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Review

Evidence-Based Management of the Anzali Wetland System (Northern Iran) Based on Innovative Monitoring and Modeling Methods

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Abstract: As an "international aquatic ecosystem" in Northern Iran, the Anzali wetland is a nursery for fish and a breeding and wintering area for a wide variety of waterfowl. The wetland is threatened by human activities (deforestation, hunting, tourism, and urbanization), leading to habitat destruction, eutrophication, and sediment accumulation. To stop the degradation and to set up effective protection and restoration in line with the Sustainable Development Goals, scientific insights must be integrated into a practical framework for evidence-based support for policymakers and managers of the Anzali wetland. In this study, the Drivers–Pressure–State–Impact–Response (DPSIR) framework is used as a suitable tool to link human pressures and state changes to derive an overview of the potential impacts. Population growth, intensive agriculture, increased urbanization, and industrialization are the major driving forces that have led to a complex cascade of state changes. For instance, during recent years, water quality deterioration, habitat degradation, and the overgrowth of invasive species in the Anzali wetland watershed have caused negative socio-economic and human health impacts. Integrated and innovative monitoring programs combined with socio-environmental modeling techniques are needed for a more evidence-based management approach as part of a multiresponse strategy for the sustainable development of the wetland system. In this respect, there is a critical gap in useful information concerning biological composition and innovative monitoring methods. Moreover, the relation of biota with human activity and environmental conditions needs to be better quantified. Therefore, ecological modeling techniques based on machine learning and statistics were reviewed for their advantages and disadvantages. The overview of approaches presented here can serve as the basis for scientists, practitioners, and decision-makers to develop and implement evidence-based management programs for the Anzali wetland.

Keywords: DPSIR framework; integrated monitoring; ecological modeling; evidence-based management; aquatic ecosystem management

Citation: Sadeghi Pasvisheh, R.; Eurie Forio, M.A.; Ho, L.T.; Goethals, P.L.M. Evidence-Based Management of the Anzali Wetland System (Northern Iran) Based on Innovative Monitoring and Modeling Methods. *Sustainability* **2021**, *13*, 5503. https://doi.org/10.3390/su13105503

Academic Editor: Marc A. Rosen

Received: 25 March 2021
Accepted: 7 May 2021
Published: 14 May 2021

1. Introduction

Large wetlands cover 1.7% (~2.8 million hectares) of Iran, half of which are occupied by 24 wetlands designated as internationally important (Ramsar wetlands) out of 2290 worldwide (Ramsar, Iran, 1971). About one-third of these 24 wetlands are under pressure or in a critical condition [1]. For example, as an "international aquatic ecosystem", the Anzali wetland provides a nursery for fish, and a reproduction and wintering habitat for waterbirds from different parts of the world [2]. Of 145 species of migratory birds in Iran, 77 are found in the Anzali wetland [3]. Due to its outlet connection with the Caspian Sea, many fish species migrate to the wetland, while 39 of 49 wetland fish species are residential [3]. A variety of mammals are also found in the wetland, of which *Felis chaus* (jungle cat), *Sus scrofa* (wild boar), and *Lutra lutra* (common otter) are the major ones [4].

However, because of severe degradation from human activity, the wetland was placed on the Montreux Record of Wetlands in 1993 [5]. The wetland is threatened by a wide range of pressures: eutrophication, deforestation, erosion, unsustainable hunting, inappropriate tourism, and road and urban development. Toxic substances are also harming organisms in the wetland [6].

It is noteworthy that a number of these problems were exacerbated after the introduction of invasive exotic aquatic plants like *Azolla filiculoides* and recently *Eichhornia crassipes* (water hyacinth) [7]. These plants are a major concern for biologists and ecologists dealing with conservation and management of Anzali wetland because of their potential threat to biological diversity and local fauna and flora. In the last few decades, the Anzali ecosystem has been threatened by the influx of chemicals, such as phosphorus and nitrogen, which has led to eutrophication in many places. This problem has created favorable conditions for the overgrowth of invasive exotic species such as *Azolla filiculoides*, which leads to reduced water quality and the degradation of several habitat characteristics [3]. As a result, controlling the rapid growth of the invasive species is considered to be one of the most critical tasks for maintaining and even increasing the sustainability of the Anzali wetland. Figure 1 presents disturbance sources (pollutants), in situ surface water conditions, and their effects on services and consumers. The pollutants can degrade wetland systems, causing a decline in biodiversity and ecosystem economics, such as providing food for consumers, income for sellers, and landscape aesthetics for tourism. Pollutants can also have potential negative consequences for human health via the consumption of contaminated fish and drinking water [8].

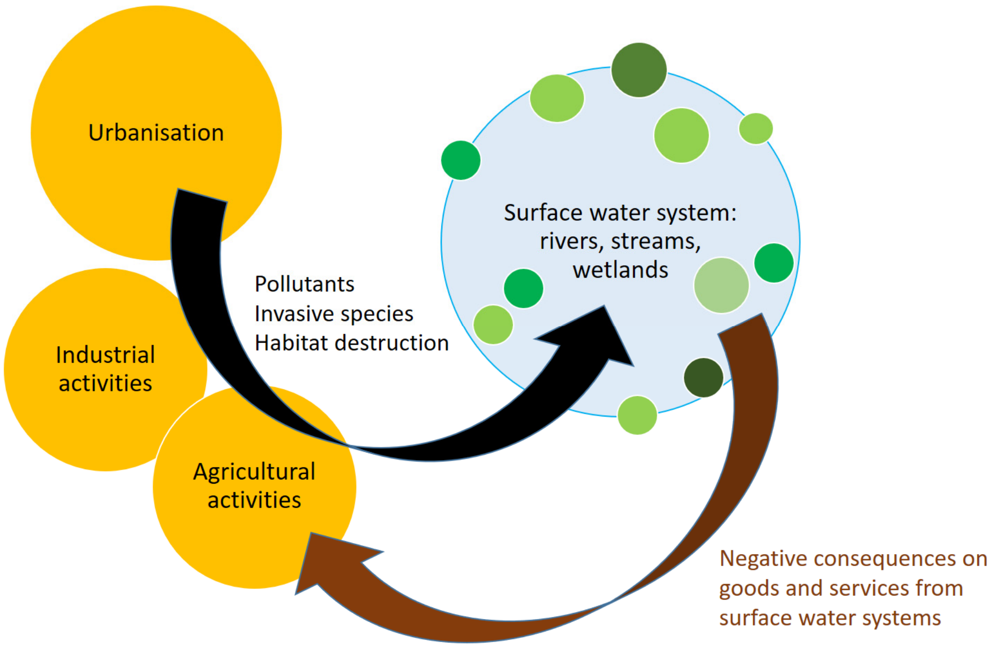

Figure 1. Disturbance sources (pollutants), in situ surface water conditions, and effects on services and consumers (adapted from [8]).

