DETERMINATION OF ENVIRONMENTAL WATER REQUIREMENTS OF THE GAVKHUNI WETLAND, IRAN: A COMPARISON OF ECOLOGICAL AND HYDROLOGICAL APPROACHES

Saeed Soltani, Ali Sarhadi and Esa Ebrahimi

Received: 08.07.2015 / Accepted: 09.12.2015

Abstract: This study presents a comparison of two ecological and hydrological approaches for determining environmental water requirements of the Gavkhuni wetland in Iran. Considering the ecological approach, water requirements of the wetland are determined based on a relationship between the biological requirements of a preferred biota (*Artemia*) and the inflow data on the wetland. The hydrological approach uses a flow duration curve (FDC) to gain a dependable base flow, whose water quality parameters remain at acceptable levels. The results reveal that there is no significant difference between the water requirement calculated by the two approaches, however the hydrological approach, which needs little information comparatively, may be used for those wetlands devoid of enough ecological information, especially in arid and semi-arid regions.

Keywords: ecological and hydrological approaches, environmental water requirements, flow duration curve, Gavkhuni wetland

Introduction:

Wetlands are globally recognized as one of the most biologically productive and diverse natural ecosystems, providing significant economic benefits for human society (Li et al. 2009). These natural ecosystems exhibit a wide array of socio-economic values and functions including improvement of water quality, pollution treatment, nutrient cycling, oxygen generation, biodiversity maintenance and flood mitigation (Brouwer et al. 1999; Cui et al. 2009). Over the past decades, the survival and the health of wetlands have been threatened due to water shortages resulting from the effects of rapid population growth and increasing industrial development, especially in arid and semi-arid regions (Cui et al. 2009; Jia and Luo 2009). Wetland net water requirements should be met to conserve these sensitive ecological systems and minimize adverse effects.

Now that the environmental and ecological advantages of wetlands have been recognized, the corresponding importance of environmental water allocation for protecting these natural ecosystems is being acknowledged (Cui et al. 2009; Jia and Luo

Saeed Soltani and **Esa Ebrahimi:**
Department of Natural Resources
Isfahan University of Technology
PO. Code: 8415683111
Isfahan, Iran

Ali Sarhadi:
Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada, N2L-3G1

e-mail (for all authors):
alisarhadi2005@gmail.com

2009). The environmental water demand is defined as the minimum water quantity and quality, in the natural environment, to maintain ecosystem functions and to protect species diversity. Though environmental water allocation for wetlands is a new issue, there have been many studies on the implications of environmental water allocation for rivers (Kashaigili et al. 2007; Mazvimavi et al. 2007; Yang et al. 2009), and only a few have investigated this issue for wetlands (Yang et al. 2005; Zhong et al. 2008).

Generally, two approaches can be used to determine a wetland's environmental water requirements: the ecological and hydrological approaches (Gippel 1996). Ecological water requirement, a recently developed concept, addresses wetland water requirement based on an existing or preferred biota's biological requirements (Davis et al. 2001). Once defined the ecological water requirement concept for wetlands in the 1970s, the application of this approach was started in the 1990s (Cui et al. 2009). Various researchers have studied different aspects of wetland environmental water requirements such as definition, threshold, timing duration and frequency, and introduced related ecological indicators based on ecological approaches (Liu and Yang 2002; Cui et al. 2009). Abbaspour and Nazaridoust (2007) applied an ecological approach to calculate the water requirements of Lake Urmia, Iran, employing three variables - ecology, water quality, and water quantity indices - as environmental indicators. The ecological indicator represented by *Artemia urmia* was considered an independent variable; conversely, the water quality index represented by a NaCl concentration and the water quantity index represented by water elevation were regarded as dependent variables. Considering the aspect of salinity concentration as the water quality requirement for the survival of *Artemia*, the corresponding water level needs were determined for Lake Urmia. Cui et al. (2009) established the ecological water requirement for wetlands in the Yellow River Delta Natural Reserve, China, by means of a correlation analysis between the habitat water requirements of rare and endangered waterfowl and the water regime. Other researchers have also traced ecological water requirements based on biological needs of the wetland's specific plants (Amoros et al. 2000; Zhao et al. 2007).

Moreover, due to information shortage about the ecological indicators' requirements or other causes, alternative hydrological methods need to be developed for successful water allocations. In some cases, large flowing quantities of treated or untreated domestic and industrial wastewater within wetlands violates the water quality standards and results in serious deterioration to the ecosystem and also removes a large amount of oxygen in the water (El-Sheikh et al. 2010). Under these circumstances, the amount of inflow that a wetland needs to reduce pollutants and perform its biological functions, as well as the self-purification of the ecosystem must be determined. Even though the hydrological approaches involve less information than the current ecological values (Davis et al. 2001), these methods that utilize limited inputs can be used to acquire a quantitative and qualitative understanding of a wetland's water requirements. Though several studies have examined the significance of the water supply for maintaining the healthy condition of river systems (Gordon et al. 1992; Song et al. 2007; Liu et al. 2002), the determination of the water requirement has not been fully investigated using hydrological approaches for wetland ecosystems.

