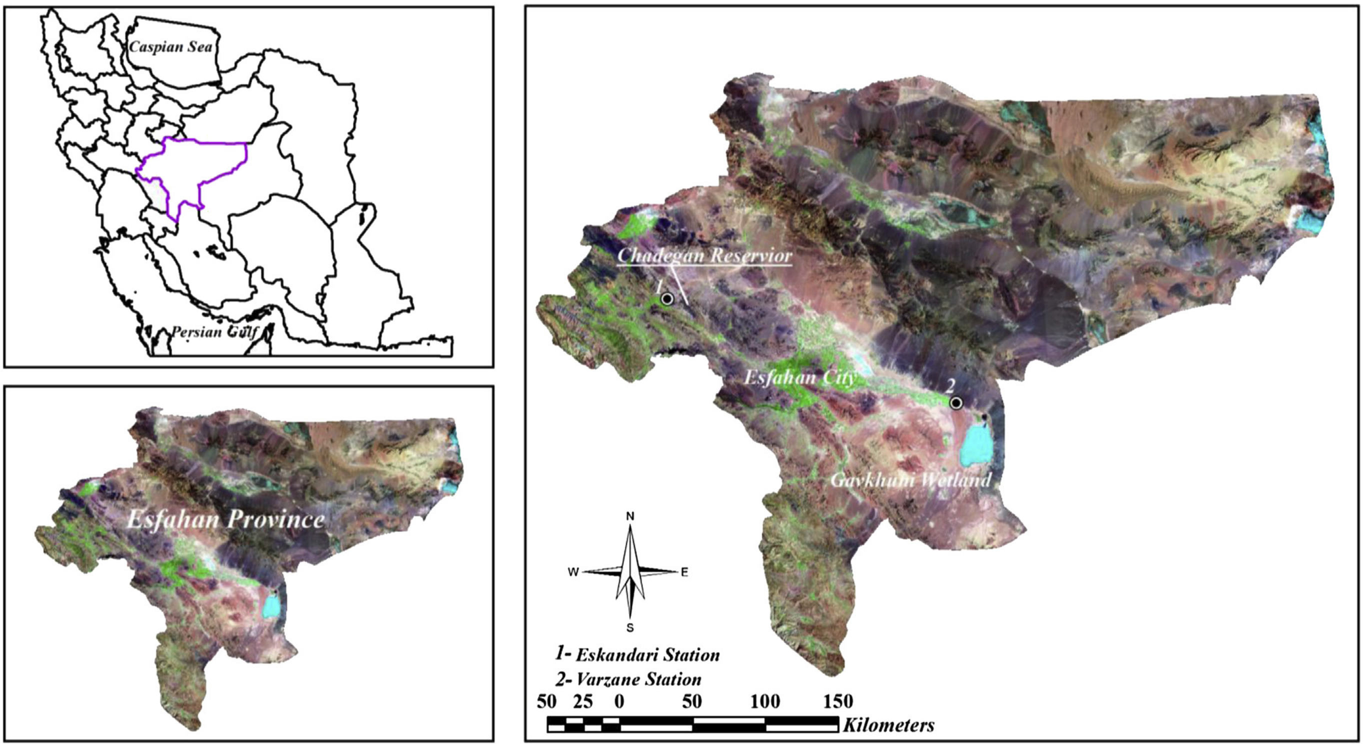


Fig. 1. Location of the Gavkhuni wetland and the study meteorological and hydrometry stations in the Zayandehrud basin.

meteorological data-set to estimate a threshold of inflow that can provide suitable wetness levels and healthy conditions for the ecosystem.

2.1. Data used

The data set used in this study is divided into two parts: hydro-meteorological data and water quality data. The hydro-meteo rological data includes daily and monthly flow magnitudes and monthly precipitation that is used to calculate the standard precipitation index (SPI). Flow information is recorded at the Varzaneh and Eskandari stations upstream of the Gavkhuni wetland and the Zayandehrud reservoir, respectively. The precipitation data is also recorded at the Eskandari meteorological station. Fig. 1 presents the location of the hydrometric and meteorological stations. The Varzane station covers the time-span of 1948–2009 for flow data. The Eskandari station time span is also from 1969 to 2007 for flow data, and precipitation data is available for the same time. The Ministry of Power and the Iran Meteorological Organization collect streamflow and rainfall data, respectively.

Water quality parameters also include: the biological oxygen demand (BOD), chemical oxygen demand (COD), NO_3 and PO_4 parameters collected daily by the Isfahan Provincial Directory of Environmental Protection for studying water quality of the wetland, between 1998 and 2009.

3. Material and methods

In order to determine an acceptable quantity and quality of the required inflow to the wetland, some simple hydrological methods are demonstrated. Because of limited inputs available, these methods are more practical than complex methods that need broader data sets. The following sections provide a brief description of the hydrological approaches used in the present study for determining the wetland's water requirement in terms of quantity and quality.

3.1. Flow duration curve and related indices

Flow Duration Curve (FDC) is a method widely used by hydrologists around the world in numerous water-related applications such as hydropower generation, river and reservoir sedi mentation, water quality assessment, water-use assessment, water allocation and habitat suitability. An FDC is the complement of the cumulative distribution function (cdf) of daily (or some other time interval) streamflows over the whole available period of record, illustrating the relationship between the frequency and magnitude of streamflow. More information about applications of this method can be found in Vogel and Fennessey (1994); Vogel and Fennessey (1995).

The construction of an FDC using streamflow observations can be performed through non-parametric procedures. Firstly, the observed streamflows $q(i)$, $i = 1, 2,\ldots, n$ are ranked to produce a set of ordered streamflows $q(i)$, $i = 1,2,\ldots,n$, where n is the sample length, and $q_{(1)}$ and $q_{(n)}$ are the largest and the smallest observations, respectively. Each ordered observation $q(i)$ is then plotted against its corresponding duration Di, which is generally dimensionless and coincides with an estimate, $p(i)$, of the exceedance probability of $q(i)$. If the Weibull plotting position (WPP) is used, $p(i)$ is (Castellarin et al., 2004; Vogel and Fennessey, 1994):

$$p_i = P\left(Q > q_{(i)}\right) = \frac{i}{N+1} \qquad (1)$$

Various other low-flow indices can be estimated from this part of the FDC. For example, the flows within the range of 60–99% times exceedance are usually most widely used in water resources management applications.

(a)

(b)

Fig. 2. The situation of the Gavkhuni wetland-(a) in the past (normal regime state), and (b) at present (abnormal regime state).

The FDC can also provide a simple and applied method for implementation of water quality management using a water quality index duration curve. Such curves are useful for determining whether a water quality standard will be violated with a specific flow frequency (Vogel and Fennessey, 1995). In other word, the probability of streamflow exceedance becomes the probability that the water quality standard will not be violated (exceeded).

3.2. Concentration-discharge (C-D) model

In order to determine a base flow in which water quality parameters remain at the standard levels, and provide a healthy condition for the wetland, a model is developed to predict concentration of water quality parameters based on inflow information. In other words, inflow data at different exceedance probabilities extracted from the FDC approach are substituted into the concentration-discharge models to select which inflow magnitude can maintain water quality parameters at an acceptable level.

