Developing a GIS-Based Decision Rule for Sustainable Marine Aquaculture Site Selection: An Application of the Ordered Weighted Average Procedure

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Abstract: Fish consumption is on the increase due to the increase in growth of the global population. Therefore, taking advantage of new methods such as marine aquaculture can be a reliable source for the production of fish in the world. It is necessary to allocate suitable sites from environmental, economic, and social points of view in the decision-making process. In this study, in order to specify suitable areas for marine aquaculture by the Ordered Weighted Averaging (OWA) methodology in the Caspian Sea (Iran), efforts were made to incorporate the concept of risk into the GIS-based analysis. By using the OWA-based method, a model was provided which can generate marine aquaculture maps with various pessimistic or optimistic strategies. Eighteen modeling criteria (14 factors and 4 constraints) were considered to determine the appropriate areas for marine aquaculture. This was done in 6 scenarios using multi-criteria evaluation (MCE) and ordered weighted average (OWA) methodologies. The results of the sensitivity analysis showed that most of the parameters affecting the marine aquaculture location in the region were as follows: Social-Economic, Water Quality, and Physical–Environmental parameters. In addition, based on Cramer's V coefficient values for each parameter, bathymetry and distance from the coastline with the most effective and maximum temperature had the least impact on site selection of marine aquaculture. Finally, the final aggregated suitability image (FASI) of weighted linear combination (WLC) scenario was compared with existing sites for cage culture on the southern part of the Caspian Sea and the ROC (Relative Operating Characteristics) value turned out to be equal to 0.69. Although the existing sites (9 farms) were almost compatible with the results of the study, their locations can be transferred to more favorable areas with less risk and the mapping risk level can be controlled and low- or high-risk sites for marine aquaculture could be determined by using the OWA method.

Keywords: marine aquaculture; site selection; GIS; ordered weighted average (OWA); Caspian Sea (Iran)

1. Introduction

Fish is an important source of protein for the growing human population. However, wild fish stocks are decreasing due to heavy utilization and increasing demand for aquatic products. Marine aquaculture is one of the most important and quickest growing industries in the world [1] as it can relieve the pressures on marine and coastal ecosystems and still supply necessary food products [2]. In addition, marine aquaculture can contribute to food security [3,4].

In per capita terms, world fish consumption is projected to reach 21.5 kg in 2030, up from 20.5 kg in 2018. However, the average annual growth rate of per capita food fish consumption will decline from 1.3 percent in 2007–2018 to 0.4 percent in 2019–2030 [5].
Marine aquaculture in Iran has been growing relatively fast in recent years. The production has risen from 3.2 thousand tons in 1987 to 320.2 thousand tons in 2014 [5]. Iran has strong potential for the development of marine aquaculture due to wide coastal areas in the north and south of the country. However, aquaculture has to compete for space with other activities like traditional fisheries, transport, tourism, oil, and gas industry, etc. [6]. Therefore, it is necessary that the aquaculture sites are appropriately selected [7,8]. This will provide the basis for both the economic benefits and also for the sustainability, quality, and durability of the farms.

The success and sustainability of aquaculture activities are heavily influenced by site selection factors [9]. This would also reduce the risk of environmental load, increase economic benefits, and minimize the competition for the use of other sources [10]. This is a complicated spatial planning problem with a large number of alternatives and environmental, economic, and social factors [11,12].

Development of the geographic information systems (GIS) and the availability of remote sensing data during the last decades made the selection of aquaculture sites possible based on the systematic analysis of different factors [13–16]. Combining the GIS software and Multi-Criteria Evaluation (MCE) techniques provides us with a potential instrument that can help users solve complex decision-making problems [17,18].