The main objective of this study is to present a comparison based on two approaches for determining the environmental water requirements of the Gavkhuni wetland: ecological and hydrological based methods. The ecological approach in this study establishes a relationship between the ecological indicator's water requirements and the inflow data of the wetland. With regard to the hydrological based methodology, a flow duration curve approach is used to determine the best possible requirement inflow upon the wetland to maintain the water quality parameters on acceptable levels.

Materials and methods:

Study area

Gavkhuni in Isfahan province, Iran, is selected as the study area because it is a unique habitat and a wetland of international importance. This natural ecosystem, with a total surface area of 47,000 ha, located at the end of Zayandehrud basin, is considered a terminal wetland (Fig. 1). Gavkhuni wetland has an important role in the sustainable development of the region. From an ecological functional standpoint, it is one of the most valuable ecosystems in Iran and provides a habitat for over 140 bird species during the cold seasons.

In recent decades, this ecosystem has been facing various threats related to the water allocation from the upstream Chadegan reservoir, caused by droughts and badly integrated water resources management in the Zayandehrud basin. This condition has resulted in the devaluing of the quantity and quality of the wetland's incoming fresh water, and destruction of this natural ecosystem (Fig. 2).

To bring the ecosystem to its normal state and provide a healthy ecological condition for the wetland biota, the water requirement of the Gavkhuni ecosystem needs to be ensured by the Chadegan reservoir. For this purpose, determining the environmental water requirements of the wetland must be an initial priority in the water resources management of the basin.

Figure no. 1 Location of the Gavkhuni wetland in the Zayandehrud Basin

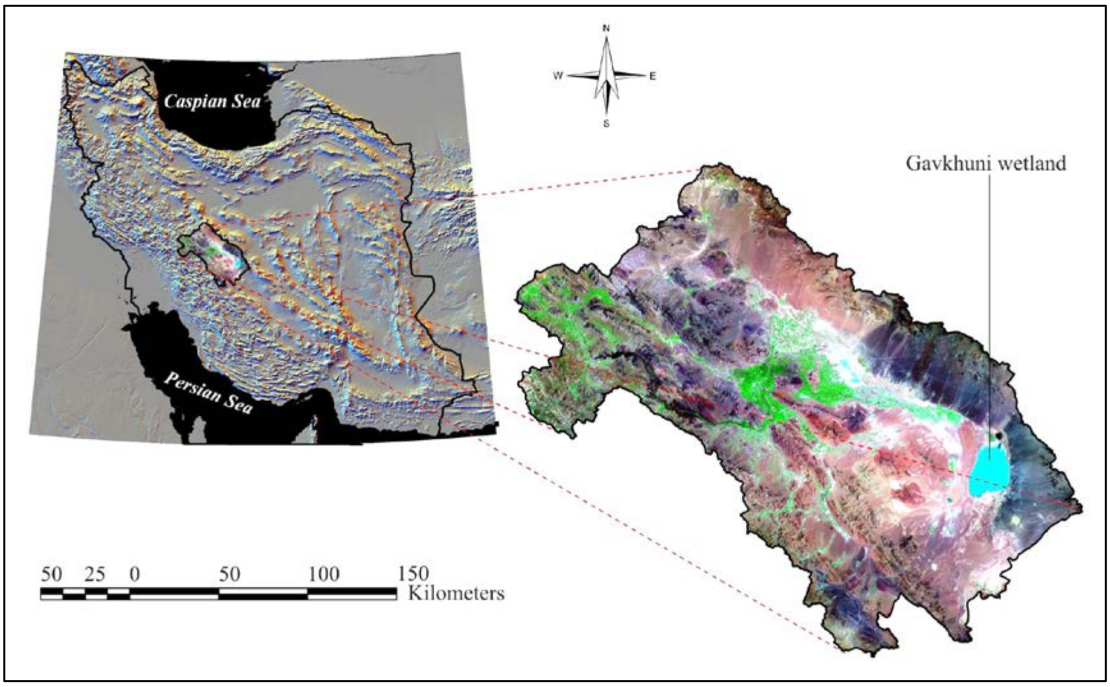


Figure no. 2 The situation of the Gavkhuni wetland at present

Data

The data used in the present study are divided into two parts: 1) water quantity data, and 2) water quality data. Water quantity data includes daily flow magnitudes registered at the Varzeneh station, located at the entrance of the wetland. The data was recorded by the Iran Ministry of Power and it covers the time-span of 1948-2009.