A bivariate linear model for the relationship between the logarithm of the concentration and flows is expressed as:

$$c = \alpha + \beta q + \varepsilon \quad (2)$$

where $c = \ln(C)$, $q = \ln(Q)$, $\alpha$and β are model parameters, and ε is normally distributed model errors with zero mean and variance $\sigma_{\varepsilon}^2 = (1-\rho_{cp}^2)\sigma_c^2$, where ρ_{cp}represents the correlation between c and q, and $\sigma_c^2$is the variance of c (Vogel et al., 2005). We assume that both c and q follow a normal probability distribution. After we establish our models, calculating flow quantity with different levels of probability calculated by the Flow Duration Curve (FDC) approach allows us to estimate the corresponding concentration of water quality parameters. Estimated water quality parameter values allow us to conclude whether or not the corresponding flow can meet water quality standards.

3.3. Low flow frequency analysis

Low flow statistics provide another index that can be used to calculate water requirements for wetlands and to investigate the effects of prolonged droughts on aquatic ecosystems.

Understanding the frequency and duration of low flows represented by the 7-day annual minimum series is critical to the efficient management of water resources. Because of short record lengths for reliable frequency quantification, different theoretical distribution functions are used to extrapolate beyond the limits of observed probabilities and improve the accuracy of low flow estimation. Several frequency distributions are used in at-site low flow frequency analysis. The most frequently recommended distribution functions in studies are different forms of Weibull, Gumbel, Pearson Type III and Log-normal distributions (Stedinger et al., 1993). The Log-normal distribution has been widely used for low-flow time series, because it is simple and has many hydrologic variables bounded by zero on the left and positively skewed (Haan, 1997). Goodness-of-fit tests, such as the Chi-Square and the non-parametric Kolomogrov–Smirnov tests, can be used to help determine the robust distribution function.

Among the most widely used low flow indices, 7-day 10-year low flow (7Q10), defined as the lowest average flow that occurs for a consecutive 7-day period at the return period of 10 year, is considered a popular low flow criterion in water resources management (Modarres, 2008). The average of the annual series of minimum 7-day flows is known as dry weather flow (Smakhtin, 2001). The 7-day period covered by the mean annual 7-day flow eliminates the day-to-day variations in the artificial component of the river flow, and analysis based on these series is less sensitive to measurement error.

The problem which often arises in low flow frequency analysis and constructing FDC is the existence of zero and insignificant flow values, which are usually found in arid and semi-arid reigns. In these regions, streamflow may frequently fall to zero or insignificant values because of severe continuous drought events and subsequent upstream water exploitation. The presence of this data may lead to difficulties in frequency analysis. In other words, the occurrence of dry periods results in most recorded flows being settled in the down tail of flow curves and influencing the results of analyses of wetland's water requirement computations. Therefore, in the present study we try to identify and modify the effects of the drought periods arising from water management of basin and their effects that deflect natural flow regimes from hydrological and ecological normal conditions, and then apply the hydrological indices to the modified flow time series.

3.4. Hydrological droughts and SPI index

Dry periods occur when a prolonged period of poor rainfall reduces streamflow and causes a continuous water deficit over a specific period of time. On the other hand, lack of precipitation for an extensive period (which is known as meteorological drought) results in water scarcity, and it propagates through the hydrological cycle and gives rise to different types of droughts.

Meteorological droughts are generally evaluated by deviation from the mean precipitation. The standard precipitation index (SPI) (McKee et al., 1993), which describes this deviation is widely used for evaluating meteorological drought. The SPI index allows hydrologists to be aware of the characteristics of the meteorological droughts (start time, duration and severity), and consequent hydrologic drought events. Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of the precipitation totals for a station. The parameters of the gamma distribution are estimated for the station, for the time scale of interest (3, 6, 12, 24 months, etc.), and for each month of the year(s). The cumulative probability according to the distribution and for each value of precipitation is transformed to the standard normal random variable Z with a mean of zero and variance of one, Z being the value of the SPI. On the basis of the SPI value, the severity of drought can be assessed and categorized into different classes. Table 1 presents the categories of drought corresponding to their SPI values. According to McKee et al. (1993), meteorological drought is defined when SPI becomes −1.0 or less. The beginning of this drought is then defined as the point when the SPI first becomes negative. The end of the drought does not occur until the SPI goes back to positive.

In arid and semi-arid regions, at times when a meteorological drought is not occurring, water abstraction upstream is increased for urban uses (drinking water and green space needs), agriculture and industrial consumption by dam regulating, and consequently, inflow of terminal wetlands is restricted. During these periods, called "dry spells", the hydrological regime of the wetland and ecological health conditions are influenced, even though technically meteorological drought is not occurring, and calculation of the wetland's water requirement by hydrological approaches leads to underestimation of the inflow despite these periods.

Almost all drought indices are based on the basic method of truncation used to derive drought events from continuous or discrete records of streamflow, precipitation, temperature, ground water drawdown and lake elevation (Chang and Kleopa, 1991).

However, in the present study, to calculate a reliable requirement inflow, after identifying meteorological droughts using an SPI index, dry spells arising from water impounding upstream (by the Zayanderud dam), are modified by an upstream station which is not affected by the Zayanderud dam, in order to make the seasonal pattern of the wetland's inflow as similar as possible to the natural flow regime's seasonal patterns. In order to confirm dry spells and detect the wetland condition during these periods, Landsat satellite images processed with geometric and atmospheric corrections are

Table 1
Drought categories based on SPI values.

Drought Category	SPI values
Near normal	0 to −0.99
Mild to moderate drought	−1.00 to −1.49
Severe drought	−1.50 to −1.99
Extreme drought	−2.00 or less

used. After modifying dry spell time series, an inflow time series of the pre-dam period is also added to the modified time series of the Gavkhuni's inflow, and this modified version is then used for reliable computation of wetland inflow requirement using hydrological criteria.

3.5. Test for trends and homogeneity

Recently, nationwide studies have reported negative trends for annual rainfall in two thirds of stations (67%) across Iran, most of which are located in the central region of the country in arid and semi-arid areas (Modarres and Sarhadi, 2009; Modarres and da Silva, 2007). Nasri and Modarres (2009) also demonstrated positive trends in dry spells and an individual abrupt change in the magnitudes of dry spells since the 1980s, especially in eastern arid and semi-arid regions of Isfahan province. To apply hydrological methods, initially it is necessary to check the homogeneity and nonexistence of trends in modified flow time series. To evaluate trends and skewed data in streamflows, we applied the popular non-parametric Mann–Kendall test (MK test), widely used in the literature for trend assessment.

For a sample of n size, $x_1, \ldots, x_n$, and the null hypothesis that the sample is independent and identically distributed, the alternative hypothesis of a two-sided test is that the distributions of x_i and x_j are not identical. The MK test statistic is written thus:

$$S = \sum_{i=1}^{n} \sum_{i=1}^{i-1} \mathrm{sign}(X_i - X_j) \tag{3}$$

The mean and the variance of S are written as follows:

$$E[S] = 0 \tag{4}$$

$$\mathrm{var}[S] = \frac{n(n-1)(2n+5) - \sum_{p}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{5}$$

where t_p is the number of ties for the pth value, and q is the number for tied values. The standardized test statistic (Z_{MK}) is computed by:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{6}$$

A positive Z_{MK} indicates an increasing trend, while a negative Z_{MK} shows a negative trend.