To support the Anzali wetland's managers and policymakers, particularly concerning protection of the wetland, scientific insight into disturbance chains must be integrated into a conceptual framework to realize, visualize, and summarize the real condition for wetland managers or policymakers in a way that is convenient [9]. Among several conceptual frameworks, the Drivers–Pressure–State–Impact–Response (DPSIR) framework has been broadly applied to describe the link between anthropogenic pressures and state changes in aquatic ecosystems like wetlands [10]. The evidence-based DPSIR framework was accepted as a conceptual framework by the European Environmental Agency in 1995 [11] and recommended by the OECD (2003) to manage and structure the cause-and-effect relationships between anthropogenic activities and environmental components to be useful to policymakers and managers. A good insight into the interactions between the drivers, pressures, state changes, and impacts is essential for articulating the acceptable responses [12].

Integrated monitoring of aquatic ecosystems and selecting appropriate ecological modeling techniques can be considered as the basis for evidence-based management. Integrated monitoring of the aquatic ecosystem is a process of coordinated evaluation of the different components of water bodies (hydromorphology, physical–chemical water characteristics, and biology) to provide holistic insights into the status and changes in the ecosystems over time [13]. By providing evidence-based documentation of the states of aquatic ecosystems (because of anthropogenic interventions and perturbations), the monitoring of water and evaluation would support the selection of effective strategies and management actions in decreasing or hampering further water degradation [8]. The present research aims to develop a DPSIR framework for the Anzali wetland watershed for a better understanding of the current problems in the wetland and its watershed. Since these problems have caused eutrophication and overgrowth of invasive species like *A. filiculoides* in the wetland, the present study proposes innovative monitoring and modeling methods to implement effective and more evidence-based environmental management programs and to control pollutants entering the rivers discharging to the wetland.

2. Material and Methods

2.1. Study Area

The Anzali wetland is situated in Northern Iran (Guilan Province) and the southwest of the Caspian Sea approximately between 36°55′ and 37°32′ N and 48°45′ and 49°42′ E [4] (Figure 2). The Ramsar site boundary of the Anzali wetland is about 19,500 ha. The expanse of the area is about 33 km from east to west and about 11 km from north to south at most. The area of the watershed is 3410 km^2. It is bordered by the Caspian Sea to the north, the Sefidroud River to the east and the Alborz Mountain to the south and west. The maximum elevation of the Anzali wetland watershed is approximately 3105 m at the mountains, whilst the elevation of the Caspian Sea coast is roughly −25 m. Rainfall normally ranges between 400 and 2000 mm/year. Temperature ranges between −0.8 °C and 37.3 °C (17 °C on average). Relative humidity ranges between 24% and 100% (66% on average) [4].

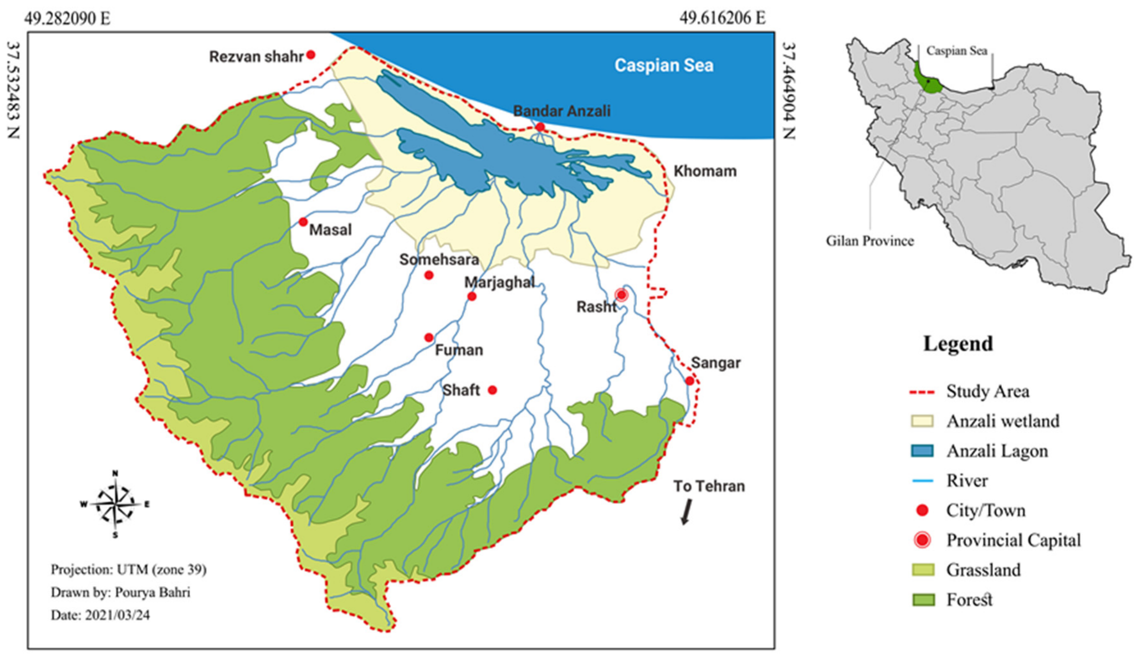

Figure 2. Map of the Anzali international wetland and its watershed.