The water quality parameters in the present study include Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), NaCl, NO_3 and PO_4 parameters collected by the Isfahan Provincial Directory of Environmental Protection for studying the health of the wetland ecosystem. All these parameters are recorded monthly in the Gavkhuni wetland.

Methodology

The objective of the present study is the application of both ecological and hydrological approaches, which are recommended to calculate the water requirements of the Gavkhuni wetland. The process of calculating the wetland water requirement by means of the ecological and hydrological approaches is explained in detail in the following sections.

Ecological approach

The main objective of the ecological approach in this study is to calculate the minimum amount of water to meet the ecological requirement of a selected biotic indicator. In this regard, the related biotic indicator is determined based on the wetland's dominant biota. Its revival will affect the other biota's life conditions and the whole ecosystem sustainability. After identifying the most important biotic indicator need(s), sufficient inflow to provide a satisfactory level is regulated to meet the ecological and biological needs of the indicator as the wetland environmental water requirement.

For determining how much inflow should be supplied to the wetland in order to maintain the biotic indicator's need(s) at a satisfactory level, a nonlinear regression model that relates the relationship between the inflow and biotic indicator's need(s) is established.

The following is a non-linear regression model developed for this purpose:

$$Q = \alpha + \ln(C) + \varepsilon \qquad (1)$$

where Q is the inflow, C is an ecological need (water quality parameter) of the biotic indicator, α is a model parameter and ε is normally distributed model errors.

To check the accuracy of the model, the residuals are tested to ensure they are normally distributed and independent.

Selection of the ecological indicator

The first step in determining the water requirement of the Gavkhuni wetland based on the ecological approach is the selection of an ecological indicator. Located in central Iran, the Gavkhuni wetland, as one of the most important aquatic ecosystems (registered by the international Ramsar convention in 1975), plays a critical role for sustainable development and a place for migratory and native birds. Since the Gavkhuni wetland is considered a terminal wetland, high temperature in this area has caused hypersaline conditions for this ecosystem. High salinity ensures a very simple tropical structure and low species diversity biotopes for the Gavkhuni wetland. Having become derelict due to the severe droughts in recent years, the Gavkhuni wetland has turned into a saltpan (the current situation of the wetland is shown in Figure 2). There is no aquatic fauna in the wetland. After searching throughout the rest of the wetted areas, we found *Artemia salina* in some existing wetted pits around the wetland, where high salinity causes the absence of other fauna except this kind of *Artemia*. Since *Artemia* is a non-selective filter feeder of organic detritus, of microscopic algae as well as bacteria (Lavens and Sorgeloos 1996), the aforementioned pits may contain these primary producers. However, they have not been identified in our studies.

Considering there is no other substitute energy pathway to upper levels of the ecosystem, this simple food chain (*Artemia*) makes the wetland sensitive and ecologically vulnerable. Therefore, any change in the ecological and biological circumstances of the *Artemia* will affect the sustainability of the Gavkhuni wetland ecosystem. Similar to Lake Urmia, located in northwest Iran (Abbaspour and Nazaridoust 2007), some terrestrial species in the Gavkhuni wetland such as flamingo (*Phoenicopterus ruber roseus*) are ecologically related to the wetland. However, they cannot be considered an ecological indicator because they feed on *Artemia* resources and have an indirect relation. Therefore, *Artemia salina* is the only existing fauna, fed by resident and migrating birds as well as fishes (if the wetlands were in a normal circumstance). Its status could represent the lower levels of the aquatic ecosystem (i.e. producers) at the top of the simple pyramid of the wetland. As a result, we have selected it as an appropriate ecological indicator that enables us estimate the water requirement of the wetland so as to restore the Gavkhuni wetland based on its ecological requirements.

Requirements of the ecological indicator

Artemias are basically seen in highly saline biotopes. The secret of their survival is their physiological adaptations to high salinity, which allows them to avoid predation and competition with other filter feeders. They have different physiological adaptation mechanisms such as an efficient osmoregulatory system, the capacity to synthesize efficient respiratory pigments to cope with low oxygen levels in high saline conditions and the ability to produce dormant cysts when the species survival is endangered. All these characteristics make efficient ecological defense for *Artemia* to survive in high saline conditions where their predators are unable to survive (salinities more than 70 gl^{-1}). Due to the importance of the salinity for the survival of *Artemia* in the Gavkhuni wetland, we have selected this quality parameter as the most important ecological requirement for the biotic indicator (Lavens and Sorgeloos 1996).