To test the homogeneity of new streamflow time series, the "run test" is applied in this study. In this test, a time series of length n and x_{med}, the median of the time series, is considered. We assign a code called 'a' for any value $x_j > x_{\mathrm{med}}$ and a code called 'b' for any value $x_j < x_{\mathrm{med}}$. Each uninterrupted series of 'a' and 'b' codes is called a 'run'. The distribution of the number of runs (R) approximates a normal distribution with the following average (E) and variance (Var):

$$\mathrm{E(R)} = \frac{\mathrm{N}+2}{2} \quad \mathrm{Var(R)} = \frac{\mathrm{N(N-2)}}{4(\mathrm{N}-1)} \tag{7}$$

The Z statistic is defined as:

$$\mathrm{Z} = \frac{\mathrm{R} - \mathrm{E(R)}}{\sqrt{\mathrm{Var(R)}}} \tag{8}$$

For a significance level of $\alpha = 0.01$ and$\alpha = 0.05$, the null hypothesis of homogeneity is verified if $|\mathrm{Z}| \leq 2.58$ and$|\mathrm{Z}| \leq 1.96$, respectively.

3.6. Performance evaluation

As a wetland's inflow should be maintained at a level adequate to create and preserve a desired wetness, after the water requirement is estimated, the area of the wetland that can be covered by the estimated flow must also be determined. For this purpose, we use hydraulic modeling. Although this method is used for flood inundation areas (Horritt and Bates, 2002; Patro et al., 2009), it can also be used for predicting the inundated areas in wetlands. As 2D modeling needs more complex aggregate parameterization, a less complicated alternative 1D model, based on the St. Venant shallow water equations, is more popular among river engineers (Aggett and Wilson, 2009). A 1D HEC-RAS hydraulic model is able to compute water surface profiles rapidly based on discharge quantity. To extract spatial components of the wetland as HEC-RAS input, a digital terrain model (DTM) with a resolution of 3 m extracted from Cartosat-1 satellite images was used in the HEC-GEO RAS environment.

In HEC-RAS, the water surface profiles resulting from the estimated flow are simulated in TIN format. Then this TIN is compared with the terrain TIN, and the inundated area is defined for those cells where the water surface is higher than the terrain elevation. In this way, the boundary and depth of water are delineated on the surface of the wetland.

To validate the HEC-RAS model, which refers to the evaluation of the hydraulic model performance for predicting wetland inflow inundation, the extent boundary of the wetland is visualized based on a low-flow event. In order to evaluate performance of the hydraulic model, an F statistic is applied to compare the observed inundation area (extracted from the Lansat satellite image at that time) and the predicted inundation area (Horritt and Bates, 2002):

$$F = \left(\frac{A_{op}}{A_o + A_p - A_{op}}\right) \times 100 \tag{9}$$

where A_o is the observed inundation area, A_p is the predicted area of inundation, and A_{op} is area that is both observed and predicted as inundated. The F statistic varies between 100 when observed and predicted areas match perfectly, and 0 in the existence of no overlap between predicted and observed areas. Fig. 3 illustrates the methodology of the present study.

4. Results and discussion

To estimate a requirement base flow that provides adequate wetness for maintaining the Gavkhuni wetland, the low flow method is first applied on the daily streamflow time series of the Varzane hydrometry station, located at the entrance of the Gavkhuni wetland. The formation of the low-flow series was initially done. Frequency analysis is used to fit a robust distribution to the low-flow series for estimation of the low flow statistics in different return periods. The root mean square error is used as a measure of goodness of fit. The result of a 7-day annual low flow frequency analysis is presented in Table 2. The evaluation suggests that the Log Pearson III distribution gives the best result for low-flow quantile estimation. But, as shown in Table 2, the estimated low flow quantiles are very low, especially 7Q10, which is considered as an appropriate low flow index for water resources management.

As an alternative, the FDC method was then applied to define a base flow for the Gavkhuni wetland. As is presented in Fig. 4, most of the recorded flows are settled in the down tail of the flow duration curve, and a popular criterion, Q90, is determined to be 0.105 m^3/s. The main reason for underestimation of the wetland's inflow using hydrological methods is the abundance of dry spells, mostly associated with impoundment and regulation of upstream

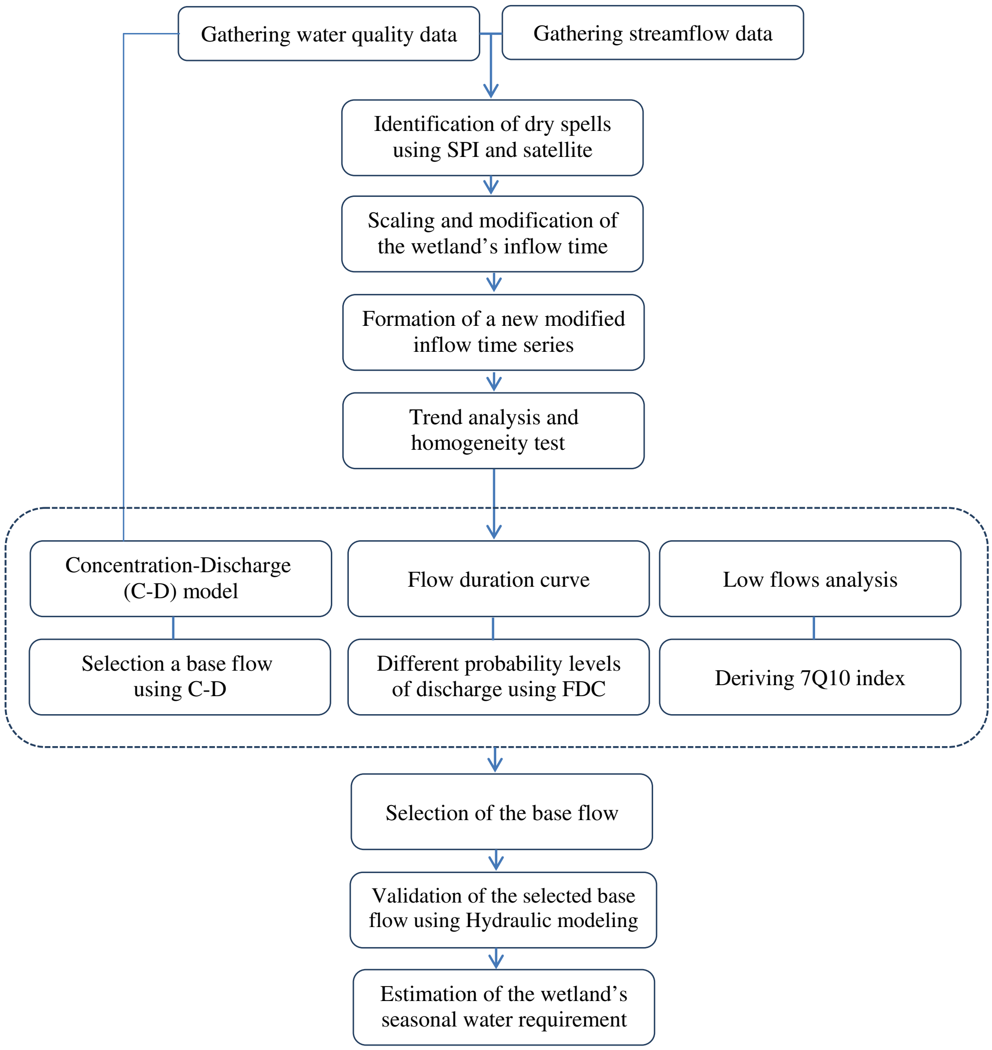


Fig. 3. Flowchart of the methodology.

flow that alter the nature discharge regime of the downstream and the Gavkhuni wetland. The results of applying the nonparametric Mann–Kendall test also confirm that dry periods influence the trend of the wetland's inflow. As is apparent in Table 3, all months except October show negative trends, and most of them are significant, at the 1% level.