2.2. Information Collection

For the present review paper, it was necessary to gather three main categories of information:

(1) Different elements of DPSIR, including (a) driving forces (e.g., societal and technological changes responsible for pressures on the wetland), (b) pressures (e.g., the anthropogenic activities that can influence the wetlands), (c) state changes (e.g., the condition of the wetland components influenced by pressures), (d) impacts (e.g., socio-economic losses or human health risks), and (e) responses (e.g., the responses to driving forces, pressures, state changes and impacts, aiming to control or compensate the negative consequences of societal changes in the area) [1–12]. A conceptual framework of DPSIR for the Anzali wetland's watershed is necessary to recognize, summarize, and visualize the real condition of the wetland's watershed to help managers and policymakers in implementing proper environmental management practices for the wetland ecosystem.

(2) Innovative monitoring methods of aquatic ecosystems that can provide numerical evidence about the changes in the wetland ecosystems and their status over time [8,13,14].

(3) Innovative modeling based on machine learning, allowing support for policy decisions related to data collection, analysis, and restoration scenario selection [13,15]. In addition to gaining critical insights in relation to wetland system variables, these techniques allow us to make simulations that can provide additional insights into which restoration actions are most optimal [16].

3. DPSIR Concept as a Basis to Understand Impacts and Needed Responses to Support Natural Recourse Management

The DPSIR framework was adopted for describing the relationships between the origins and consequences of environmental problems to support the Anzali wetland management. According to the adopted DPSIR framework in the Anzali wetland and its watershed, there is a link that starts with 'driving forces' (economic sectors and human activities) through 'pressures' (potential emissions of biota and chemicals, as well as land and habitat alterations) to 'state changes' (physical, chemical, and biological changes in the systems) and 'impacts' on human society (e.g., changes in income, health, possible activity, etc.), ultimately resulting in diverse 'responses' (prioritization, target setting, limiting or even banning of activities) in the wetland. The DPSIR framework, thus, provides a conceptual overview of the interactions between human pressures, state changes, and potential management options in the Anzali wetland watershed and stimulates integrated communication among the public, policymakers, and scientists, improving the cooperation among them. Therefore, the concept can help to bridge the gap between different scientific disciplines as well as various stakeholders and system engineers, and support the Anzali wetland management in its sustainable development.

3.1. Driver–Pressure–State–Impact–Responses (DPSIR) Framework Focusing on Population Growth and Intensive Agriculture, Urbanization, and Industrialization in the Anzali Wetland Watershed to Assess and Manage Environmental Problems of the Wetland

3.1.1. Driving Forces

The Anzali watershed (situated in Guilan Province) includes important environmental systems such as the Anzali wetland and the Hyrcanian forests. Over the last few years, there has been a rapid degradation in the watershed of the Anzali wetland [17]. Based on Table 1, population growth and intensive agriculture, urbanization, and industrialization are the main driving forces that are responsible for the degradation of the Anzali wetland and its watershed. Iran's population increased dramatically during recent decades (Figure 3), reaching about 80 million by 2016 [18]. In 2016, the average annual population growth of Iran was 1.2% higher compared in 2011 and the largest age group was 30–34 (10.8% of the population) [19]. The population growth was also significant in Guilan Province from 1990–2013. For example, in the three main cities located within the Anzali wetland watershed, e.g., Somesara, Rasht, and Fuman, population growth increased by 38%, 25%, and 11%, respectively [20].

Table 1. Driver–Pressure–State–Impact–Responses (DPSIR) framework focusing on population growth and intensive agriculture, urbanization, and industrialization in the Anzali wetland watershed to assess and manage environmental problems of the wetland. The italicized text implies "Responses" with (i) indicating implemented responses.

Driving Forces with Responses	Pressures with Responses	State Changes with Responses	Impacts with Responses
1. Population growth and increasing demand for food [21] * *Family planning: few children and/or at a later age (i)* 2. Increased agriculture [21], urbanization, and industrialization [22] * *Development of a sustainability maximization framework, scenarios, and planning (cf. [14]), as a basis for integrated and evidence-based wetland management to solve the problems in a pro-active manner*	1. Inefficient land use and deforestation [21] * *Implementation of smart land use planning policies (minimal changes allowed from forest to agricultural, urban, and industrial land)* 2. More manure and fertilizers released on land [23] * *Applying green manure (e.g., clover, Azolla water fern) as a soil protection and nutrient source (i)* * *Regulation of the use of fertilizers and manure (i)* 3. More chemicals (pesticides, drugs, etc.) released on land [24] * *Regulations for sustainable use of pesticides,* e.g., *integrated pest management and banning of most harmful chemicals (i)* 4. More domestic and industrial wastewater [25] * *Implementation of efficient municipal and industrial wastewater treatment plants (i)* * *The banning of most harmful chemicals (i)* 5. Increased number of people and harmful activities via tourism [4] * *Proper policy implementation for tourism:* e.g., *visitor quota for fragile ecosystems, restrictions on fishing*	1. Deforestation and erosion [26] * *Afforestation and implantation of erosion control measures (i)* 2. Deterioration of soil and water quality, e.g., increased nutrient levels leading to (toxic) algal blooms [27] and reduced biodiversity * *Nature restoration and protection (i)* * *Construction of buffer strips along the river channel* * *Remove nutrients, algae, and invasive plants from the system* via *dredging or harvesting measures (i)* 3. Overgrowth of invasive species, development of monoculture, and damage to original biodiversity [4] * *Chemical or mechanical removal of invasive species* * *Stricter regulations on application of exotic plants and animals, with strict banning of import and use of invasive species* 4. Increasing organic materials and deposit loads at the bottom of the wetland which lead to increasing the wetland area and flood risk [4] * *Dredging of sediments and organic material in wetland (i)* 5. Degradation of habitats and biodiversity [4] * *Protect and restore habitats (i)* * *Restocking of species (i)*	1. Food and drinking water poisoning, leading to disease and mortality related to pollution * *Prevent human consumption of contaminated products* * *Improved health care* * *Financial compensation for illness and mortality* via *pollutant tracing and liability systems* 2. Damage to economy of local human community, the deteriorated system is not able to provide goods (e.g., food for consuming and selling) [28] and services (e.g., landscape aesthetics for tourism and loss of income from tourism in Anzali wetland) * *Compensation payment systems for affected economic activities* * *Providing or developing alternative livelihoods*

In Guilan Province, about 40.8% and 47.8% of lands were used for agricultural production in 1990 and 2013, respectively. According to earlier reports, e.g., Aghsaei et al. [21], the area of agricultural land increased by 7% in the watershed area during two decades.