As the cause is associated to temperature, there is no well-defined optimum for salinity. For physiological reasons, this optimum must however be situated towards the lower end of the salinity range (Persoone and Sorgeloos 1980). This is because *Artemia* cysts are unable to hatch when salinity is close to NaCl saturation (i.e 250 gl^{-1} or higher) as a result of extreme physiological stress water toxicity. A salinity concentration of 240 ppt of NaCl is considered the upper threshold of the water quality requirement for the survival of a sustainable population of *Artemia salina*. In the present study, this salinity rate is determined as an optimum condition for estimating the Gavkhuni wetland's water requirement.

Hydrological approach

In the hydrological approach, we use a Flow Duration Curve (FDC) for determining the water requirements of the wetland. An FDC represents the relationship between the magnitude and frequency of stream-flow discharges, providing an estimate of the percentage of time that a given stream-flow equals to or exceeds over a historical period (Vogel and Fennessey 1995).

The construction of an FDC using stream-flow observations can be performed through non-parametric procedures. The FDC can be constructed using different temporal resolution of stream-flow data: annual, monthly, or daily. In the present study the FDC is constructed on the basis of a daily flow time series as this resolution provides the most detailed way of examining duration characteristics of a river. First, the observed stream-flows $q_{(i)}$, i = 1, 2,…, n are ranked in order to produce a set of ordered stream-flows $q_{(i)}$, i = 1, 2 ,…, n, where n is the sample length, whereas $q_{(i)}$ and $q_{(n)}$ stand for the largest and the smallest observations, respectively. Each ordered observation $q_{(i)}$ is then plotted against its corresponding duration D_i, which is generally dimensionless and coincides with an estimate, $p_{(i)}$, of the exceedance probability of $q_{(i)}$ (Vogel and Fennessey 1994; Castellarin et al. 2004). The next step suggests that flows on different probability levels (Q_{50}, Q_{75}, and Q_{95}) can be extracted. Q_{60} - Q_{95} are considered to be dependable criteria for the selection of the requirement base flow in numerous water resources management applications. We used the water quality criterion aiming at ensuring which level of these flows on different exceedance probabilities could provide adequate quantity and quality of the requirement inflow for the Gavkhuni wetland. In other words, after extraction of the flows on the different probability levels using FDC approach, these flows are substituted by the concentration-discharge models to select which inflow magnitude can provide sufficient wetness and also keep water quality parameters within an acceptable level to maintain healthy wetland ecosystem functions. A bivariate model for the relationship between the logarithm of the concentration and flows is used to do this and may be expressed as follows:

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

where c = ln(C), q = ln(Q), α and β are model parameters, ε is normally distributed model errors with zero mean and variance $\sigma_\varepsilon^2 = (1-\rho_{cp}^2)\sigma_c^2$, where ρ_{cq} represents the correlation between c and q, and σ_c^2 is the variance of c (Vogel et al. 2005).

The models demonstrate that with the probability of the stream-flow exceedance, the water quality standards will be violated (exceeded). According to this methodology, the calculated water requirement of the wetland not only provides sufficient water quantity, but it also maintains the water quality parameters in a state of good health.

In order to support a permanent pool of water throughout the year and during drought conditions, the water balance of the wetland should be calculated after measuring the requirement base flow based on ecological and hydrological approaches. Because of the saturated soil in the wetland, the evaporation is recognised as the most important outflow. Due to severe seasonal differences of temperature, water loss from pool surfaces via evaporation is highly significant in the Gavkhuni wetland. The water needed to replace losses through evaporation from water surfaces is calculated as:

$$W_e = (Em - p)A \qquad (3)$$

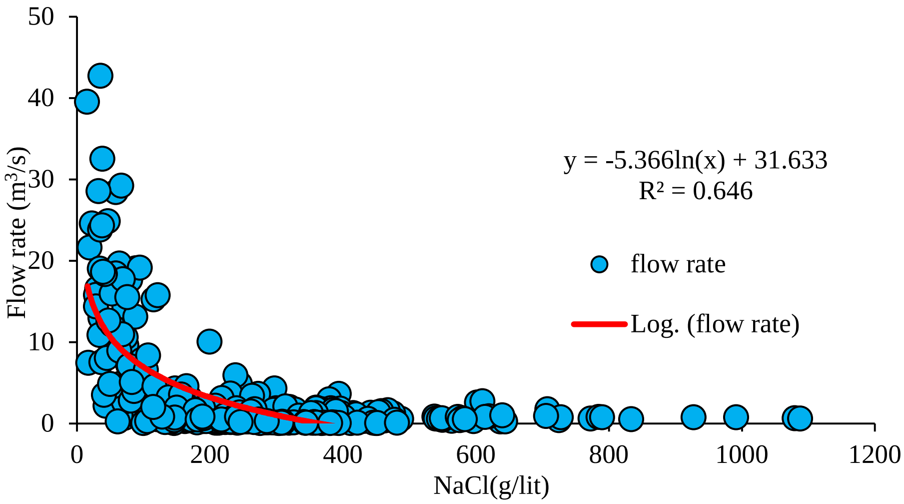
where W_e is the net water requirement for evaporation, E_m and P are the average evaporation and precipitation in the water surface area, respectively, and A is the total water surface area (Yang et al. 2009). The amount of water losses is then added to the wetland's requirement inflows, calculated by both the ecological and hydrological approaches.