The MCE approach is one of the most common methods used to identify suitable aquaculture sites throughout the world [19]. This is a combination of multiple variables in a structured model (e.g., depth, chlorophyll-a, temperature, turbidity, distance to coastline, etc.), which is made by using a weighted overlay in which a relationship exists between weights area and relevance [20]. This is useful because it allows the marine aquaculture-related spatial variability of the environmental, biological, and socioeconomic specifications to be evaluated. It includes consideration of the different relevance levels amongst various parameters and provides a useful qualitative and quantitative output that can be easily understood by decision-makers. Various studies have been performed to select appropriate sites for marine aquaculture. Some of these studies include identifying suitable sites for coastal aquaculture in Camas Bruaich Ruaidhe, Mexico [21], selecting Margarita Island’s oyster farms in Venezuela [22], application of biophysical models for Japanese scallop (Mizuhopecten yessensis) farms in Funka [16], selecting suitable sites for oyster farms in Geoje-Hansan Bay in the South Sea of Korea [10], examining the potential impact of climate change on the development of Japanese kelp aquaculture [23], selection of suitable sites for 13 aquaculture candidates (seaweed, bivalves, fish, and crustaceans) to modify the scenario in the German EEZ of the North Sea [24], identification of suitable sites for aquaculture farms of offshore medium size marine fish (especially sea bream and sea bass) in the Ligurian Sea, Italy [25], and analysis of the potential for using two SDMs (Species distribution models), Mahalanobis Typicality and Maxent, for aquaculture site selection in the Mekong Delta in Southern Vietnam [26]. These studies have been performed using Boolean and WLC (Weighted Linear Combination) methods for the selection of suitable sites for marine aquaculture.

Thus, OWA (Ordered Weighted Average) procedure has not been used to site selection of marine aquaculture that the level of risk and tradeoff can be controlled and providing different decision-making scenarios. Therefore, this paper provides a quantitative analysis based on Multi-Criteria Evaluation (MCE) with the Ordered Weighted Averaging (OWA) methodology and also satellite remote sensing technology in order to determine appropriate sites for marine aquaculture in the southern parts of the Caspian Sea, Coasts of Mazandaran Province.

2. Materials and Methods
2.1. Case Study Specification

The Caspian Sea is the largest lake on Earth with no outlets. Its area is divided into three, approximately equal, parts: Northern, Middle, and Southern. The Southern Caspian has the largest volume, some 64% of the total volume, and its area is 35% of the total area of...
the sea. It is the deepest part of the sea, with a maximum depth reaching 1025 m [27]. The mean salinity of the Caspian Sea equals 12.85 g/L. The salinity of the Southern Caspian is 13 g/L. Water temperature in the Southern parts of the Caspian Sea never falls below 13 °C in winter and increases up to 25 or even 30 °C in summer [28]. The study area included the Coasts of Mazandaran Province in the south of the Caspian Sea to the depth of 50 m in 35047′ and 38005′ N and 50034′ and 56014′ E (Figure 1). The coastline length in the southern part of the Caspian Sea is 873 km (Mazandaran Province coastline: 487 km). The coastline is relatively smooth. There are no bays or capes that are considered the best locations for cage culture.

![Image](image_url)

**Figure 1.** Location of the study area on the coast of Mazandaran Province, the southern part of the Caspian Sea, with the position of current aquaculture farms and geographic indexes.

2.2. Identification, Obtaining, and Preparing the Environmental Criteria and Spatial Database Acquisition

The conceptual structure of the spatial analysis method for the selection of suitable sites for marine aquaculture operations is illustrated in Figure 2. In Table 1, the main factors and constraints by their sources are mentioned. This study identified 18 criteria according to the basic requisite for Rainbow trout (*Oncorhynchus mykiss*) aquaculture in Mazandaran Province, southern part of the Caspian Sea. These criteria were organized into three submodels (Physical–Environmental, Social–Economic, and Water Quality) and constraints (Harbor, River mouth, Bathometry, Distance from the coastline) represented either as factors or constraints (Nath et al., 2000). Identification, acquisition, and normalizing the criteria are the first steps in the conceptual structure. The second step requires one or more decision-makers to determine the weight of their criteria and ORness values for the calculation of order weights. The ORness value reveals the risk level in the decision-making process [29]. The GIS-based OWA model was used in the third step to utilize the criteria and decision-makers’ priorities for the development of suitable areas for marine aquaculture. Finally, to verify the suitability of the final model outputs, comparisons were made between the predicted suitable sites and existing farm locations.
Figure 2. Conceptual structure of GIS-Based OWA approach for developing marine aquaculture. (MCE: Multi-criteria evaluation; OWA: Ordered weighted average; ZLS: Zonal land suitability; ROC: Relative operating characteristics).