In Guilan Province, urban sprawl is considered as one of the main factors transforming land use [29]. In this province, the urban population increased from 1956 to 1986 and had a falling trend from 1986 to 1996. In these periods, the urban population growth rate was more than the rural population growth rate and also the total population growth rate. In 2006, the urban population surpassed the rural population. The increase in extent and ratio of urbanization has been attributed to the increase in rural immigration and the transformation of villages to towns [30]. More than 40% of Guilan Province's population inhabit the cities situated in the wetland watershed. There are 41 major factories in the surrounding regions [25]. Paper mills and wood, metal, textile, rubber, ceramic, and food industries situated in the Anzali wetland watershed constitute the main sources of pollution. Some of the wastewater coming from the industries discharges into the streams/rivers and finally arrives in the wetland [31].

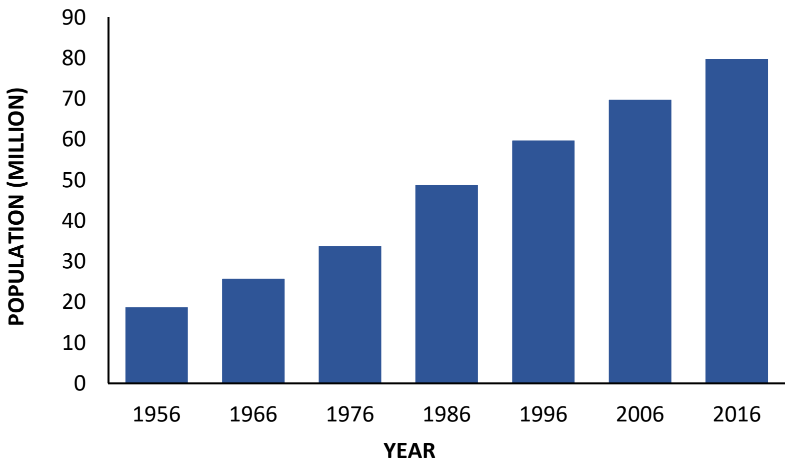

Figure 3. Annual population growth of Iran.

3.1.2. Pressures

Increasing demand for food and the farmers' interest in agricultural intensification practices has led to pressures via land use change for plant production and increased application of fertilizers and pesticides. According to Aghsaei et al. [21], in 1990, forest (45.8%) and agricultural lands (40.8%) were the most dominant lands in the upper part of the Anzali wetland watershed. 8.0% of land belongs to the grassland and it is mainly found at the border of the forest ecosystem. Urban areas (2.5%), wetland (1.5%), and water (1.4%) constituted other lands in the watershed of the Anzali wetland in 1990 (Figure 4). For almost two decades (1990–2013), the area of agricultural land increased by 7% in the watershed of the Anzali wetland, while that of forests, grasslands, and wetlands declined by 6.8%, 1.0%, and 0.7% of the watershed area, respectively. Many forest areas were converted into agricultural land (91%) and grassland (9%). Various problems, including overgrazing and conversion of forests and rangelands to urban and agricultural lands, can lead to a reduction in the grassland area as well as erosion. The rangeland areas are degraded by farmers as the forest and grassland were changed for farming purposes [26]. The surface water area of the Anzali wetland watershed remained constant during the period. The urban area increased slightly when the total area of the watershed is compared (e.g., an increase of 1.5%) [21].

The area of agricultural lands in the watershed of the Anzali wetland is 98,700 ha, comprising 80,900 ha for paddy fields and 17,900 ha for other croplands [4]. Guilan Province, with a 34.2% share of total rice crop production, is among the main rice production areas in Iran. Therefore, efforts are required to increase the production of rice by applying more chemical fertilizer (e.g., N, P_2O_5, and K_2O) [32] and pesticides. In 2000, over 27,000 tons of pesticides were used in Iran, and 60% of all pesticides were applied in three northern provinces (e.g., Guilan, Mazandaran, and Golestan), close to the Caspian Sea, while rice production alone accounts for a quarter of the national pesticides usage [33]. A portion of the pesticides applied on the cropland has been discharged into the Anzali wetland which has led to deterioration of the water quality of the wetland [4].

The use of more manure and fertilizers to increase production (especially in the rice paddy fields) led to the eutrophication of the Anzali wetland. Furthmore, in the context of increasing agricultural production, the Iranian Ministry of Agriculture introduced in Iran a new exotic plant species, namely *Azolla filiculoides* (Lam.) (Azollaceae, Salviniales), from the Philippines in 1986 [4]. At that time, the aim of introducing *A. filiculoides* was to fix nitrogen. Hence, the exotic species was then cultivated in the northern Iranian province of Guilan and applied as a cheap and effective fertilizer (green fertilizer) for paddy fields and a suitable source of food for cattle [34]. After a few years, the fern was spread across northern Iran and arrived in the Anzali wetland. Some years later, it covered approximately a quarter of the Anzali wetland [3].