Results and discussion:

Determination of ecological water requirement

To calculate the water requirement of the wetland based on the requirements of the biotic indicator, the relationship between inflows and water quality parameter needed for the indicator of the wetland (salinity) was first established. Figure 3 represents the best-developed non-linear regression model between inflows as a dependent variable (Q) and the selected water quality parameter for the biotic indicator as an independent variable (C). The performance of the model is given in terms of R^2. To regulate the water requirement for the Gavkhuni wetland, the optimum range of the water quality parameter for the indicator (*Artemia*) was replaced in the model, and the corresponding requirement flow, which can meet the need of the biotic indicator so as to have a sustainable population, was determined. The model calculated inflows of 2.22 m^3/s is for salinity of 240 ppt. In other words, if the inflow rate of 2.22 m^3/s is provided for the Gavkhuni wetland, this amount of water can provide the minimum health condition for *Artemia* to reproduce and increase its population growth. Consequently, other fauna species can feed on *Artemia* and in turn, increase their population. Thus, the Gavkhuni wetland could be revived and keep its ecological functions sustainable.

Figure no. 3 Non-linear relationship between inflows and water salinity parameter



Determination of hydrological water requirement

To calculate the water requirement of the Gavkhuni wetland based on the hydrological approach which can provide adequate wetness for maintaining water quality parameters, a FDC was first developed by a daily stream-flow dataset of the Varzane hydrometry station, located at the entrance of the wetland. Figure 4 represents the FDC of the inflow of the Gavkhuni wetland. According to the FDC, flows on different probability levels Q_{95}, Q_{75}, and Q_{50} were extracted and replaced in the concentration-discharge models. Since water quality parameters of BOD, COD, NO_3 and PO_4^- are considered as the most important quality indices regarding wetlands, they were selected to establish the concentration-discharge models. Table 1 summarizes the regression analysis between the concentrations of the water quality parameters c and the inflow of wetland q, including the model coefficients, the standard error and the square of correlation of c and q, ρ^2_{cq} .

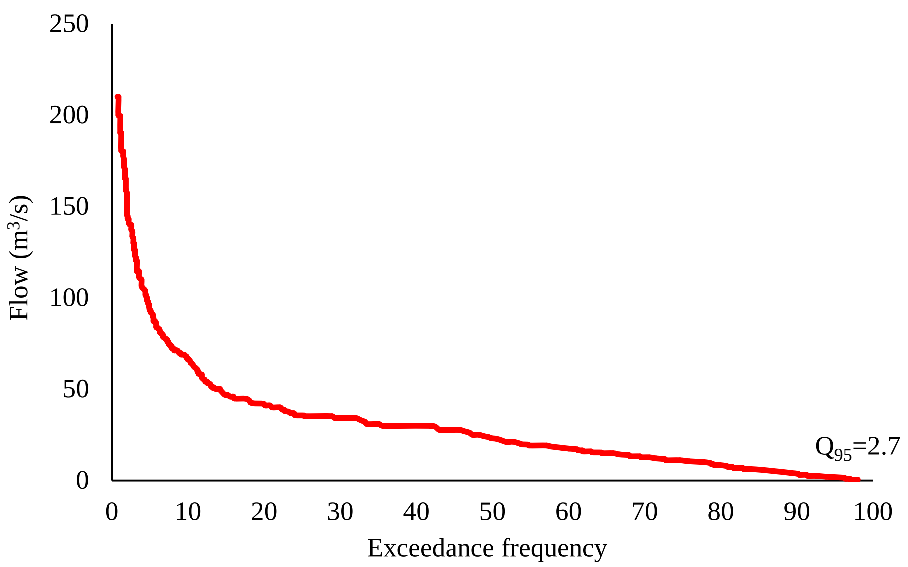
Table no. 1 The concentration-discharge regression models

ρ^2_{cq}	$\sigma\varepsilon$	β	α	Parameter
0.72	0.40	0.45	-0.258	BOD
0.66	0.36	0.74	-0.329	COD
0.58	0.32	3.86	-1.34	NO_3
0.49	0.31	2.644	-0.726	PO_4^-