After construction of the Chadegan reservoir, water harvesting for various purposes (agriculture, industry and drinking water) has significantly increased at upstream regions, influencing the nature hydrological flow regime. To study the effects of water impounding upstream and the regulation effect of the Zayanderud dam in altering the natural flow regime downstream, inflow conditions in pre (1948–1970) and post-dam periods are compared. Since the FDC is a useful indicator of temporal behavior, the FDC of the Varzaneh station is analyzed for the two aforementioned periods. As is obvious in Fig. 5, the slope of the FDC of the inflow pre-dam development fluctuates naturally, while after dam construction, the FDC demonstrates steady status for the recorded discharge. The results of the pre-dam and post-dam mean daily discharges in Table 4 also reveal a significant reduction (12.2 Versus 5.9 m^3/s respectively).

It is quite clear that the regulated flow is different from the natural condition. The Zayanderud dam has altered the natural flow regime downstream and affected the Gavkhuni inflow, such that

Table 2
Estimated low flow quantiles (m^3/s) in different return periods. Bold indicates the consecutive 7-day low flow at the return period of 10 year (7Q10).

Distribution	Return Period (year)				
LPIII	2	5	**10**	20	50
	0.28	0.065	**0.02**	0.006	0.002

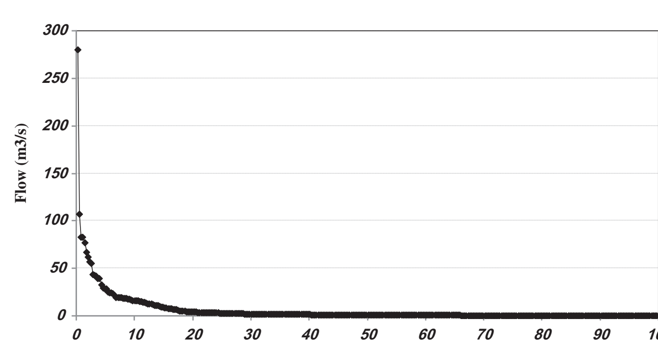


Fig. 4. Flow duration curve of the original inflow time series to the wetland.

Table 3
Statistics of Mann–Kendall test for monthly flows at Varzaneh station.

Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AGU	SEP	OCT	NOV	DEC
Z_{MK}	−0.125**	−0.203**	−0.251**	−0.326**	−0.188**	−0.29	−0.31	−0.089**	−0.12	0.02	−0.45**	−0.72**

**Significant at 1% level.

this wetland has experienced dry conditions with very low inflow many times, which never occurred before dam construction. In other words, after dam development, even when no meteorological drought exists, the inflow to Gavkhuni has frequently been intentionally blocked by the dam and water harvesting activities upstream. In order to identify these dry periods and modify them to decrease the noise from the inflow time series, we use a combination of hydrologic analysis and remote sensing techniques.

4.1. Identifying dry spells

Since different time scales of SPI can reflect the impact of drought on the availability of water resources (Fiorillo and Guadagno, 2010), different time scales of 3, 6, 9, 12 and 24 months were calculated based on monthly precipitation at Eskandari station (located upstream of the Zayanderud dam). To evaluate the dependency of the wetland inflows and the SPI time scales, correlation coefficients of monthly streamflows at Varzaneh station and the SPI at Eskandari station for different time scales are calculated. The results show that the highest correlation occurs for a time scale of 24 months (SPI_{24}), indicating that the accumulated rainfall of the antecedent 24-month period controls the variability of the wetland inflow.

Fig. 6 shows spearman rank correlation between the SPI_{24} time series during the recording period and the corresponding standardized monthly streamflow time series. Although the correlation coefficient does not show a high correlation (part of which returns to the reservoir regulation effect on the wetland's inflow), it is statistically significant, as other scales do not show significant correlation. As is apparent in Fig. 6, one period of an extremely intense drought (SPI ≤ -2) caused hydrologic dry periods during 1971, while three periods of low flow during 1974–1975, 1990–1991 and 2001–2002 seem to be connected to severe drought ($-2<$SPI ≤ -1.5).

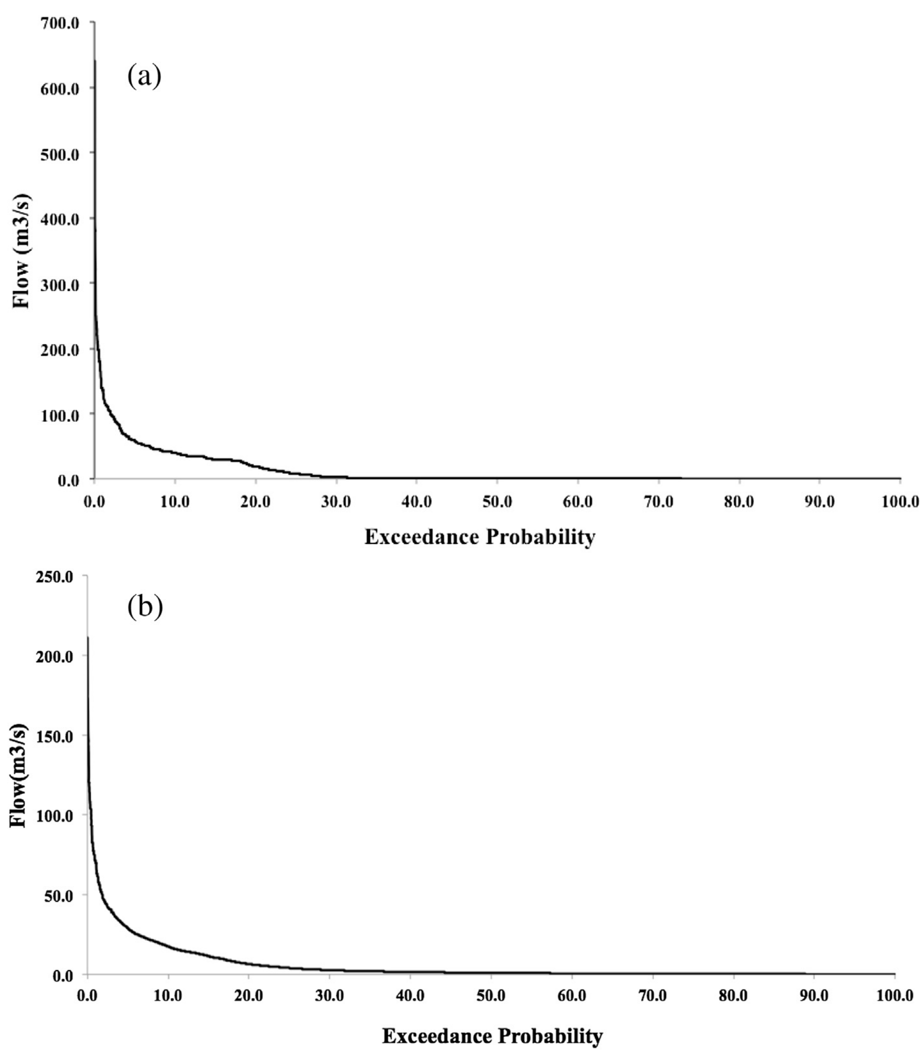


Fig. 5. Variation of the FDC in pre (a) and post (b) development period of the Zayandehrud dam.