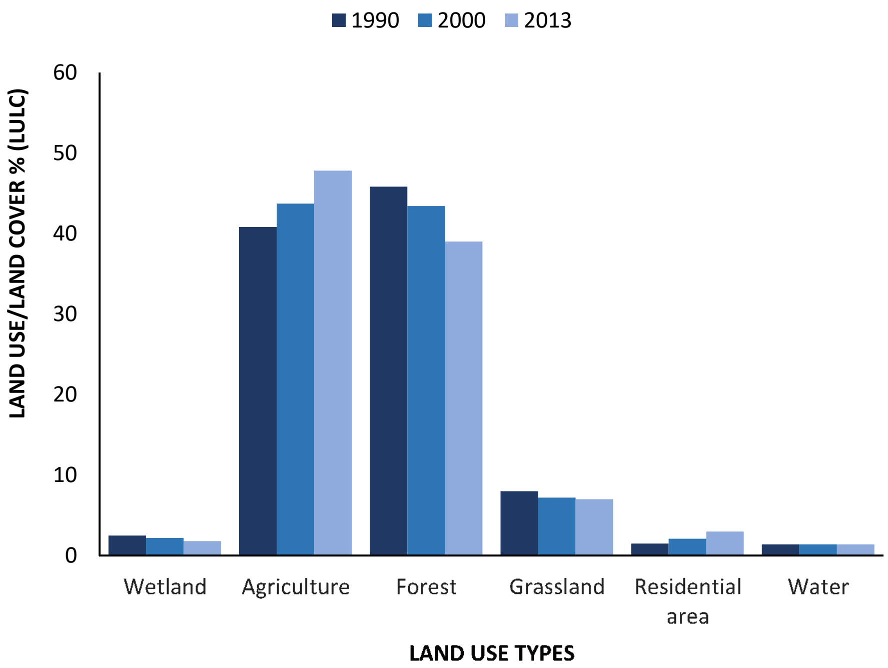

Figure 4. The percentage of land use/land cover (LULC) area and the variations from 1990 to 2013 in the Anzali wetland watershed.

Other pressures are land use changes (mainly from agricultural land to urban and industrial areas) and increasing domestic and industrial wastewater discharges into the rivers and finally to the wetland. In addition, a huge amount of sediment ends up in the Anzali wetland through the surface run-off from upland erosion and unsustainable tourism in the Anzali wetland.

To date, a lot of pollutants, including heavy metals (e.g., lead, copper, zinc, nickel, chromium, and cadmium from different industries), have led to the accumulation of metals in sediments in the Anzali wetland [35]. The high trace metal concentrations in sediments of the wetland are a consequence of the fast industrialization and urbanization. Additionally, the lack of wastewater treatment can intensify the problem [22]. Pollutants are discharged by streams/rivers which receive wastes from various industries and plants near the wetland [31]. Several factories and industries, consisting of rubber manufacturing, steelmaking, plastic, dairy, and ceramic industries, are the main pollutant sources discharging into streams and the rivers and ultimately end up in the Anzali wetland [35].

In addition, the Anzali wetland is a focal point for tourism and about two million people visit the Anzali wetland every year. The wetland is used for recreational purposes such as fishing and hunting [4]. Development of fishing and tourism in the area could lead to an ecological risk for the wetland [31]. Moreover, oil leaks from tourist and fishing motorboats are important sources of oil pollution in the Anzali wetland [36].

3.1.3. State Changes

The pressures on the watershed have led to state changes in the Anzali wetland ecosystem. Specifically, deforestation, deterioration of soil and water quality, high concentration of nutrients (e.g., phosphate), induction of algal blooms, overgrowth of invasive species, increasing organic materials and deposit loads, rainwater storage capacity reduction and flooding risk, degradation of habitat conditions, and decreasing biodiversity are some of the state changes in the Anzali wetland (Table 1).

Regarding deforestation, the forests located on the southern border of the Caspian Sea cover an area of 2 million hectares and are the most valuable and economical in the area [37]. The forests supply timber, fuel, fodder, and other various products and mitigate floods and soil erosion and maintain soil fertility, but are now faced with deforestation. Deforestation has caused a decrease in forest biodiversity. The deforestation can cause greenhouse gas emissions, a disrupted water cycle, increased soil erosion, and disrupted livelihoods of people relying on the forest ecosystem [38]. The destruction of the forests and uplands is a serious threat to the Anzali wetland and its watershed. This resulted in massive soil erosion, decreased soil fertility, and sedimentation in river channels and siltation of dams and, finally, led to a catastrophic flood [38].

Another state change in the Anzali wetland ecosystem is the invasion of exotic species such as water fern (*A. filiculoides*), water hyacinth (*E. crassipes*), and water lettuce (*Pistia stratiotes*) [7]. Application of a huge amount of chemical fertilizers to promote soil fertility and increase plant growth in the wetland watershed (mainly paddy fields and fish farming) has led to eutrophication of the wetland and overgrowth of these exotic species. Presently, most parts in the southern and eastern basins of the Anzali wetland are densely covered by *A. filiculoides*. In sheltered parts, it forms thick mats (even up to 20 cm deep), making the passage of boats very difficult. Furthermore, this fern can cause severe problem for fishing activities [4]. The overgrowth of the invasive exotic *A. filiculoides* in this ecosystem has resulted in reduced water quality and degradation of several habitats in the wetland. After the invasion of *A. filiculoides* in the Anzali wetland, the habitat conditions of some submerged plants (e.g., *Ceratophylum demersum*, *Potamogeton pectinatus*, *Myriophylum spicatum*, and *Chara* spp.) significantly decreased. Thick mats of *A. filiculoides* prevent the penetration of sunlight into the water and hence cause problems for the submerged plant species. Populations of some valuable, native floating plant species such as *Lemna* spp., *Spirodella* spp., *Nelumbium nuciferum*, *Salvinia natans*, and *Trapa natans* (water chestnut) have also been diminished [34]. The latter species is considered as a valuable nature-based pollution removal method since it easily takes up various heavy metals. This species also provides habitat and food to diverse and unique waterfowl species. Dense *A. filiculoides* carpets compete with other species for nutrients and suppress plants which serve as food for waterbirds [4]. Moreover, the thick mats of *A. filiculoides* generate difficulties for the Caspian Sea fish migrating through the wetland [39]. Many fish species migrate from the sea to wetlands through this outlet. Dense surface mats of *A. filiculoides* in the outlet prevent fish from migrating to and laying eggs in the wetland, and the fingerlings from returning to the Caspian Sea. The fern has deteriorated living conditions for fish and nearly all other biological communities that are related to them. Each year, thousands of fish perish in the wetland as a result of oxygen deficiency [39]. Since the biomass production of this water fern is too high, dead *Azolla* can quickly increase deposited loads at the bottom of the wetlands. Based on this, significant *A. filiculoides*-based dead organic matter accumulation combined with increased sedimentation has lowered the water depth extremely, leading to a significant decrease in the wetland's rainwater storage capacity and an increase in flood risks [4].

