



Risk Assessment of Alien *Azolla filiculoides* Lam in Anzali Lagoon Using Remote Sensing Imagery

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Abstract

Long-term evaluation of the population change trend of different plant species in lagoons is of great importance in preserving the environment. Lagoons are the fundamental habitats for aquatic biodiversity conservation, which has at least one relatively narrow connection to the sea. In this research, Landsat time-series data are used to investigate the changes in *Azolla* (or green devil) expansion, and its effective factors over 30 years from the arrival of this aquatic fern from 1988 to 2018 in the International Lagoon of Anzali in the North of Iran using the spectral angular mapper (SAM) method and related field data. The results indicated that (1) the changes of *Azolla* plant expansion have a direct correlation with the volume of lagoon water and rainfall and an inverse relation with the region temperature, (2) The spread of *Azolla* has not been steady over three decades, increasing in some years and decreasing in others, (3) The high *Azolla* surface cover has caused environmental hazards in the lagoon and has reduced the value in the eastern, southwestern, and partly central parts of the area. Therefore, in order to maintain balance in the natural ecosystem of Anzali Lagoon, fundamental decisions must be made for determining the range and shelter of the lagoon and controlling the outflow of water resources.

Keywords *Azolla filiculoides* Lam · Landsat · Time series data · Anzali Lagoon · Remote sensing

Introduction

Among aquatic ecosystems, lagoons are very important ecologically (Guo, 2017). In recent years, mismanagement and neglect of the exploiters have increased the flow of urban, industrial, and agricultural waste into lagoons, leading to various chemical and biological processes, such as nitrification, and serious problems such as collapsing of biological and ecological balance (Nazarhaghghi, 2014; Sharifi, 2020b). This phenomenon enriches water with nutrients, especially nitrogen and phosphorus compounds,

and promotes the growth of algae and ferns (Zazouli et al., 2014).

In 1986, the Iranian Ministry of Agriculture introduced the *Azolla* plant from the Philippines to the International Lagoon of Anzali port. The species ferns that the ecosystem of the region had no previous acquaintance with and the environmental conditions are very suitable for its growth. This action aims to study nitrogen fixation capacity and use it as feed for livestock and green manure for rice paddy rice. From this year, *Azolla* spread to northern Iran. Although in August 1990 only a few dispersed plants are found in the Lagoon of Anzali, in November 1990, and then six months later, some canals and surface waters were worn in the eastern part of the lagoon with a thick layer by it. *Azolla* growth was not observed only in the western part of the lagoon, and also due to the strong wind blowing (Blunden et al., 2018; Kotlewski & Dudzińska-Jarmolińska, 2017). Among the seven species known in the world, *Azolla filiculoides* Lam. have been shown to grow and adapt to the climate of Iran (Sadeghi et al., 2013). The vegetation of the lagoon Anzali port is divided into three main categories:

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- Emergent Plants: The most important plants in this group are the straw (*Phragmites australis*) and Levi (*Typha latifolia*), which are in combination together.
- Floating plants: Such as Azolla and lotus (*Nymphaea alba*).
- Submerged plants: Such as all kinds of algae.

Four species of dominant aquatic plants are identified at the surface lagoon including straw, Louis, Azolla, and lotus.

In some of the lagoons, Azolla aquatic ferns grow rapidly in a favorable environment and create a dense cover over the water in the summer season. At this time, Azolla competes with other herbs to absorb food. Although the presence of this plant is beneficial for agricultural and livestock purposes, it is important to control its population due to its rapid growth (Sadeghi et al., 2012). Air humidity plays a very important role in increasing Azolla biomass. It becomes dry and brittle in the relative humidity of less than 60% (Lyu & Peterson, 2018). The optimum moisture content should be between 70 and 75% for growth (Basha, 2005; Sleutel, 2008). Sadeghi et al. (2012) state the expansion of this plant decreases when air humidity reaches more than 80%.