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

It is noticeable that the values of the ρ^2_{cq} remain on an acceptable level, while the variation coefficients are almost low, an aspect which is possibly associated to the insufficiency and shortness of the data records of the quality parameters. Flows of different probability levels were then replaced in the concentration-discharge patterns, and the corresponding concentrations were calculated. Compared to the standard levels for the Gavkhuni wetland (BOD: 5 gl^{-1}, COD: 10 gl^{-1}, NO_3: 50 mgl^{-1}, PO_4^-: 30 mgl^{-1}) (Daneshvar 2004), all of the quality parameters were acceptable in Q_{95}=2.7 m^3/s. Therefore, none of the quality parameters exceeds its critical threshold if this discharge is provided for the wetland. Thus, as estimated by hydrological approach, Q_{95} could be considered an appropriate inflow, which can preserve the aforementioned water quality parameters below the standard levels and make a healthy condition for the wetland.

Figure no. 4 Flow duration curve of the wetland's inflow time series



Seasonal water requirement

To calculate the seasonal water requirement, the amount of evaporation in each season must be added to the calculated base flow by the ecological and hydrological methods. Table 2 shows the evaporation from the wetland's water surface in different seasons and the water required in compensation. The amount of evaporation was then added to the equivalent water volume of the calculated inflows by the ecological and hydrological approaches, and the total water requirement volume for the Gavkhuni wetland was calculated in each season (Tab. 2). On the whole, the water requirement of the Gavkhuni wetland is computed as 82.56 MCM and 99.27 MCM, based on ecological and hydrological approaches respectively. It is obvious that there is no significant difference between the water requirement volumes envisioned by the two methodologies.

Table no. 2 Evaporation from water surface of the wetland and water requirements for consumption in different seasons

	Season			
	Spring	Summer	Autumn	Winter
Evaporation (mm)	662.5	772.1	204.7	99.2
Ecological water requirement (m^3)	22414320	23266569	18854467	18034488
Hydrological water requirement (m^3)	21018360	27899018	22586947	21766579

To demonstrate which parts of the wetland are covered by meeting the inflow required, the inundation mapping of the wetland was simulated using HEC-RAS software. Figure 5 (Annexes) conveys the simulated inundation mapping of the Gavkhuni wetland based on the results of the ecological and hydrological approaches. The calculated base flow determined by the hydrological method covers 58 percent of the wetland area, whilst the base flow acquired by the ecological method covers 53 percent of the whole wetland. Therefore, the hydrological-based inflow cannot only keep the water quality parameters at optimum levels, but also cover the minimum ecological needs of the biotic indicator (*Artemia*). It must be noted that these inflows show the minimum conditions that should be maintained to meet ecosystem sustainability so as to renovate biodiversity and maintain the ecological and hydrological functions of the ecosystem at the lowest level. Undoubtedly, the threshold of inflows should be increased to determine the perfect water requirement of the wetland, which should maintain wetland ecosystems in a sustainable state and a waterlogged condition.

Conclusions:

Meeting the water requirements is an essential need for wetlands located in arid and semi-arid regions if they are to perform their biological function and be shielded against disasters such as extended droughts and other environmental problems. The research on the determination of the environmental water requirements for wetlands is a new field, requiring the use of reliable methods and techniques. This study has established an applied methodology for determining water requirements for wetlands in such areas based on ecological and hydrological approaches. The results demonstrated that the hydrological approach could determine a base flow to meet the minimum health condition for the quality parameters of the wetland and cover the biological and ecological needs of the biotic indicator. Though the lack of information on current ecological values is considered a limitation of non-biotic approaches, their low cost and need for comparatively little information make them preferable for environmental water allocation when there is no detailed knowledge about the biological requirements of the wetland biota, especially in arid and semi-arid regions. Therefore, in those wetlands in arid and semi-arid regions with low biodiversity and tangible ecosystem, hydrological-based methods (non-biotic approach) could be preferred to ecological methods, which rely on biological requirements of biota indicator(s) (biotic approach). The primary 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.

Rezumat:

DETERMINAREA CERINȚELOR DE MEDIU PENTRU APĂ DIN ZONA UMEDĂ GAVKHUNI, IRAN:
O COMPARAȚIE ÎNTRE ABORDAREA ECOLOGICĂ ȘI HIDROLOGICĂ

Acest studiu prezintă o comparație între două abordări, ecologică și hidrologică, pentru determinarea cerințelor de mediu pentru apă din zona umedă Gavkhuni, Iran. Considerând abordarea ecologică, cerințele pentru apă ale zonei umede au fost determinate pe baza relației dintre cerințele biologice ale speciei *Artemia* și influxul de informații din ecosistemul acvatic. Abordarea hidrologică folosește curba de durată a fluxului (FDC) pentru a obține un flux de bază constant, ai cărui parametri pentru calitatea apei rămân la niveluri acceptabile. Rezultatele obținute sugerează că nu există nici o diferență semnificativă între cerințele de apă calculate prin intermediul celor două abordări; totuși, abordarea hidrologică, care necesită mai puțină informație comparativ cu cea ecologică, poate fi folosită pentru acele zone umede lipsite de suficiente informații ecologice, în special în zonele aride și semi-aride.