Table 4
Descriptive characteristics of Gavkhuni inflow in pre and post-development periods of the dam construction and after modification of the inflow.

Time period	Mean	Max	Min	St. Deviation	Q25	Q50	Q75	Q95
Pre time dam construction	12.18	640	0.2	30.36	8.7	2.8	0.5	0.3
Post time dam construction	5.9	211	0.1	13.99	3.8	0.6	0.3	0.1
After modification	9.30	640	0.2	22.56	5.3	2.4	0.4	0.2

When SPI_{24} becomes less than -1, a meteorological drought condition is started (McKee et al., 1993; Mishra and Desai, 2005) and inflow to the Chadegan reservoir is decreased. Simultaneously, water abstraction for various purposes upstream of the Gavkhuni wetland is increased and, as a result, inflow quantity and quality to the wetland is gradually reduced. These periods are considered meteorological droughts and are natural dry periods. However, sometimes, in spite of the nonexistence of the meteorological droughts at upstream, based on SPI information, the Landsat satellite images show dry conditions for the wetland. In these periods, the reservoir outflow is manipulated or completely assigned for the industry section upstream, and no flow enters the wetland. For example during 2003–2005, the SPI24 shows a normal condition, while the standardized inflow represents an abnormal and dry period. These long dry spells are associated with water management policies. To identify and check the accuracy of these periods, and to differentiate them from meteorological droughts, the results of the SPI24 and the status of the wetland (using different Landsat satellite images including MSS, TM, and ETM+) are checked. Fig. 7 represents the condition of the wetland during dry spells. It is clear that the wetland and its vicinity are in dry conditions, and the white reflectance of the wetland indicates no water body in the wetland during these periods. This condition is compared with the times of meteorological drought after dam construction in Fig. 8.

As a consequence of the abundance of dry periods and the long-term effects on the ecological regime of the wetland, especially in the 1990 and 2000 decades, these periods are modified based on information from a hydrometry station (Eskandari), which is not under the effect of hydraulic construction. In doing so, a ratio of means of the standardized hydrograph for the Eskandari station (upstream of the dam) and Varzaneh station (at the entrance of the wetland) is calculated for the same time span, in which dry spells also occurred. Using this ratio, we modified the Varzaneh streamflow to keep the seasonal pattern of the wetland's inflow as close as possible to the natural flow regime's seasonal patterns. Table 4 presents descriptive statistics of the pre-and-post-dam development, and the new-formed time series for the whole period of Varzaneh station. The results show that after we modified the dry spells, inflow properties of the wetland show an increase, especially for the upper quantiles, and the properties of the post-development period of the dam construction time series approach those of the time series of the pre-development period of the dam construction. These results demonstrate the effects of the long-term harnessing and manipulating of the reservoir output on changing the hydrological flow regime of the Gavkhuni wetland.

The new modified stream flow time series then replace the original time series for subsequent analyses and the selection of the wetland's requirement base flow.

4.2. Calculation of the water requirement

4.2.1. Test for homogeneity and trend

To investigate the homogeneity of the newly modified streamflow time series, a run test was applied. The Z value of this test and its significance level were calculated as 0.76 and 0.29, respectively. The results of the run-test show that the modified time series is homogenous, and there is no effect from variability due to climate change in this time series.

The nonparametric Mann–Kendall test was also applied to investigate trends in the modified daily time series. Results of Mann–Kendall testing show ($Z_{MK} = -1.76$ with p-value $= 0.13$), an insignificant trend. After modifying man-made dry spells in the original time series, low flow methods are employed to measure the requirement base flow of the Gavkhuni wetland.

4.2.2. Base flow selection

To evaluate an initial flow to support water quality functions of the wetland ecosystem, a log-linear relationship is established between the related water quality parameters of the wetland (BOD, COD, NO_3 and PO_4^-) and inflows. Table 5 summarizes the regression analysis between concentrations of these parameters c and q, including the model coefficients, the standard error and square of correlation of c and q,ρ^2_{cq}. In the next stage, flows with different probability levels of Q_{95}, Q_{75}, Q_{50} and Q_{25} were substituted in the concentration-discharge model, and the corresponding concentrations were calculated. Compared with the standard levels (Esmaili sari, 2003; U.S. EPA, 2000), all of the quality parameters

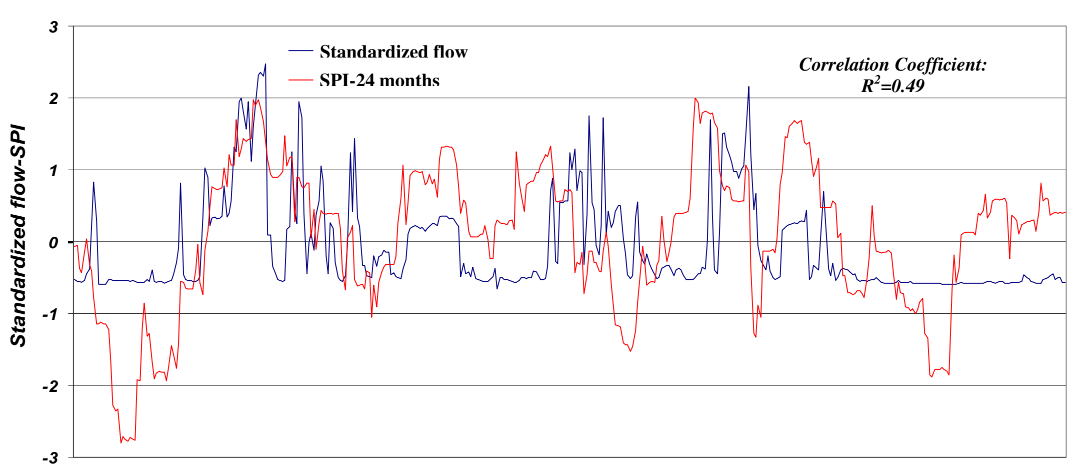


Fig. 6. Correlation of the standardized flow and SPI_{24} time series of the Eskandari station.

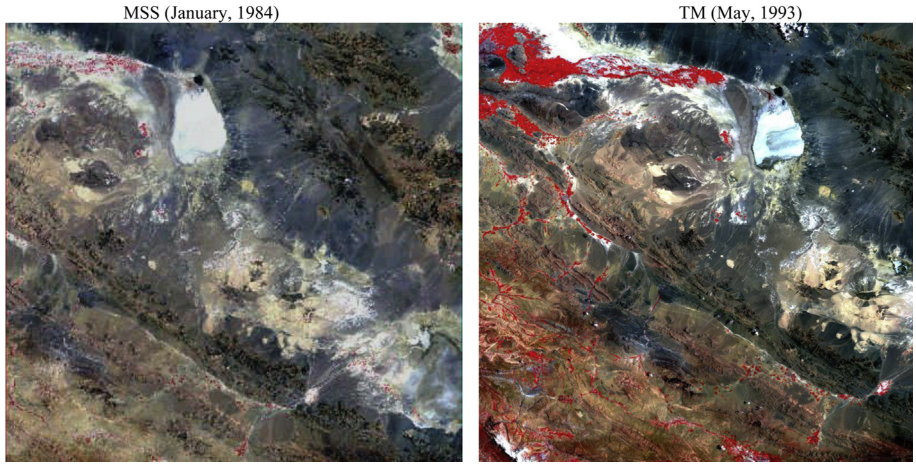


Fig. 7. Condition of the Gavkhuni wetland during dry spells periods.