Most studies have been done on the Azolla plant, focusing on its role as a biofertilizer and nitrogen fixation, including the economic evaluation of Azolla biologic control in South Africa (McConnachie, 2003). The use of Azolla as a biological fertilizer (Mus, 2016; Sharifi et al. 2016), and the effect of nitrogen produced by Azolla in rice fields (Amiri Larijani & Hoseini, 2012). But little research has been done on the role of Azolla in lagoons and rivers using remote sensing technology and satellite imagery (Kosari, 2020; Sharifi & Hosseingholizadeh, 2020; Sharifi, 2020a).

Zhang (2016) used three hyperspectral sensors installed on an airborne platform (AISA-Hawk, AISA-Eagle, and AHS) and a CHRIS sensor installed on the Probe platform to provide a map of the expansion and differentiation of Azolla from other Aquatic plants (Zhang et al., 2016). The results showed that two methods of matched filtering and the Target Constrained Interference Minimized Filter have resulted in better consequence in comparison with other methods (Matched Filtering, Adaptive Coherence Estimator (ACE), Spectral Angle Mapper (SAM), Constrained Energy Minimization (CEM), Orthogonal Sub-project Projection (OSP) and Target Constrained Interference Minimized Filter (TCIMF)). But SAM algorithm does not show good results. Meanwhile, Díaz-Delgado et al. (2011) suggested that the SAM supervised classification method proposed the best way to map dense patches of Azolla using satellite images compared to other standard pixel classification methods (Díaz-Delgado et al. 2011).

Espinar (2015) study the correlation between increases of winter temperature with Azolla expansion at the Donana lagoon in the southwest of Spain (Espinar et al., 2015). In this research, digital satellite images with a medium spatial resolution (TM and ETM⁺ sensors) and Spectral Angel Mapper algorithm of supervised classification are used to map the annual cover distribution of Azolla ferns from 2001 to 2011. Results show study area is significantly invaded by the plant when the winter temperature rises during the years.

The high density of Azolla fern at the surface of the lagoon causes the ecological balance to be problematic and creates environmental hazards. Therefore, it is imperative to study the process of changes and factors affecting its reduction or increase in its growth overtime to carry out proper and preventive management measures. It is impossible or very difficult to carry out a study in traditional and conventional ways due to the specific biological characteristics of Azolla (including its small size, as well as the proximity to other aquatic plants on the water surface and the formation of plant complexes) and the large size of the International lagoon of Anzali port, and the denial of access to many parts due to protection.

The purpose of this study is: (1) investigates the process of changes in Azolla spatial expansion and some of its effective climatic factors in the international lagoon of Anzali port during the last three decades. (2) The effect of Azolla expansion on the growth of other indigenous plants at the surface water. (3) Study of changes in the boundary lines of Anzali port lagoon in 30 years and at the same time as possible changes in the Azolla expansion level.

Materials and Methods

Study Area

Anzali Lagoon is one of the greats and important lagoons in Iran and the world. High ecological diversity and wildlife have created a unique ecosystem from it. It has a special place in the list of Ramsar conventions since 21 December 1975 (Coates, 2018). It is a coastal lagoon in the northern Iranian province of Gilan and at the southwest of the Caspian Sea. It is coordinated in terms of universal transverse Mercator (UTM) and in North Zone 39 is from north to south in the range of 356,908 MN and 4,138,748 ME to 364,660 MN and 4,147,326 ME and from west to east in the range of 345,380 MN and 4,155,887 ME to 375,840 MN and 4,146,128 ME (Fig. 1).

The area of the lagoon is variable and depends on the rainfall differs between 150 and 170 km². Water depth also fluctuates between 0.5 and 2.5 m (Jafari, 2009; Ayati, 2003). It is composed of four parts. These areas include (1)