References:

ABBASPOUR M., NAZARIDOUST A. (2007), Determination of environmental water requirements of Lake Urmia, Iran: an ecological approach, *International Journal of Environmental Studies*, 64: 161-169.

AMOROS C., BORNETTE G., HENRY C.P. (2000), A Vegetation-Based Method for Ecological Diagnosis of Riverine Wetlands, *Environmental Management*, 25: 211-227.

BROUWER R., LANGFORD I.H., BATEMAN I.J., TURNER R.K. (1999), A meta-analysis of wetland contingent valuation studies, *Regional Environmental Change*, 1: 47-57.

CASTELLARIN A., GALEATI G., BRANDIMARTE L., MONTANARI A., BRATH A. (2004), Regional flow-duration curves: reliability for ungauged basins, *Advances in Water Resources*, 27: 953–965.

CUI B., TANG N., ZHAO X., BAI J. (2009), A management-oriented valuation method to determine ecological water requirement for wetlands in the Yellow River Delta of China, *Journal for Nature Conservation*, 17: 129-141.

DANESHVAR N.A. (2004), *Principal of Water Quality Control*, Tabriz University Press, (in Persian).

DAVIS J., FROEND R., HAMILTON D., HORWITZ P., McCOMB A., OLDHAM C. (2001), Environmental Water Requirements to Maintain Wetlands of National and International Importance, Environmental Flows Initiative Technical Report Number 1, Commonwealth of Australia, Canberra.

EL-SHEIKH M.A., SALEH H.I., EL-QUOSY D.E., MAHMOUD A.A. (2010), Improving water quality in polluted drains with free water surface constructed wetlands, *Ecological Engineering*, 36: 1478-1484.

GIPPEL C.J. (1996), *Water Management Manual of Wetlands Management Wetlands Conservation Report Series No. 4*, National Parks Service and Department of Natural Resources and Environment, East Melbourne, Victoria, p.101-152.

GORDON N.D., McMAHON T.A., FINLAYSON B.L. (1992), *Stream Hydrology* (An Introduction for Ecologists), Wiley, New York, 526 p.

JIA Z., LUO W. (2009), A modified climate diagram displaying net water requirements of wetlands in arid and semi-arid regions, *Agricultural Water Management*, 96: 1339-1343.

KASHAIGILI J.J., McCARTNEY M., MAHOO H.F. (2007), Estimation of environmental flows in the Great Ruaha River Catchment, Tanzania, *Physics and Chemistry of the Earth*, Parts A/B/C, 32: 1007-1014.

LAVENS P., SORGELOOS P. (1996), *Manual on the production and use of live food for aquaculture*, FAO Fisheries Technical Paper, No. 361, Rome, FAO, 295 p.

LI L., LI J., LIANG L., LIU Y. (2009), Method for calculating ecological water storage and ecological water requirement of marsh, *Journal of Geographical Sciences*, 19: 427-436.

LIU J.L., YANG Z.F. (2002), Study on the ecological and environmental water demand of the lakes in the Haihe-Luanhe Basins of North China, *Journal of Environmental Science*, 14: 232–237.

LIU L., DONG Z., CUI G., ZX Y. (2002), Quantitative study on ecological water requirements in continental river, *Journal of Lake Sciences* (in Chinese), 14: 25–30s.

MAZVIMAVI D., MADAMOMBE E., MAKURIRA H. (2007), Assessment of environmental flow requirements for river basin planning in Zimbabwe, *Physics and Chemistry of the Earth*, 32: 995–1006.

PERSOONE G., SORGELOOS P. (1980), General aspects of the ecology and biogeography of *Artemia*, in: G. Persoone et al. (Eds) *The Brine Shrimp Artemia*, Vol. 3. Ecology, Culturing, Use in Aquaculture (Wetteren: Universal Press), p. 3–24.

SONG J.X., XU Z.X., LIU C.M., LI H.E. (2007), Ecological and environmental instream flow requirements for the Wei River—the largest tributary of the Yellow River, *Hydrological Processes*, 21: 1066-1073.

VOGEL R.M., FENNESSEY N.M. (1994), Flow Duration Curves. I: A New Interpretation and Confidence Intervals, *Journal of Water Resour. Plan. and Management*, (ASCE), 120: 485-504.