The degradation of habitat conditions for the biological communities, combined with the release of toxic materials from agriculture, urbanization, industrial development, and tourism, resulted in drastically reduced physical–chemical conditions and related negative biological state changes in the Anzali wetland. The factories and industries will, moreover, further develop and expand in the near future. The high concentration of toxic materials can threaten the ecological environment and the aquatic organisms of the Anzali wetland [31], causing retarded growth, behavioral and genetic changes, and a general decline in biodiversity and related ecosystem services [40,41]. Based on this, they will become the main sources of the toxic materials and heavy metals in the wetland. Consequently, serious environmental impacts will be expected if no measure is taken [4].

3.1.4. Impacts

The Anzali wetland is characterized by its distinctive ecological and socio-economical features, and a variety of animals and plants, so this unique wetland is a suitable habitat for wildlife communities and the main source for feed for various animals. Various ecological functions and economic benefits are attributed to the Anzali wetland. The Anzali wetland provides valuable habitats to several endangered species and many migratory birds. Moreover, the livelihood of many local people is provided by the wetland, including several fish species, waterfowl, and other organisms [28]. As a result, maintaining the natural properties of the wetland is important to protect the welfare of the people. Many economic activities are necessary for the welfare of the local people, but overexploitation should be avoided in the Anzali wetland and more sustainable alternatives need to be implemented. To achieve this, the activities related to economic and conservation activities need to be balanced to accomplish sustainability of natural resources. The current condition of the Anzali wetland demonstrates that the natural properties of the wetland have been significantly deteriorated by anthropogenic activities [28]. Moreover, the traditional products of the system, such as fish and birds, might be unacceptable for human consumption due to high level of toxicity from pesticides [24].

These impacts were exacerbated after the introduction of the exotic aquatic plant *A. filiculoides* in the Anzali wetland. Overgrowth of the invasive fern in the Anzali wetland has negative impacts on human activities and introduces extra risks such as floods, while interventions such as mechanistic removal and pesticide-based selective killing are very expensive and not without other risks to biodiversity and human society. Waterways and irrigation canals all around the wetland watershed are clogged by the fern and hamper the irrigation of rice paddies and other farming activities in the neighboring regions [4].

Currently, a large amount of pollutants such as heavy metals discharges into the wetland and eventually flows into the Caspian Sea. This can be attributed to the development of various factories and industries around the wetland, and discharge of various pollution by rivers which receive wastes from numerous plants. Thus, heavy metals are considered a major hazard to the wetland, the Caspian Sea, and all people relaying on these systems [31]. The wastewater discharge negatively affects human health through associated waterborne diseases such as diarrhea and typhoid [42], which lead to both medical as well as economic challenges.

4. Integrated and Innovative Monitoring of Wetlands

According to the DPSIR analysis of the Anzali wetland watershed, population growth, intensive agriculture, increase in urbanization, and industrialization are considered the main driving forces in the Anzali wetland watershed, resulting in various state changes such as deterioration of water quality and degradation of habitat conditions as well as the overgrowth of invasive *A. filiculoides* in this international wetland. This can, in turn, have negative impacts on the health of local human community and socio-economic conditions as well as the ecology of the Anzali wetland.

Currently, invasive species like *A. filiculoides* are a serious threat to aquatic biodiversity in the Anzali wetland, so the occurrence of such invasive species is a major concern for ecologists and biologists dealing with the management of the Anzali wetland ecosystem [3]. Therefore, it is crucial to evaluate and monitor the ecological quality of the wetland in order to have successful management programs for controlling the invasive species in the Anzali wetland ecosystem. This can be justified that monitoring valuable aquatic ecosystems like the Anzali wetland can provide insight into the current states of such aquatic ecosystems. Due to the interconnected web of various biotic and abiotic characteristics (e.g., hydromorphology, geological structure, water, and climate) in the aquatic ecosystems, monitoring campaigns often need to be implemented in an integrated manner to get sufficient insights into aquatic ecosystems' statuses (Figure 5). To achieve this, it is valuable to integrate both species occurrence and species interactions to better understand nutrient cycling, energy transfer, and the effects of invasive species. To do so, wetland managers must become acquainted with the ecosystem's stability and its potential shifts towards another state. As such, decisionmakers can ascertain the relationship between the components and the cause and effect of an environmental effect or human activities as a basis to determine sustainable restoration options [14].