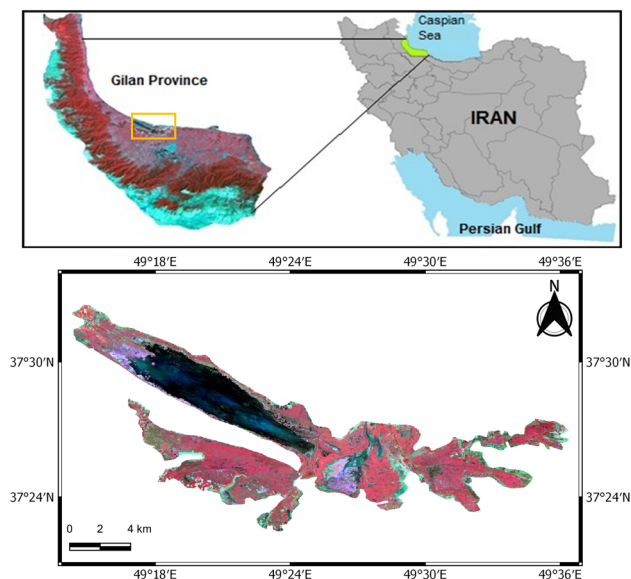


Fig. 1 **a** Location of the study area in the North of Iran. **b** The Landsat-8 over Anzali Lagoon, which was acquired on July 10, 2018

the Abkenar Basin, which is the deepest and most lagging part of the lagoon. It has not vegetation and wildlife refuge in its central part. (2) The Shijan lagoon is located in the eastern region, which is the shallowest part of the Anzali port lagoon, and the aquatic plants are vast and a wildlife refuge. The central part of the Anzali port lagoon is named Sorkhankol, which is of central importance to the environment and wildlife refuge, and the Siah Keshim, which forms the southwest of the lagoon and has a wide range of plants such as Levi, Luis, and Azolla's fern is covered. The western, southwest, and most of the central Anzali port lagoon are protected areas and cannot be accessed due to special environmental conditions.

The growth of plants in the Anzali port lagoon and its boundary changes are affected by some climatic factors of the region such as temperature, relative humidity, and rainfall besides human factors. The annual average temperature, humidity, and rainfall data of the nearest synoptic station (Anzali port station) are used to assess the effect of these climate parameters on the growth and distribution of them (Table 1).

Minimum, maximum, and average annual moisture content in the study area is 73, 93, and 84 percent, respectively. The average annual rainfall is 1854 mm per year. Temperature is one of the most important determinants of the growth rate of floating plants at the surface of the water (Van Der Heide, 2006). Azolla ferns can grow rapidly in warm and humid climate conditions and causing problems in lagoon ecosystems. The temperature suitable for Azolla growth is between 20 and 30 °C, and the most suitable temperature for growth is between 23 and 25 °C (Sadeghi et al., 2013). The average water temperature of the Anzali port lagoon is 19.0 °C, and the minimum and maximum air temperatures are 9.9 and 32.5 °C (Nazarhaghighi et al., 2014).

Data Set

In this research, satellite imagery is used with medium spatial resolutions (Landsat series 5 and 8) which are recorded in the period from 1988 (before the arrival of Azolla to the lagoon of Anzali port) to 2018 (Table 2). They are downloaded from the earthexplorer.usgs.gov site freely. The reason for using data of 1988 is to compare the variations in the area of aquatic plant cover at the surface of the lagoon water before and after Azolla's arrival to the region. All dominant aquatic species are green in color at the water surface of the lagoon in spring, and summer seasons and changes of color in all species are roughly the same in autumn and winter seasons (Talebi et al., 2019). Therefore, multi-date satellite images are used from late spring to early summer. Also, the production of Azolla biomass and its growth reaches a maximum between late spring and mid-summer in the region (Sharifi & Amini, 2015; Tsikliras & Froese, 2018). Meanwhile, it is tried to download satellite images related to this period concerning their suitable quality.