Table 1. Parameter requirements for Rainbow trout (Oncorhynchus mykiss) aquaculture development in the coasts of Mazandaran Province, the southern part of Caspian Sea, Iran.

| Sub Models      | Criteria                        | Unit          | Scale/Resolution | Sources                                                                 |
|-----------------|---------------------------------|---------------|------------------|-------------------------------------------------------------------------|
| (Water Quality) | Temperature (Maximum and minimum) | °C            | 4 km             | Moderate Resolution Imaging Spectroradiometer (MODIS)                   |
|                 | Suspended solid                 | μm<sup>-1</sup> Sr<sup>-1</sup> |                 | Satellite, Aqua sensor http://oceancolor.gsfc.nasa.gov                  |
|                 | Chlorophyll-a                    | Mg/m<sup>3</sup> |                 | accessed on 17 February 2021                                           |
| (Physical–Environmental) | Bathymetry                      | M             | 1/25,000         | Iran National Cartographic Center                                          |
|                 | Maximum wave height              | M             |                  | Iran Ports and Maritime Organization (Iranian Seas Wave Modeling ISWM)   |
|                 | Maximum wind speed               | m/s           |                  | (Depth/distance of the beach) × 100                                     |
|                 | Maximum Current velocity         | m/s           | 3 km             | HYCOM Model, (Kara et al., 2010)                                       |
| (Social–Economic) | Distance to touris areas         | m             | 1/25,000         | Iran National Cartographic Center                                          |
|                 | Distance to industry             |               |                  | Iran Department Environmental                                          |
|                 | Distance to beach                |               |                  | Iran Ministry of Defence                                                |
|                 | Distance to City                 |               |                  | Google Earth 7.1.5.1557                                                 |
|                 | Distance to coastal protected areas |           |                  | (Gholamalifard et al., 2012)                                            |
| (Constrain)     | Harbor                           | m             | 1/25,000         |                                                                         |
|                 | The main river mouth             |               |                  |                                                                         |
|                 | Distance from the coastline (3–20 km) |       |                  |                                                                         |
|                 | Depth (20–50 m)                  |               |                  |                                                                         |

2.2.1. Water Quality Parameters: Sea Surface Temperature

Data for sea surface temperature (SST) were obtained using a Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua sensor with a resolution of 4 km, provided by the Distribution Active Archive Centre Goddard Space Flight Centre National Aeronautics and Space Administration (DAAC/GSFC/NASA). Monthly data was obtained for the period of 2010 to 2015. Then, the 72 images obtained were processed from the maximum and minimum SST image (Figure 3).
2.2.2. Water Quality Parameter: Suspended Solids

A high correlation between suspended solids and the normalized water-leaving radiance at 555 nm, \( n_{Lw} \) (555), has been observed in several studies [30,31]. Therefore, we used the \( n_{Lw} \) (555) as a proxy of the concentration of suspended solids. The \( n_{Lw} \) (555) values were obtained from MODIS images. Monthly data were collected between 2010 and 2015. All images were combined to generate a single image, which was used to generate average values of suspended solid (Figure 4).