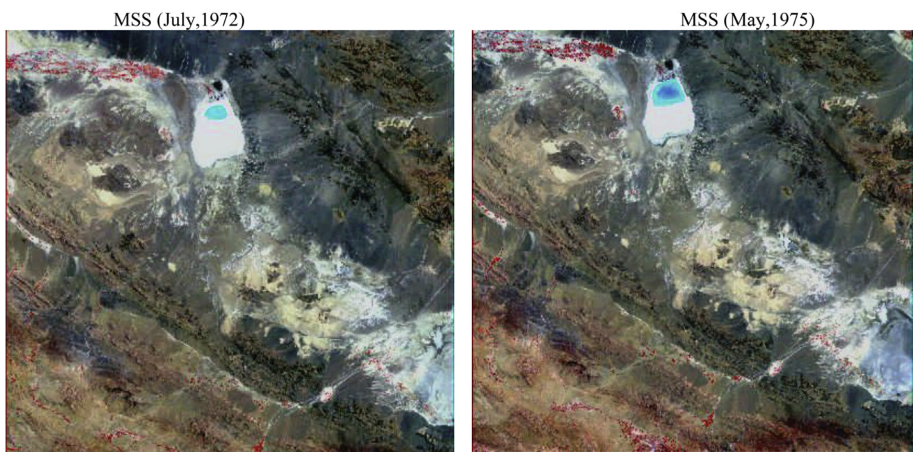


Fig. 8. Condition of the Gavkhuni wetland in the meteorological drought periods after dam construction.

were acceptable in $Q_{50} = 2.4\ m^3/s$. In other words, Q_{50} can provide an acceptable threshold for water quality functions of the wetland, and it can be applied as a satisfactory initial flow for maintaining the healthy condition of the wetland ecosystem.

Since the wetland needs to have an adequate inflow to cover the whole area of its surface, and preserve the ecosystem, it is necessary to calculate a reliable requirement inflow for providing a permanent wet condition for the whole area of the wetland based on the hydrological low flow methods. For this purpose, once more we employ the low flow and FDC methods in the modified daily streamflow time series.

At first, after formation of the annual flow minima series (minimum discharge of flow) based on the new streamflow time series, the low flow statistics were estimated using several theoretical distribution functions for different return periods. The results of the low flow frequency analysis are given in Table 6. As shown, a 2-parameter Log-normal distribution is recommended to describe the frequency of the 7-day annual low flow series. Although 7Q10 as a popular low-flow criterion reveals a higher value based on the modified time series than the original time series, it is logical that this criterion shows an insignificant level of base flow even once the inflow regime is modified. In part, this level can be attributed to the nature of climate in arid and semi-arid regions, and of course, the effects of the prolonged drought conditions. Therefore, this low-flow criterion cannot be used for determining the base flow requirement, and it is not suggested for arid and semi-arid regains, such as Esfahan.

The FDC approach was then also applied. Since the FDC illustrates the frequency distribution of the flows without regarding the sequence of the occurrence, this method seems to be an appropriate alternative, which can represent the variability and exceedance probability of the inflow during record periods for estimating

Table 5
Summary of the concentration-discharge regression models.

Parameter	α	β	$\sigma\varepsilon$	[1] ρ^2_{cq}
BOD	−0.258	0.45	0.40	0.72
COD	−0.329	0.74	0.36	0.66
NO3	−1.34	3.86	0.32	0.58
Po4⁻	−0.726	2.644	0.31	0.49

[1] In simple linear model, ρ^2_{cq} is equivalent to $R^2/100$.

Table 6
Estimated low flow quantiles (m^3/s) in different return periods based on the modified inflow time series. Bold indicates the consecutive 7-day low flow at the return period of 10 year (7Q10).

Distribution	Return Period (year)				
LN2	2	5	**10**	20	50
	0.413	0.135	**0.075**	0.046	0.03

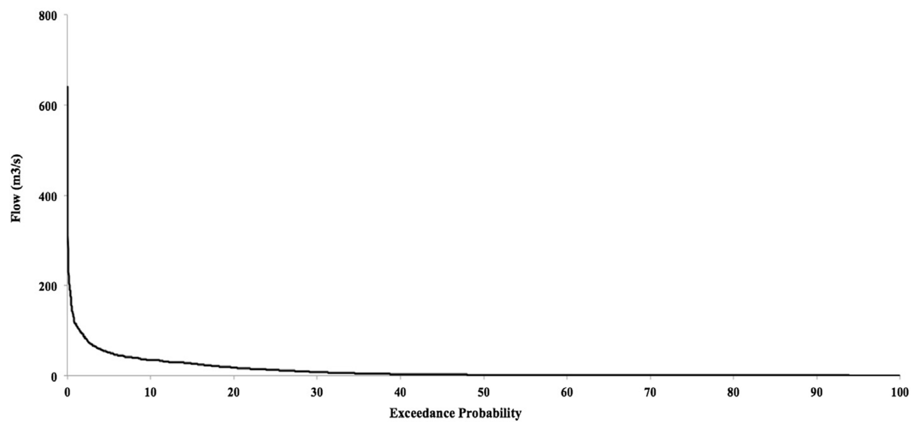


Fig. 9. Flow duration curve of daily streamflow with dry spells modified.

a reliable base flow. Fig. 9 represents the FDC extracted from the flow time series after modification of the post-development period of the dam time series. As Q90 represents the exceedance probability of a 90% time series and is used for numerous water resources management applications, it was employed to select the requirement base flow. The results of Q90 after modification of the time series do not seem to satisfy the wetland's base flow requirement, although it shows an increase, unlike the unmodified time series (Table 4). Due to the insignificant value of Q90, we move to the rest of the potential quantiles (including Q75, Q50, Q25). According to the results of the concentration-discharge relationship, it seems that only Q50 and Q25 (given in Table 4) can be considered as appropriate alternatives, as Q75 represents a rate of inflow lower than the selected initial base flow based on the water quality parameters. On the other hand, since the quantiles of Q50 and Q25 are considered able to provide enough inflow to satisfy the minimum healthy conditions from a water-quality perspective, both of these criteria are selected as alternatives to be checked for the ability to provide an adequate wetness condition spatially for the Gavkhuni wetland. For this purpose, hydraulic modeling is applied in the following section.