Methodology

Various factors affect the quality of satellite imagery. Therefore, some pre-processing is performed including geometric, radiometric, and atmospheric corrections. Then,

Table 1 Annual average of climatic parameters

Year	Annual average temperature (°C)	Annual average precipitation (mm)	Annual average humidity (%)
1988	24	1750.4	91
1998	26	1815.4	86
2008	27.8	1442.6	84
2018	28.9*	980	81

Table 2 Characteristics of data sets used

Data type	GSD (m)	RMSE (m)	Spacecraft identifier	ID
TM	30	4.558	LANDSAT_5	LT05_L1TP_166034_19880605_T1
TM	30	3.745	LANDSAT_5	LT05_L1TP_166034_19980617_T1
TM	30	4.246	LANDSAT_5	LT05_L1TP_166034_20080628_T1
OLI	30	7.099	LANDSAT_8	LC08_L1TP_166034_20180710_T1

the spectral processes scanner plots and principal component analysis are used to purge the spectral signatures to carry out the classification, select the appropriate bands, minimize the correlation between different bands, prevent the entry of duplicate data, and reduce the amount of data (van der Meer, 2012).

Field studies were conducted to find out the types of aquatic vegetation coverage prevailing at the lake water surface and determine the number of classes as well as the production of training samples. These educational classes are categorized according to the size and distribution of plant species and expert knowledge by the random stratified method and using a differential global positioning system (DGPS). Then, Iso-Cluster unsupervised classification method is carried out to compensate for the lack of training area and to increase the classification accuracy. This method is the most common classification method in the mapping of lagoons and areas where access to them is difficult or impossible (Nelson et al., 2018).

The Spectral Angle Mapper (SAM) method is used among the different supervised image classification algorithms. It is based on the angle formed between a reference spectrum or end member (can be extracted from both field studies and images used) and the spectrum of each pixel (de Carvalho Jr. & Meneses, 2000). Each spectrum is considered as a vector in N-dimensional space (N is the number of bands to be used.). The angle formed can vary from 0° to 90° or between 0 and 1 (best adaptation). In this method, a quick comparison is made in terms of spectral similarity between the two spectra. This technique is only sensitive to the direction vector and does not have the sensitivity to the vector length. This algorithm does not sensitive to illumination caused by some factors, such as topography. In the output of this method, the darker the pixels are, the smaller the angular distance and the better alignment with the reference spectrum. Sometimes, the output is shown in terms of cosine angle (Carvalho Júnior, 2011). The main advantage of this mapping method is its speed and simplicity. Mathematically, the Spectral Angle Mapper algorithm is calculated based on the following formula (Eq. 1):

$$\alpha = \text{Cos}^{-1} \frac{\sum XY}{\sqrt{\sum (X)^2 \sum (Y)^2}} \quad (1)$$

where α is angle formed between the reference and image spectral, X is image spectral, and Y is reference spectral.

The results of unsupervised classification (Iso-cluster), multiple field observations, selection of repeated training area for each dominant aquatic class, spectral signature analysis, and repeated purifications of signatures are used to conduct a supervised classification. It should be noted that Azolla has a special spectral signature at a range of 0.68 to 0.73 μm (Díaz-Delgado et al. 2011). In the supervised image classification process, a combination of Levi and Louis plants class is used due to the growth of them in the form of complex and in the vicinity. Azolla and lotus are defined as a separate class, and one class is defined known as other plants. Part of the lagoon, which is exposed to temporary droughts, is identified as the dry land class. Finally, six classes are defined for the study area. These classes included water, Azolla, lotus, Levi and Lotus combination, dry land, and other plants.

Results and Discussion

The results of this study showed Azolla spatial variations did not have a specific trend between 1988 and 2018 (Fig. 2). In 1988, Azolla expanded rapidly in the marginal areas of various parts of the lagoon. The reason for its rapid growth and expansion at the boundary of the lagoon is probably due to the suitability of growing conditions and location of Azolla mass entering to the lagoon by experts for preliminary studies as well as easy access to these areas. These areas are mainly located on the margin of the Southwest (Siyah-Kisham part) and eastern lagoon (Shijan part) and are scattered with less area in the central and western parts of the lagoon (Fig. 2). In 1998 and after 10 years, this plant was broadly distributed in its early places of arrival and covered about 25% of the area of the lagoon. The area of the lagoon was increased by 9.5% during these years, mostly in the southwest and east. The reason for increasing the area of the lagoon is increasing rainfall and consequently, increasing the volume of water entering the lagoon by the rivers supplying it.