2.2.3. Water Quality Parameter: Chlorophyll-a

Phytoplankton is food for many fish species, but the high amount of phytoplankton is also an indication of eutrophication. The concentration of chlorophyll-a is often used as a proxy to describe phytoplankton biomass. In various studies, chlorophyll-a is considered an important factor in site selection for marine aquaculture [31]. MODIS data at 4 km resolution imagery was used in the analysis. The chlorophyll-a product using the OC4 algorithm was utilized. Monthly data were collected from 2010 to 2015. The images were combined into a single image to obtain average values of chlorophyll-a concentration (Figure 5).
2.2.4. Physical–Environmental Parameter: Bathymetry

The fish cages have to be located in regions where the water depth is sufficient. This allows avoiding harmful feedback from the accumulation of waste material [9]. According to this criterion, the depth of 30 to 50 m was chosen as the most suitable depth for marine aquaculture development. Bathymetry lines in the Southern Caspian Sea were installed by the Iranian National Cartographic Center Using GIS (10.2) software and by the raster function to produce raster format images (Figure 6).

![Figure 6. (a): Hydrographic lines (b): Bathymetry raster image.](image)

2.2.5. Physical–Environmental Parameter: Slope of Seabed

Farm construction and cage drainage could be affected by the bottom slope of the area. The slope of Seabed (%) was obtained from the bathymetry image such that the Bathymetry raster image was divided into distance to beach image [23,31] (Figure 7).

![Figure 7. Slope of Seabed in the southern part of the Caspian Sea.](image)

2.2.6. Physical–Environmental Parameter: Maximum Wave Height and Wind Speed

The maximum wave height and wind speed may incur cage damage, cause stress on structures, and make an environment unsafe for operators [24,25,32]. Therefore, these two parameters have to be considered when making decisions about the locations of fish farms. The modified operational wind field of European Centre for Medium-Range Weather Forecasts (ECMWF) and the national project called ISWM (Iranian Seas Wave Modeling) from 1992 to 2002 were used as the best available data source in this study. Maximum wind speed and wave height in a 12-year period for the depth zone between 20 to 50 m is shown in Figure 8.

![Figure 8. Maximum wind speed (m/s) (a) and wave height (m) (b) in a 12-year period (depth of 20 to 50 m).](image)
2.2.7. Physical–Environmental Parameter: Current Velocity

High current velocity affects both the physical structure of the cages by incurring torsional forces on the netting, fatigue, and fracture on couplings and welding points and also the fish production and behavior by deforming the nets, oxygen supply, or waste clearance, and even causing excessive forced swimming [33]. To this purpose, current velocity simulation results have been used by the Hybrid-Coordinate Ocean Model (HYCOM) model for the Caspian Sea [34]. According to this model, current velocity was obtained in two directions of U and V. Finally, current velocity was provided using Equation (1). Figure 9 shows the maximum current velocity of sea-level in the case study.

\[ V = \sqrt{u^2 + v^2} \]  

(1)

![Figure 9. Maximum current velocity (m/s) in the Caspian Sea according to the HYCOM model.](image)

2.2.8. Social–Economic Parameters

There are also several socio-economic criteria that affect fish farming (such as distance from the coastline, distance to industries, distance to tourist areas, distance to cities, distance to coastal protected areas) because new development will be constrained by current land use and cannot occur on already developed land. Figure 10 illustrates them in the southern part of the Caspian Sea.

![Figure 10. (a) Distance from the coastline; (b) Distance to industry; (c) Distance to tourist areas; (d) Distance to city; (e) Distance to coastal protected areas.](image)

2.3. Standardization and Priority Weighting of Criteria

All criteria were standardized in a range of 0–255 (255 high suitability) using fuzzy membership functions in TerrSet software that is based on maximization or minimization of the attribute. The choice of function and control points based on expert opinions of the research team and literature, the shape of the suitability curve, and the control points are shown in Table 2.
Table 2. The shape and type of fuzzy membership function with corresponding parameterization (start/endpoints) based for Rainbow trout on literature research and expert knowledge.