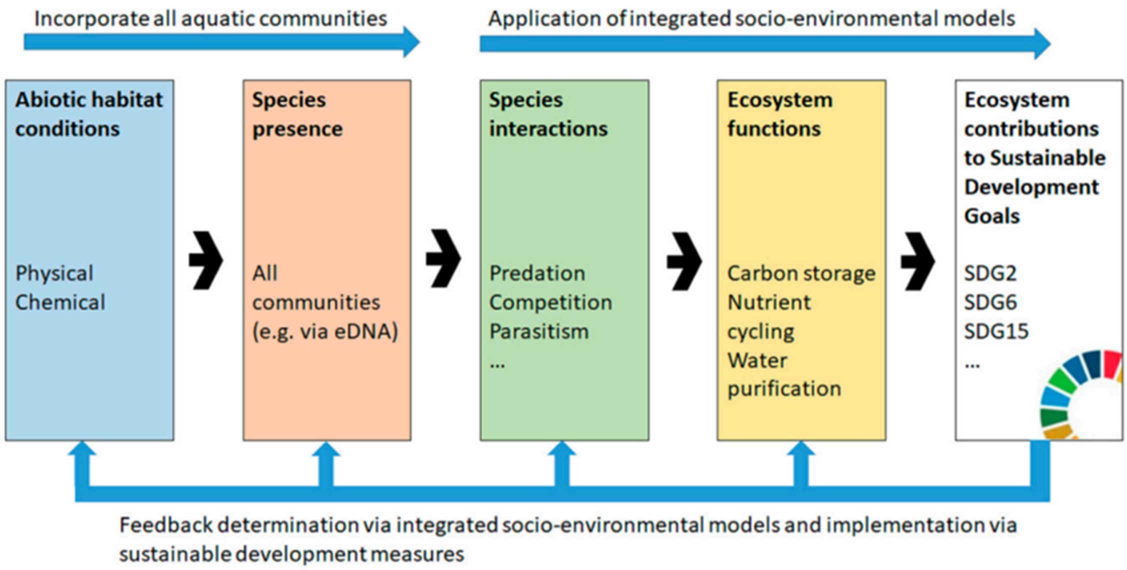

Figure 5. Conceptual diagram for the integrated monitoring and assessment method to select an optimal balance between the Sustainable Development Goals (SDGs) [14].

It is important to assess the ecological quality of the Anzali wetland based on its physical and chemical and habitat characteristics but also its biological properties [3]. Depending on the focus of the research (e.g., fish, aquatic birds, amphibians, aquatic macrophyte community), several properties of the aquatic organisms (such as abundance, density, dry and wet biomass, coverage percent, presence/absence, etc.) need to be examined. Biological monitoring can usually provide a more precise assessment of both water and overall environmental quality than abiotic measurements alone [43]. Specifically, for the follow-up on invasions by floating plants, remote sensing can be a valuable innovative monitoring instrument. Via comparing and coupling of field observations of plant communities in the wetland and data derived from high spatial resolution multispectral satellite imagery yield, new and better information on the invasion status and control could be made available to wetland managers.

Some of the major physical–chemical and structural habitat elements of the wetland which need to be monitored (especially for *A. filiculoides*) could be water depth, air and water temperature, light intensity, humidity, growing seasons and day length, flow velocity, wind and waves, salinity/conductivity, pH, macronutrients (e.g., phosphorus, nitrogen, potassium, calcium, and magnesium), and micronutrients (e.g., iron, molybdenum, and cobalt). Some of these variables, like pH, conductivity, water temperature, and dissolved oxygen, can be measured in the field via probes. However, for most chemical variables, water samples should be collected and immediately brought to the laboratory for analysis with standard methods. The methods for collecting, preserving, and analyzing water samples need to be implemented with a standardized procedure, e.g., APHA/AWWA/WEF (1998) [44]. More information concerning the protocols and methods to analyze the physical characteristics and chemical composition of the water can be found in Bartram and Balance (1996) [45]. Furthermore, the number of tourists that visit the wetland needs to be monitored, and their behavior needs to be analyzed as a basis to determine the impact of tourism. It is also worth monitoring the type and composition of wastewater that is discharged and enters the rivers and then ultimately enters the Anzali wetlands. Moreover, fertilizers and pesticides applied in the agricultural areas should be measured as a basis for health risk assessment and improvement of agricultural practices. Since there are land use changes in the watershed of the Anzali wetland, this issue needs to be considered. This can be monitored using remote sensing methodologies, combined with ground truth-based validation.

In aquatic ecosystems, data collection is often very time-consuming, highly dynamic, and expensive. During recent few years, substantial technological advances have been implemented in ecological and monitoring strategies, and can be very valuable to enhance the monitoring and status assessment of the Anzali wetland system. Environmental DNA (eDNA) is such an example of a very recent technology for species detection. Real-time monitoring systems can also be utilized to assess the physical–chemical characteristics of water with more proficiency over a long period [14], remote sensing can offer broad-scale automated and repeatable methods for monitoring indicators of vegetation condition [46], trait-based monitoring and assessment can provide signals regarding what environmental factors may be responsible for the impairment [47], intelligent camera systems, hydroacoustics, and animal tagging can offer cost-effective measurements and observations for organisms and their interactions underwater [14], and citizen science or public participation in scientific research [48] can provide monitoring data and offer a mechanism for engaging the public [49].

5. Modeling as a Basis for Evidence-Based Management

Gaining insight into the habitat preferences of (invasive) species in an aquatic environment is useful to decide on the conservation management or wetland restoration methods. Based on the particularly large impact of the invasive plants in the Anzali wetland and connected systems, it is essential to assess the impact of invaders on the ecological appraisal of aquatic systems. To do so, proper modeling techniques are needed to accomplish a reliable analysis and prediction for the given invader [3]. Such ecological models are able to successfully determine the relation between biotic and abiotic factors [50]. Therefore, these models can be used to assess, monitor, and control environmental conditions based on numerical and quantitative evidence [51].

For the development of these models, several techniques can be applied, ranging from complex process-based ones using partial differential equations with long development times, to machine learning methods that allow for gaining insights into the major relations of data and which are characterized by much shorter development times. A variety of machine learning techniques has already been successfully applied on water- and ecosystem-related datasets [16]. Each method has some advantages and disadvantages, related to data characteristics, ease of interpretation, development time, and user convenience. Some popular methods are briefly described here; however, a more complete overview can be found in Van Echelpoel et al. (2015) [16]. Decision trees (DTs) [52] predict the value of a discrete dependent variable with a finite set of values from the values of a set of independent variables, which may be either continuous or discrete [53]. The clarity of such models is useful for easy integration into an environmental decision support system [54]. A related method is support vector machines (SVMs), that are based on more recent developments by Vapnik (1995) [55]. SVMs can help to draw out temporal/spatial patterns from data that are highly nonlinear and complex [56] and generate more stable and reliable results compared to classification trees. Multiclass problems can be solved by using pairwise classification with this technique [57]. Artificial neural networks (ANNs) are also powerful computational tools that can be applied for both regression and classification [58]. The tool is particularly useful when large datasets are available [59] and high reliability is needed, but the development time is often much longer than DTs and SVMs. Another modeling technique is Bayesian belief networks (BBNs). This network type of modeling method is based on the principles of Bayes' theorem. The distinctive feature of Bayesian models is the explicit consideration of probability. It is a powerful way to increase knowledge about a certain system of the real world by the integrative analysis of probabilities of models and observation data [40]. Similar to BBNs, fuzzy logic (FL) models have also been successfully applied in ecological studies [60,61]. The FL models assume that the classification of observations is not always straightforward and ecologically sound. When dealing with classification, one can use strict boundary conditions, as is commonly done in DTs. This might lead to a significant reduction in the number of environmental parameters and a loss of information [16], but, on the other hand, increase the transparency about the rules and relations among variables. Fuzzy logic models potentially have as main strength the fact that expert knowledge can be easily integrated [62].