VOGEL R.M., FENNESSEY N.M. (1995), Flow duration curves. II: A review of applications in water resources planning, *Water Resources Bulletin*, 31: 1029–1039.

VOGEL R.M., RUDOLPH B.E., HOOPER R.P. (2005), Probabilistic behavior of water-quality loads, *Journal of Environmental Engineering*, (ASCE), 131: 1081-1089.

YANG Z., CUI B., LIU J. (2005), Estimation methods of eco-environmental water requirements: Case study, *Science in China* Series D: Earth Sciences, 48: 1280-1292.

YANG Z.F., SUN T., CUI B.S., CHEN B., CHEN G.Q. (2009), Environmental flow requirements for integrated water resources allocation in the Yellow River Basin, China, *Communications in Nonlinear Science and Numerical Simulation*, 14: 2469-2481.

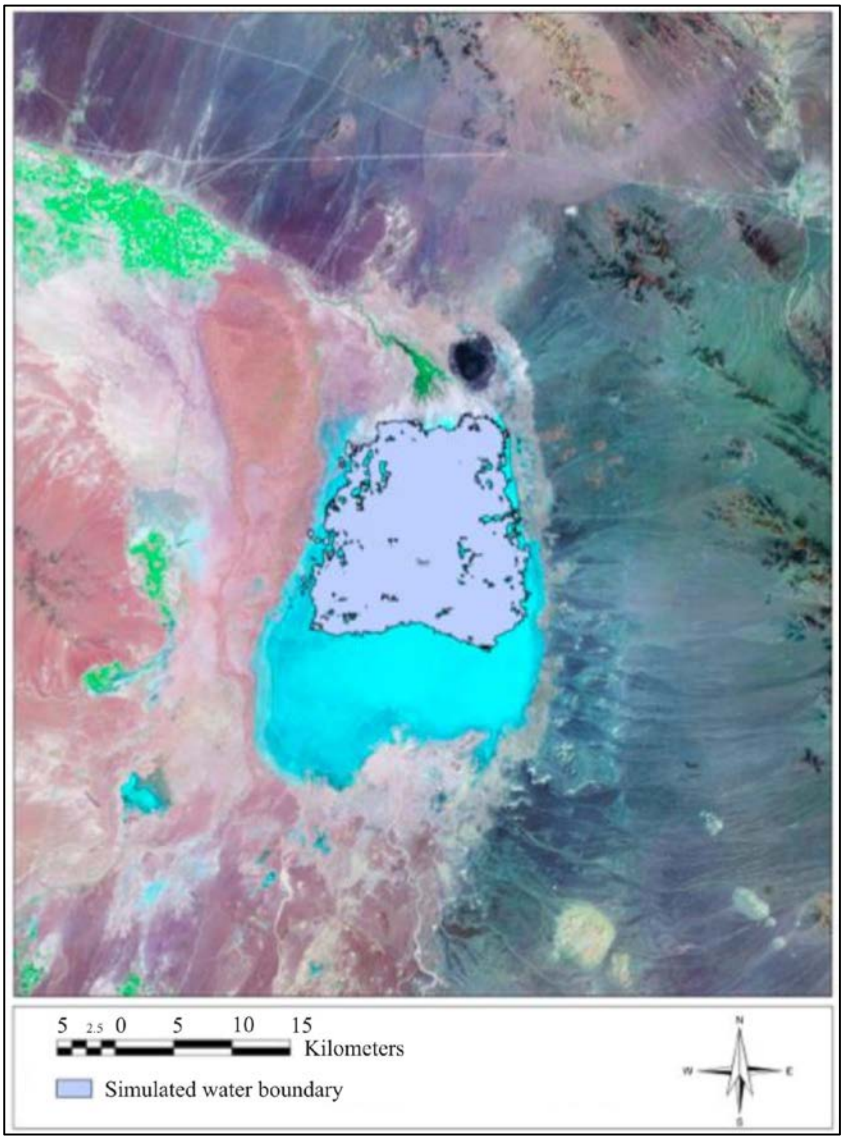
ZHAO W., CHANG X., HE Z., ZHANG Z. (2007), Study on vegetation ecological water requirement in Ejina Oasis, *Science in China*, Series D: Earth Sciences, 50: 121-129.

ZHONG P., YANG Z., CUI B., LIU J. (2008), Eco-environmental water demands for the Baiyangdian Wetland, *Frontiers of Environmental Science & Engineering in China*, 2: 73-80.

Annexes:

Figure no. 5 Simulated inundation mapping of the wetland after meeting environmental water requirements based on ecological (a) and hydrological approaches (b)

a. Ecological approaches



b. Hydrological approaches