| Criteria                     | Control Points | The Shape and Type of Fuzzy Membership Function | Function Equation | Source |
|------------------------------|----------------|-----------------------------------------------|-------------------|--------|
| Maximum Temperature          | a: 20 b: 25 c: 25 d: 30 | Liner and Symmetric                           | $X_i = \left( \frac{R_i - a}{b - a} \right) \times 255$ | [32]   |
| Minimum Temperature          | a: 6 b: 10 c: 12 d: 15 | Liner and Symmetric                           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [32]   |
| Suspended solid              | a: 0 b: 0 c: 0.1 d: 3.5  | Liner and Monotonically decreasing           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [16]   |
| Chlorophyll-a                | a: 0 b: 0 c: 0 d: 10  | Sigmoidal and Monotonically decreasing        | $\mu = \cos^2 \alpha \times 255$ | [11]   |
| Maximum wave height          | a: 0 b: 0 c: 4       | Sigmoidal and Monotonically decreasing        | $\alpha = \frac{(x - c)}{(d - c)} \times \mu$ | [32]   |
| Maximum wind speed           | a: 0 b: 0 c: 27      | Sigmoidal and Monotonically decreasing        | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |
| Seabed Slope                 | a: 0 b: 0.5 c: 1 d: 10 | Liner and Symmetric                           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [25]   |
| Maximum Current velocity     | a: 0.02 b: 0.15 c: 0.2 d: 0.3 | Liner and Symmetric                           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |
| Bathymetry                   | a: 0 b: 30 c: 50 d: 100 | Liner and Symmetric                           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [11]   |
| Distance to industry         | a: 0 b: 12,000 c: 0 d: 0 | Liner and Monotonically increasing           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |
| Distance from the coastline   | a: 3000 b: 5000 c: 7500 d: 20,000 | Liner and Symmetric                           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [32]   |
| Distance to City             | a: 0 b: 0 c: 4500 | Liner and Monotonically decreasing           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |
| Distance to coastal protected| a: 0 b: 50,000 c: 0 d: 0 | Liner and Monotonically increasing           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |
| Distance to tourist areas    | a: 0 b: 7500 c: 0 d: 0 | Liner and Monotonically increasing           | $X_i = 1 - \left( \frac{R_i - a}{b - a} \right) \times 255$ | [33]   |

The next stage was to establish a weighting for each criterion and factor, where a weight is assigned to each factor to express the importance of every variable in relation to others, and the pairwise comparison method of the Analytical Hierarchy Process (AHP) was used to determine the weight of the factors (standardized criteria) by priority [35]. The weighting of the factors was done according to the optimal growth under farm conditions and was judged by experts. Moreover, the consistency ratio (CR) of the matrix was calculated, which indicates the probability that ratings are assigned in a random manner. A consistency ratio of 0.10 or less was considered acceptable [36]. Tables 3–5 show the obtained criterion weights. In this stage for each category (Physical–Environmental; Social–Economic; Water Quality), a separate multi-criteria evaluation model was implemented and then the outputs of each group were imported in another multi-criteria evaluation model (final model).
Table 3. Pairwise comparison matrix for the analysis of the relevance of Physical–Environmental parameters.

| Criteria | (Bath) | (SIS) | (WH) | (CV) | (WS) | Weight Criteria |
|----------|--------|-------|------|------|------|-----------------|
| (Bath)   | 1      |       |      |      |      | 0.2575          |
| (SIS)    | 2      | 1     |      |      |      | 0.3183          |
| (WH)     | 1/2    | 1/2   | 1    |      |      | 0.2011          |
| (CV)     | 1/3    | 1/2   | 1/2  | 1    |      | 0.0956          |
| (WS)     | 1/3    | 1/2   | 1    | 1    | 1    | 0.1275          |

CR = 0.03

1 Bathymetry, 2 Seabed Slope, 3 Maximum wave height, 4 Maximum Current velocity, 5 Maximum wind speed.

Table 4. Pairwise comparison matrix for the analysis of the relevance of Social–Economic parameters.