4.3. Validity test of the selected base flow

Hydraulic modeling was used to evaluate whether the selected base flows from the C-D and FDC approaches are sufficient to satisfy

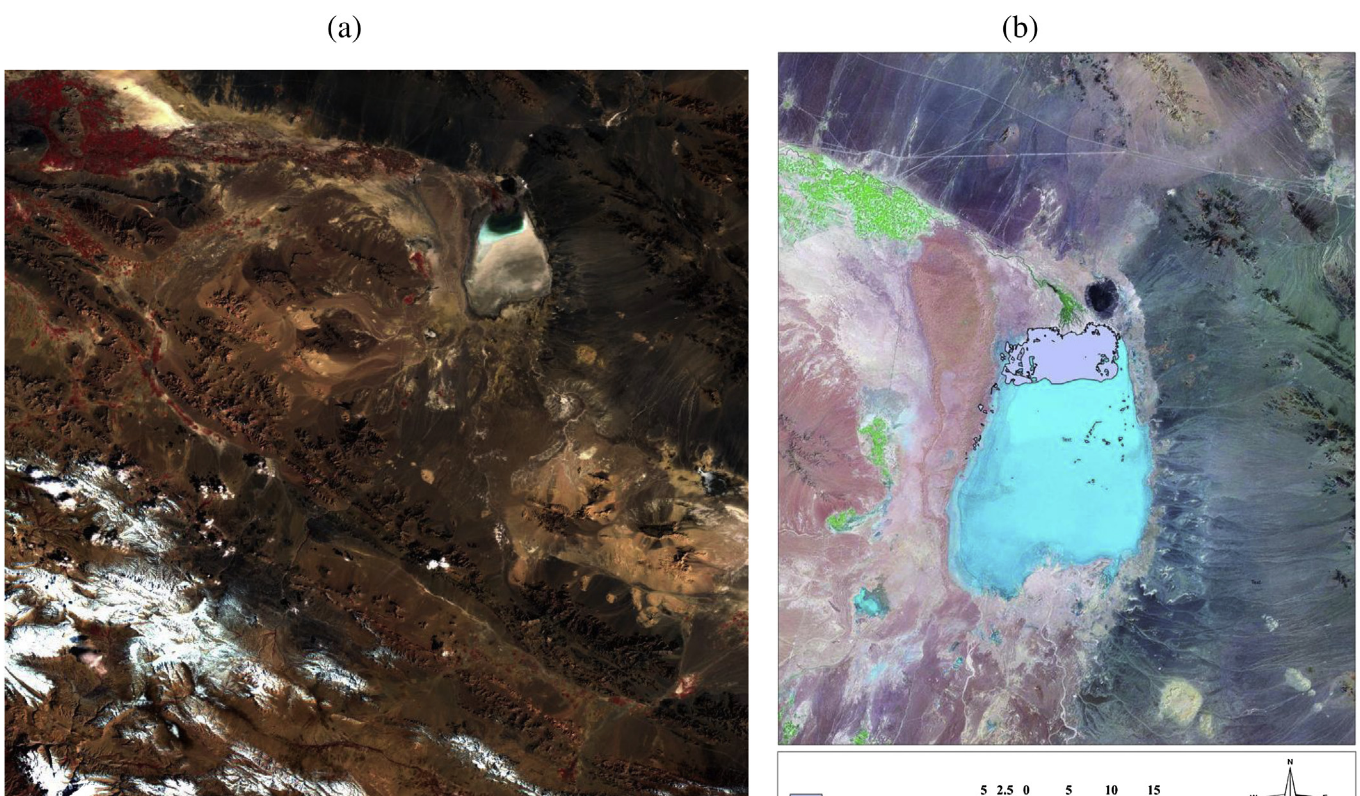


Fig. 10. Inundation mapping of the wetland in a low flow event, a) natural boundary of the low flow, b) simulated boundary using hydraulic modeling.

minimum water quality needs and provide adequate level of wetness to the wetland. High resolution Cartosat-1-based DTM was used to develop the geometry and extract 3D spatial features of the wetland. These parameters were then imported into HEC-RAS for water-surface-profiles calculation.

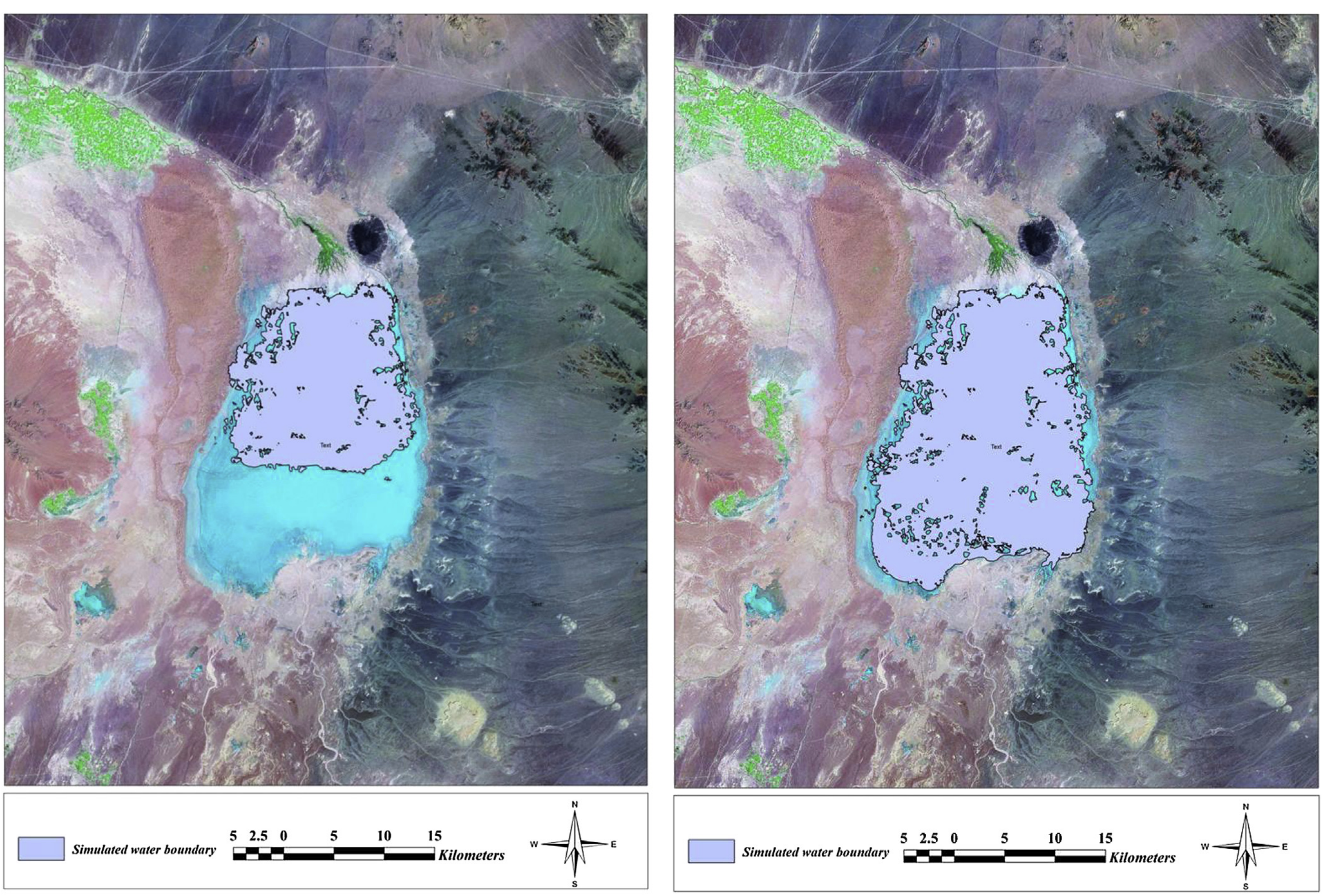
To calibrate the hydraulic model, which refers to the evaluation of the model performance for predicting water inundation, information of a low-flow event on February 1st, 1985 was used for the hydraulic modeling. By running the hydraulic model based on inflow of the wetland on this date, a water extent boundary was visualized (Fig. 10). In order to evaluate the model validity, the total water boundary area predicted by the model was compared with the actual water boundary area extracted using Landsat satellite images in terms of F statistic. The value of the F coefficient (96.3%) reveals that the hydraulic model provides a coherent match when simulating the observed inundation extent. Therefore, the results of the hydraulic model are reliable in simulating inundation area of the estimated inflows.