The increase in Azolla coverage between 1988 and 1998 was probably due to the support of the Ministry of Agriculture in increasing the level of expansion of this fern, as well as the favorable environmental conditions for Azolla

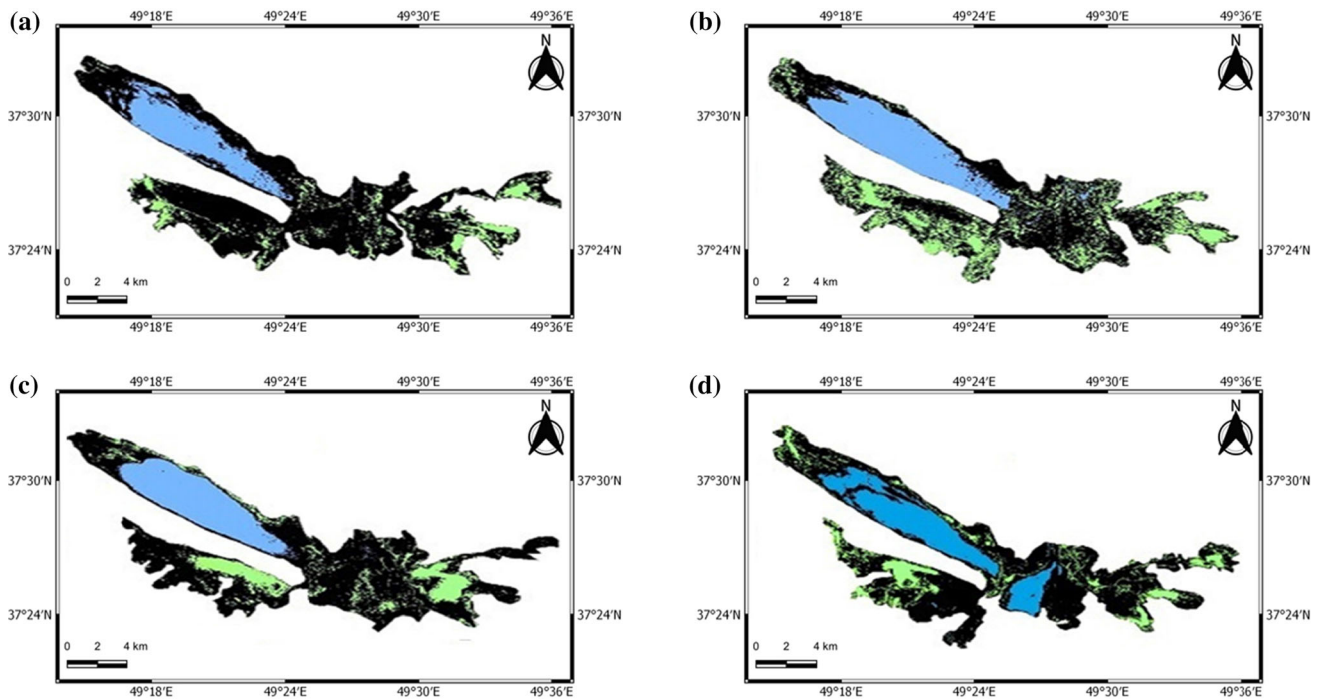


Fig. 2 Azolla distribution (Green color) across 30 years; **a** 1988, **b** 1998, **c** 2008, and **d** 2018

growth. In 1998, the Azolla surface coating was transferred from the borderline of the lagoon to the central and more internal parts of it, where the depth of water was higher in those areas. It is because of drying of the southwest margin and much of the eastern portion of the lagoon and a significant reduction in their area, as well as reducing the depth of water. Shallow water is not a suitable condition for optimal growth and production of Azolla biomass (Singh et al. 2011).

The area of the lagoon increased between 1998 and 2008 years. As a result, the Azolla distribution was reshaped from the central parts to the marginal. These changes are due to the low or increasing amount of water entering the lagoon by its water supply rivers and the temporary and seasonal seizures of the lagoon by residents. Most borderline changes are first seen in the eastern part and then in the southwest of the lagoon, which are adjacent to agricultural and residential uses. The trend of these species changes is calculated after calculating the coverage of four dominant aquatic species in the lagoon, (Table 3,

Fig. 3). As can be seen, the distribution of Azolla in the years 1988 to 1998 uptrends, but then a downward trend until 2018. In the years 2008 and 2018, its growth is almost constant, and no significant change is observed.