| Criteria | (DB) | (DP) | (DI) | (DT) | (DC) | Weight Criteria |
|----------|------|------|------|------|------|-----------------|
| (DB)     | 1    | 0.1992 |      |      |      |                 |
| (DI)     | 1/3  | 1     | 0.3195 |      |      |                 |
| (DT)     | 1/3  | 1     | 1/3  | 0.2808 |      |                 |
| (DP)     | 1/3  | 1/3   | 1/3  | 1/3  | 1    | 0.0746          |
| (DC)     | 1/3  | 1/3   | 1/3  | 1/3  | 1    | 0.0746          |

CR = 0.02

1 Distance to beach, 2 Distance to industry, 3 Distance to tourist areas, 4 Distance to coastal protected, 5 Distance to City.

Table 5. Pairwise comparison matrix for the analysis of the relevance of Water Quality parameters.

| Criteria | (MaxT) | (MinT) | (SSC) | (Chl-a) | Weight Criteria |
|----------|--------|--------|-------|---------|-----------------|
| (MaxT)   | 1      |        |       |         | 0.4901          |
| (MinT)   | 1/3    | 1      |       |         | 0.2310          |
| (SSC)    | 1/3    | 1/2    | 1     |         | 0.1634          |
| (Chl-a)  | 1/3    | 1/2    | 1/2   | 1       | 0.1155          |

CR = 0.04

1 Maximum Temperature, 2 Minimum Temperature, 3 Suspended solid, 4 Chlorophyll-a.

2.4. GIS-Based Multi-Criteria Evaluation (MCE) with Ordered Weighted Averaging (OWA) Method

Ordered Weighted Averaging (OWA) makes use of a group of multi-criteria operators and two sets of weights: criterion or relevance weights and order weights. By using OWA, a range of weighting designs were modeled to control the decision risk in the determination of the factors affecting the aquaculture site suitability [37]. Considering a set of \( n \) criteria, an OWA operator can be defined as the function \( F: \mathbb{I}^n \rightarrow \mathbb{I} \) with a related set of order weights \( V = [v_1, v_2, \ldots, v_n] \); \( v_j \in [0, 1] \) for \( j = 1, 2, \ldots, n \) and \( \sum_{j=1}^{n} v_j = 1 \). Considering the set of standardized attribute values \( A_i = [a_{i1}, a_{i2}, \ldots, a_{im}] \) for \( i = 1, 2, \ldots, m \), in which \( a_{ij} \in [0, 1] \) constitutes the \( j \)-th attribute related to the \( i \)-th location, the OWA operator will be defined as follows.

\[
\text{OWA}_i(a_{i1}, a_{i2}, a_{i3} \ldots, a_{im}) = \sum_{j=1}^{m} v_j z_{ij}
\]

where \( z_{i1} \geq z_{i2} \geq \ldots \geq z_{in} \) is the sequence which is obtained by reordering the attribute values \( a_{i1}, a_{i2}, \ldots, a_{im} \). The reordering process is a determining factor for the OWA operator and involves a weight, \( v_j \), with a predetermined ordered position of the attribute values \( a_{i1}, a_{i2}, \ldots, a_{im} \) for the \( i \)-th location. The first order weight, \( v_1 \), is assigned to the highest attribute value for the \( i \)-th location, \( v_2 \) is assigned to the second-highest value for the same
location, and so on; and finally, \( v_n \) is assigned to the lowest attribute value. It is important to note that a particular value of \( a_{ij} \) is not related to a particular weight \( v_j \), but rather the weight is assigned to a particular ordered position \( a_{ij} \). The generality of OWA is due to the fact that by selecting the appropriate order weights, it is able to provide a wide range of map combination operators [29]. OWA operators can be characterized by two features; the first of which is the attitudinal character (ORness). The ORness represents the risk level of factor attribute misinterpretations (on a scale of 0 to 1). This characterizes emphasis on better and worse values and shows the degree of risk in decision-making, and can be achieved through Equation (3). The more the amount of ORness, the higher will be the amount of risk-taking and vice versa. Another measure in operation OWA is ANDness which is defined in Equation (4) [35,38].