After calibration, the HEC-RAS model was run again to simulate the hydraulic condition of the estimated base flows based on the C-D model and FDC approach. Simulated water-surfaces-profiles based on inflows were then exported into the HEC-GEO RAS. Geo RAS is able to export the hydraulic modeling results into the GIS, where the intersection between the computed water level and the cross-section enables the graphical georepresentation of the inundated areas to be made over the digital terrain model.

Fig. 11 demonstrates the inundation mapping of the estimated inflows to the Gavkhuni wetland based on the C-D and FDC approaches. In order to determine which parts of the wetland can be covered by the estimated inflows, the simulated inundation areas derived from the two approaches are compared with the wetland while it is in a normal condition (with 100% coverage) in a hydrologic normal year. Although the estimated base flow based on the C-D model Q50 provides minimum health conditions for ecological functions of the wetland, this flow covers only 47% of the wetland's area in a normal condition, whereas Q_{25} extracted from the FDC not only provides minimum conditions of the water quality, but also covers more than 93% of the wetland's area. Thus, Q_{25}, supplying particular standard levels of quality and quantity (in which deep water varies from 0.21 m to 2.8 m in the middle of the wetland) for ecological functions and migrating birds, is determined to be the best inflow of the Gavkhuni wetland's requirements.

4.4. Seasonal water requirement

In order to support a permanent pool of water during the year and during extreme drought conditions, the water balance of wetlands must be determined. As wetland soil, ideally, should be in an almost saturated condition, and there is no significant infiltration, outflow losses from soil can be ignored. But in arid and semiarid regions, due to severe seasonal differences of temperature, water loss from pool surfaces via evaporation is highly significant. To compensate for water deficiency, the volume of evaporation



(a) (b)

Fig. 11. Predicted inundation mapping of the wetland, a) based on the estimated base flow using C-D model, and b) based on the FDC approach.

Table 7
Evaporation from water surface of the wetland and water requirements for consumption in different seasons.

Season	Fall	Winter	Spring	Summer
Evaporation (mm)	204.7	99.2	662.5	772.1
Water Requirement (m^3)	8943803.2	4333075.4	28937813.6	33725132.3

Table 8
Seasonal water requirements of the Gavkhuni wetland.

Season	Fall	Winter	Spring	Summer
Water Requirement (m^3)	50156603.2	45545875.4	71524373.6	76311692.3

losses must be determined and added to the wetland's required inflow, especially in dry seasons. This water requirement to compensate losses through evaporation from water surfaces, is calculated as:

$$W_e = (Em - p)A \tag{10}$$

where W_e is the net water requirement for evaporation, E_m and P are the average evaporation and precipitation in the water surface area, respectively, and A is the total water surface area (Yang et al., 2009). Table 7 presents evaporation from the wetland's water surface in different seasons and the water required for compensation. The equivalent water volume of the calculated base flow was then added to the evaporation amount, and the total water requirement volume for the Gavkhuni wetland was calculated for each season (Table 8). According to the results of this study, the Gavkhuni wetland requires almost 243.5 MCM of water in a year if it is to remain as a functionally healthy wetland ecosystem during prolonged extreme droughts and in the existence of domestic wastewater.

5. Conclusion

Determination of wetland water requirements is of considerable importance for maintaining healthy wetland ecosystem functions in arid and semi-arid regions. When there is a lack of information about ecological indicators in these areas, hydrological approaches are used to establish wetland water requirements to support sustainability of the ecosystem's ecological and hydrological functions. The purpose of this study was to present the results of a comparison of the three hydrological approaches for determining Iran's Gavkhuni wetland's water requirements. As two hydrological methods, low flow frequency analysis and flow duration curve (FDC), were used to determine the requirement base flow, a concentration-discharge model was also used to consider the wetland's water quality parameters. Due to the effects of water impounding upstream, and water abstraction on the water regime of the wetland, none of hydrological approaches led to a dependable estimation. To determine a reliable requirement base flow, periods called dry spells, in which the wetland's inflow is influenced by regulation of the upstream dam that affects the wetland's ecological and hydrological functions, were modified by a scaling process using an upstream station's information in the same time span as the original time series. To separate these periods from the meteorological drought periods, a SPI_{24} index and satellite images were used.

After modifying the time series, a significant improvement was observed in the quantiles, and the study approaches were used for determining the requirement base flow. The results of the low flow frequency demonstrated that even after modifying the flow time series and removing the effects of dry spells arising from reservoir regulations and water harvesting upstream of the wetland, 7Q10 does not show a reasonable inflow for the wetland. Therefore, due to the nature of arid regions, and the effects of subtropical high-pressure dynamics, which lead to the permanent drought conditions in these regions, the 7Q10 low flow criterion is not recommended for determining base flow requirement of wetlands in such areas. The results of the C-D approach based on the new modified time series showed that Q_{50} can provide a minimum health condition for ecological functions of the wetland from water quality perspectives, while the results of the FDC demonstrated that Q_{25} not only supplies a minimum health state in terms of water quality conditions, but also provides enough water quantity so that it can cover more than 93% of the wetland boundary. According to the latter indicator, and involving the evaporation rate, the volume of the water requirements of the Gavkhuni wetland was estimated as 243.5 MCM a year. Therefore, to protect and maintain a sustainable ecosystem, this water requirement must be regarded in integrated water resources management of the Zayanderud basin and be allocated by the Chadegan reservoir.

Overall, the results of the implemented methodology in the present study demonstrate that the hydrological approach could determine a reliable base flow to meet the minimum health condition for the water quality parameters and for ecological functions of the wetland. Although the lack of ecological information is considered a limitation of hydrologic-based approaches, their low cost and need for comparatively little information make hydrological-based methods preferable for environmental water allocation when there is no detailed knowledge about the biological requirements of the wetlands' biota, especially in arid and semi-arid regions. Therefore, in such wetlands with low biodiversity and tangible ecosystems, hydrological-based methods (non-biotic approaches) could be more preferable than ecological methods, which are based on biological requirements of biotic indicator(s) (biotic approach). Since there is no similar study applying the same approaches for determining the wetland's inflow in arid and semiarid regions prior to this study, the generality of the finding of this study needs to be tested for other wetlands located in arid and semi-arid areas of the world. The focus of the present study has been on water quality and quantity, with less emphasis on timing, duration and frequency. Further research is required to develop techniques into methodologies that include consideration of other critical aspects of the water regime.

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