The area of the dry land and the lagoon and water cover is in the opposite direction. This is in line with the climate change of the region and the decline in rainfall in recent years. On the other hand, the coverage percentage of the Levi and Louis combination has an inverse trend toward Azolla. The variation in the lotus area is low than Azolla and Levi and Louis combination and is free of sudden fluctuations. The competition between the four dominant herbs has reduced the area of other plants. To investigate the effect of Azolla on the distribution of other aquatic and dominant plants in the region, the comparison of the average of supervised classification classes in the studied years (1988, 1998, 2008, and 2018) and the year, without Azolla (1984) is used (Fig. 4). With the decrease in the average area of the water class in the years studied (compared with 1984), the area occupied by other plants as well

Table 3 Percentage of aquatic and dominant aquatic plants in the lagoon

Year	Water	Azolla	Lotus	Levi and Louis combination	Other plants	Dried land
1984	28.48	–	10.00	48.46	12.47	0.59
1988	22.87	11.72	6.86	46.55	10.94	1.06
1998	20.73	23.96	7.82	35.68	8.82	2.99
2008	19.75	17.67	11.89	37.48	6.62	6.59
2018	16.93	16.58	9.88	40.30	5.88	10.43

Fig. 3 Distribution percentage of classes

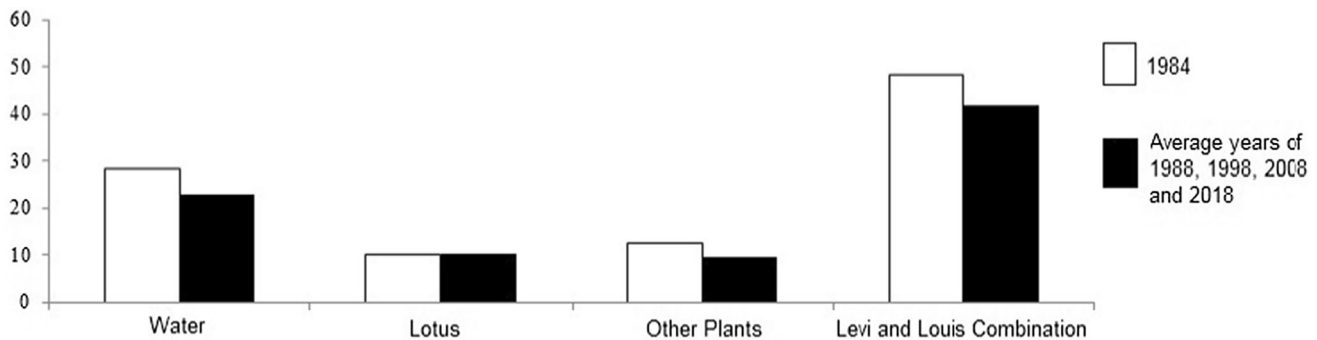
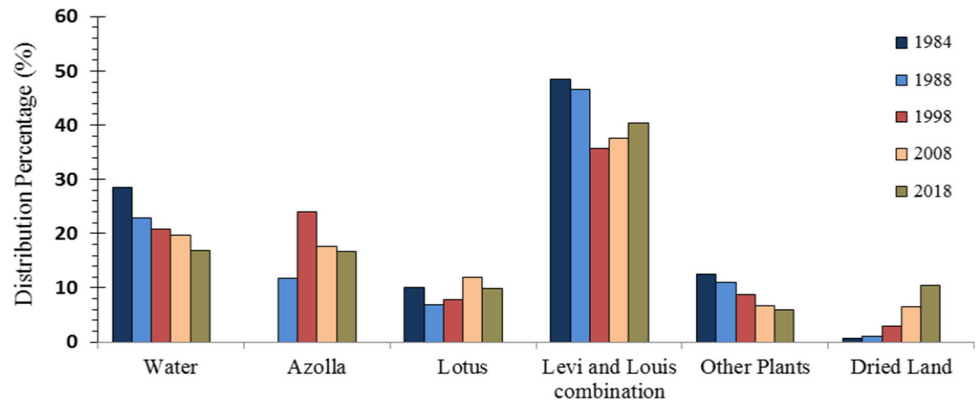