\[
\text{ORness} = 1 - \left( \frac{1}{n} - \frac{1}{n-1} \sum_r (n-1)w_r \right) \\
\text{ANDness} = 1 - \text{ORness}
\]  

(3)  

(4)

where \( n \) is the number of factors, \( r \) is the order of factors, and \( w_r \) is the weight for the factor of the \( r \)th order.

The second feature by which the OWA operators can be characterized is the degree of dispersion (tradeoff). On a scale of 0–1, the tradeoff represents the level by which the good performance of one factor can be substituted with the poor performance of another (compensation). The tradeoff feature can be obtained by using Equation (5).

\[
\text{TRADE-OFF} = 1 - \sqrt{\frac{n \sum_r (w_r - 1/n)^2}{n - 1}}
\]  

(5)

where \( n \) is the number of factors, \( r \) is the order of factors, and \( W_r \) is the weight for the \( r \)th order factor. The Tradeoff is dependent on the weights that are distributed across all factors used in a weighting combination [37]. Table 6 indicates the calculated values for ORness, ANDness, and Trade-off in this study.

**Table 6.** Ordered weighted average (OWA) operators; order weights used to control levels of ORness (risk underestimating factor values) and tradeoff (compensation between factor values) for the factors that predict the suitable sites for Rainbow trout, modified after.

| OWA Operator | Owa Weights | Andness | ORness | Trade-Off |
|--------------|-------------|---------|--------|-----------|
| A            | Sc1 (WLC)   | [0.071, 0.071, 0.071, ..., 0.071, 0.071, 0.071] | 0.5    | 0.5       | 1         |
| B            | Sc2 (AND)   | [1, 0, 0, 0, 0, ..., 0, 0, 0, 0] | 1      | 0         | 0         |
| C            | Sc3 (OR)    | [0, 0, 0, 0, ..., 0, 0, 0, 1] | 0      | 1         | 1         |
| D            | Sc4         | [0.5, 0.2, 0.1, 0.05, 0.03, 0.02, 0.01 ... , 0.01, 0.01] | 0.64   | 0.36      | 0.47      |
| E            | Sc5         | [0.01, 0.01, ..., 0.01, 0.02, 0.03, 0.05, 0.1, 0.2, 0.5] | 0.36   | 0.64      | 0.47      |
| F            | Sc6 (AVG)   | [0, 0, ..., 0, 0.16, 0.16, 0.16, 0.16,0 ... , 0, 0] | 0.55   | 0.44      | 0.62      |

The risk level to be assumed in the MCE can be controlled by using OWA. Furthermore, the degree to which factor weights (trade-off) will affect the final suitability map OWA, which will provide us with a range of possible solutions for our aquaculture sites problem. In this case, 14 order weights corresponding to the 14 factors which were rank-ordered for each site were used after the application of the modified factor weights. Six typical sets of order weights for the 14 factors are shown in Table 6: (a) average level of risk and full trade-off, (b) low level of risk and no trade-off, (c) high level of risk and no tradeoff, (d) low level of risk and average trade-off, (e) high level of risk and average trade-off, (f) average level of risk and trade-off. Illustrated in Figure 11 are the locations of typical sets of order weights in the decision-support space [39].
2.5. Site Selection

In order to select the most appropriate sites, ZLS (Zonal Land Suitability) method [40] was used based on a minimum suitability threshold and minimum area that the FASI (Final Aggregated Suitability Image) layers in each of six typical sets of order weights were grouped into several zones. Then, zones were ranked in descending order by using Equation (6).

$$S_z = \left( \frac{\sum (L_i)_z}{n_z} \right)$$

where \( S_z \) is the ZLS of each zone, \((L_i)_z\) is the local suitability of the cell \( S_i \) which belongs to zone \( z \), and \( n_z \) indicates the number of cells in zone \( z \).