A main aspect of applied ecological modeling is to determine an appropriate equilibrium (Figure 6) between the number of processes and the user convenience (development time and reliability) of the models [15]. Several biotic and abiotic characteristics of the aquatic ecosystems can be integrated to determine the wetland conditions with human activities [14]. However, wetland systems are complex in themselves and are characterized by many internal system interactions, which can be drastically altered via diverse human activities. Therefore, an efficient and applied modeling approach should determine an appropriate equilibrium between the combination of more processes and environmental parameters, in balance with development and simulation times (and costs) that wetland managers and stakeholders can offer. In some cases, relatively simple models might be more practical to investigate particular aspects in a short time span, while in other cases, a higher level of model complexity and reliability is more important than a shortened simulation time [15]. The latter can be the case when large interventions are needed, which entail huge investments (e.g., dredging for channel deepening and maintenance, land use reshuffling).

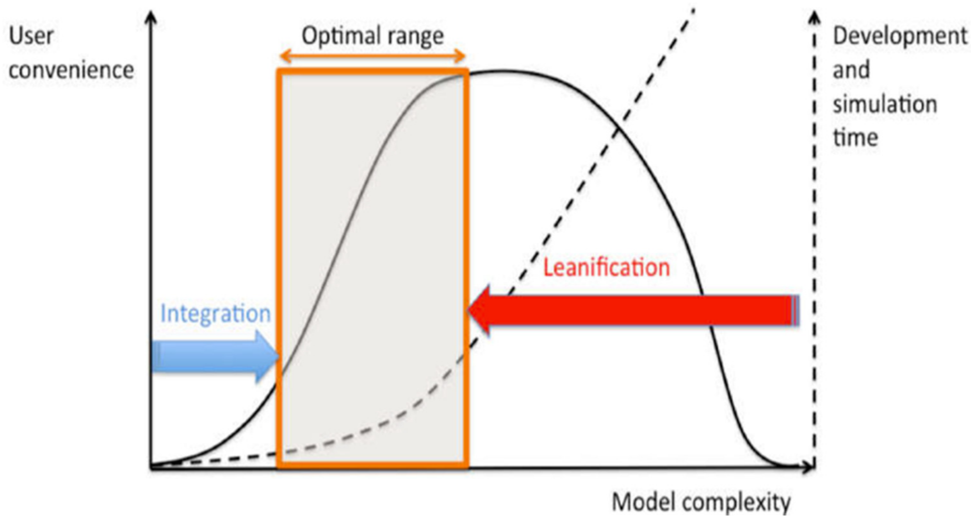

Figure 6. User convenience in relation to the level of complexity.

Gaining insight into the habitat quality and environmental variables to preserve a high biodiversity is crucial to develop wetland conservation and management programs which are threatened as a result of the extension of agricultural and other development activities [63]. Designation and appropriate management of protected areas are essential to reduce the habitat degradation and maintain a high biodiversity [64]. By doing this, wetland managers/decisionmakers can benefit from the models for selecting an appropriate management program to forecast future ecological water quality conditions which result from various management strategies. Furthermore, models can be used to compare the management options quantitatively so that, in this manner, they contribute to a more sustainable selection of environmental investments [65].

6. Conclusions

The provided DPSIR framework of the Anzali wetland watershed can provide a conceptual insight into the interactions between anthropogenic pressures in the watershed, state changes in the wetland, and potential management options in the Anzali wetland and its watershed. In the analyses, population growth, intensive agriculture, increase in urbanization, and industrialization were considered the main driving forces in the watershed of the wetland. These driving forces can lead or have led to various state changes, including deterioration of water quality, degradation of habitat conditions, and the overgrowth of invasive *A. filiculoides* in this valuable wetland. These changes, in turn, have caused negative impacts on the socio-economic conditions and human health of the local community as well as the ecology of the wetland. Furthermore, the DPSIR analyses highlighted that not all responses are beneficial but may lead to more serious threats, as exemplified in the introduction of the invasive species *A. filiculoides* as a green fertilizer, which later led to more problems within the wetland. The DPSIR framework can potentially bridge the gap between different scientific disciplines and support Anzali wetland management concerning the control of the invasive species *A. filiculoides* by stimulating efficient communication and cooperation among policymakers, scientists, and the public. Moreover, to gain a better insight into aquatic ecosystems' statuses, integrated monitoring was proposed for the wetland. It is essential to assess the ecological quality of the wetland based on its physical–chemical and habitat characteristics and also the biological properties of the wetland to implement holistic environmental management programs. It is also valuable to integrate both species occurrence and species interactions for a comprehensive understanding of nutrient cycling, energy transfer, and the effects of invasive species on the wetland system. Furthermore, the selection of appropriate ecological and integrated socio-environmental modeling techniques was proposed as the basis for evidence-based management. Wetland managers/decisionmakers can benefit from such models for quantitatively comparing different management options as a basis to determine sustainable options of environmental investments.

Author Contributions: Conceptualization, P.L.M.G.; writing—original draft preparation, R.S.P.; writing—review and editing, R.S.P., M.A.E.F., L.T.H., P.L.M.G.; supervision, M.A.E.F., L.T.H., P.L.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. Long Ho is a postdoctoral fellow of the FWO (project number 1253921N).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge Pourya Bahri (University of Guilan, Iran) for providing the map of the Anzali international wetland and its watershed.

Conflicts of Interest: The authors declare no conflict of interest.

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