Fig. 4 Comparison of distribution percentage of aquatic and dominant plant species before and after of the 1988 year

as the combination of Levi and Louis has slightly decreased. But there is no change in the lotus class. Investigation of the relationship between the three important climatic parameters (temperature, rainfall, and humidity) with Azolla distribution for growth and biomass production of it showed that with increasing and decreasing annual average rainfall, Azolla expansion level increased and decreased, respectively (Fig. 5a).

As the temperature approaches the optimum level for the growth of this plant (25 °C), Azolla also continues to increase its distribution. But at higher than optimal temperatures, its growth decreases (Fig. 5b). The distribution and expansion of the Azolla are influenced by the relative humidity of the air. However, relative humidity is influenced by two factors: temperature and rainfall. According to the data in Table 1, the moisture content in the studied years was higher than the Azolla plant growth rate. Therefore, except for the gap between 1988 and 1998, the Azolla expansion in the region could be justified (Fig. 5c). Possibly, Azolla growth in the interval between the above two years is the appropriateness of temperature conditions and rainfall. But since 1998, the Azolla expansion has decreased. Due to the lack of favorable temperature and rainfall conditions, despite the relative humidity approaching favorable conditions.

It is very difficult to select the image classification method for areas that have the spectral similarity reflection between the lagoons and adjacent lands with similar vegetation. Landsat satellite imagery multi-dates and Spectral angle mapper algorithm are suitable for mapping and studying the trend of Azolla distribution. Especially for areas where access to them is difficult for various reasons including being protected. As discussed, a variety of supervised classification methods have been used by a small number of scholars to prepare the Azolla distribution map. But obtained results are contradictory to choose the best method. The key to the SAM classification method is to purge the spectral signature as much as possible.

The purer the spectral signatures, the better the accuracy and quality of the generated map. This is especially important for regions with heterogeneous and complex phenomena and when using satellite images with moderate ground resolution (such as Landsat satellite sensors). If the pixels are impurities, the spectral signatures and the resulting spectral classes will be error-prone. The use of supervised and unsupervised classification hybrid, especially in a large regions and complex data sets, can lead to better results. Unsupervised classification can be used to create an initial training area and then use supervised classification to identify more and better the classes and results. The use of remote sensing techniques is very

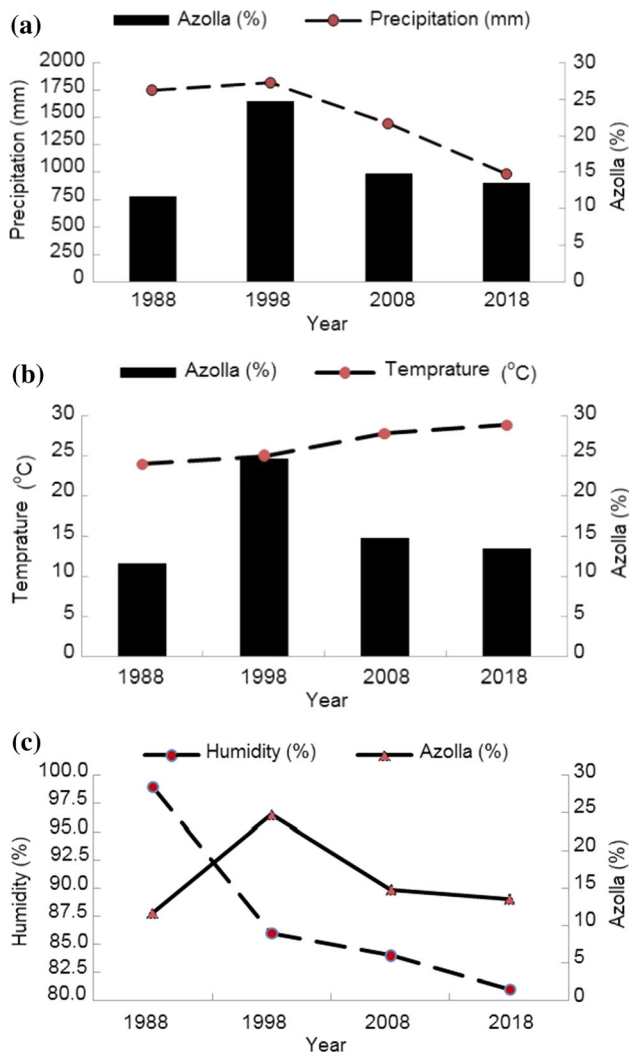


Fig. 5 **a** Relationship between Azolla distribution and precipitation; **b** Relationship between Azolla distribution and temperature. **c** Relationship between Azolla distribution and humidity

important for sustainable development and protection of lagoons. It reduces costs and increases the accuracy and speed of studies (Sharifi, 2020c, 2020d).

The variation in Azolla and other aquatic plant species distribution in the Anzali International lagoon does not show a decrease or increase steady trend. The results imply that different spatial variations are affected by fluctuations in air temperature, relative humidity, and rainfall. Consequently, change in water depth and boundary of the lagoon. Drying of the marginal areas led to the redistribution of Azolla to the central parts of the lagoon where water has a higher depth. The boundary changes were occurred more in the eastern part of the lagoon (Shijan pond) and the southwestern part of the lagoon (protected section of the Siyah-kisham pond). This is because of less depth of water and temporary or permanent change by residents in these areas. Almost all of the eastern and southwestern regions of

the lagoon are covered by a dense layer of Azolla. It penetrates and deepens into the lagoon.

Conclusion

Unlike other drought ecosystems, lagoons are often destroyed and threatened from the borders due to the presence of wide areas of water. Therefore, determining the exact boundary of the Anzali International lagoon is an essential step in its sustainable management as well as contributing to more detailed studies. Probably the change in direction of the Azolla distribution toward the lagoon boundary can indirectly affect the biological drying of these areas in the rainy years. The accumulation and concentration of industrial and urban wastewater in the marginal areas of the lagoon increase the Azolla distribution in horizontal and vertical directions along with the lagoon's boundary areas. Because there are often many phosphorus and nitrogen compounds in these areas, which have a great influence on the growth of Azolla (Espinari et al., 2015; Gresshoff & Plazinski, 2018). Therefore, if efforts are not taken to reduce or stop the entrance of pollutants into these areas, the body caused by the massive death of aquatic fauna during the decomposition and mineralization process, both significantly reduces the water-soluble oxygen content and also the death of animals' Aquatic in the lagoon. The accumulation of the remains of such materials over the years will cause the death of the lagoon. Azolla's entry into the region could cause competition to occupy the space suitable for growth among other plants. The result will be a disturbance to the natural ecosystem and even a reduction in the diversity of plants and animals. There is a direct and inverse relation between Azolla expansion level with two climatic factors of rainfall and temperature, respectively. But the effect of the relative humidity factor is influenced by two parameters of temperature and rainfall. It seems that the two previously mentioned climate factors have a more significant effect than air relative humidity on the growth and development of Azolla. Despite the high relative humidity of the air, the growth and expansion of Azolla are continued in the period between 1988 and 1998. As air relative humidity content was approaching the optimum level, the amount of rainfall decreased and the air temperature was too high Raised. So the growth of this plant has declined after 1998. In general, humidity and extreme temperature of air and as well as low rainfall and low water depth, reduce the growth and expansion of Azolla, especially in dry seasons. It is in the worst environmental condition in many aspects. Azolla's rapid growth has caused the ecological balance to collapse in Anzali international lagoon. Therefore, the need for further

research and the adoption of proper management performance is very essential to preserve this ecosystem.

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