In this study, it was stipulated that a minimum score of 200 for suitability and 10 ha of area are required for a cage culture (Source: Iranian Fisheries Organization). Therefore, zones less than 10 hectares were deleted from the final suitability areas.

2.6. Comparison of OWA Model’s Results with Existing Sites (ROC)

Comparisons were made between the predicted suitable sites and existing farm locations to verify the suitability of final model outputs. In this study, accuracy assessment was used on ROC (Relative Operating Characteristic) Statistics [41]. In order to assess the validity of a model that predicts the location of the occurrence of a class by comparison of a suitability image depicting the likelihood of class occurring (i.e., the input image), ROC represents a very promising method. In the present study, where that class actually exists, is determined by the Boolean image (i.e., the reference image). The ROC is defined in the range of 0 to 1 [41].

2.7. Sensitivity Analysis

In the sensitivity analysis, the most important element to be considered is weight because weights are the basis of value judgments and include a subjective number about which decision-makers may disagree. In this study, the sensitivity analysis was aimed at investigating the sensitivity of the weights of various criteria on the spatial pattern of site suitability. Sensitivity analysis was made by increasing each parameter by a given percentage while keeping the others constant in quantifying the change in the model output. Intervals of ±5%, ±10%, and ±20% were chosen for the reference values. Suitability maps for every interval were created. The change of areas under the suitability score of every weighting scheme was investigated. The output map of each scenario with the base map) FASI of scenario a) was compared through relationships between image difference (9), percentage change (10), and ratio image (11) [42]. In addition, Cramer’s V coefficient was used to investigate the correlation between the criteria and suitable sites for aquaculture. In total, it was discovered that the variables with a Cramer’s V of about 0.15 or higher were considered useful while those with values of 0.4 or higher were good [43].

$$\text{Image difference} = \text{Second image} - \text{First image}$$

Figure 11. Decision–strategy space and typical sets of order weights (see Table 6).
3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Standardization and Priority Weighting of Criteria

Every constraint was acquired as a Boolean map while fuzzy membership functions were used to standardize the factors. The standardized results of all 18 factors and the constraints for marine aquaculture are shown in Figure 12.

\[
\text{Percentage Change} = \frac{\text{Second image} - \text{First image}}{\text{First image}} \times 100 \quad (8)
\]

\[
\text{Ratio Image} = \frac{\text{Second image}}{\text{First image}} \quad (9)
\]

Figure 12. Standardization of evaluation criteria. (a): Seabed Slope (b): Minimum Temperature (c): Maximum Temperature (d): Distance to industry (e): Distance to city (f): Distance from the coastline (g): Chlorophyll-a (h): Suspended solid (i): Distance to tourist areas (j): Maximum wind speed (k): Maximum wave height (l): Maximum wind speed (m): Bathymetry (n): Distance to coastal protected areas, (o–r): constraint maps ((o): Harbore, (p): Bathmetry (20 m, 50 m), (q): Distance from the coastline (3 km, 20 km), (r): the main river mouth) (unit of all maps is suitability).
Then, using the Extract function, the average value of each parameter and also the amount of utility (fuzzy number) in all 9 available farms were calculated. The results of this function are shown in Table 7.

Table 7. Average value and fuzzy number of 14 factors in all 9 aquaculture farms on the coast of Mazandaran.

| Parameters | MaxT | MinT | Bath | SSC | Chl-a | WH | WS | SIS | CV | DI | DT | DC | DB | DP |
|------------|------|------|------|-----|-------|----|----|-----|----|----|----|----|----|----|
| Farm 1     | 256  | 20   | 0.50 | 2.7 | 5.9–6.4 | 18.5 | 0.3 | 0.1  | 4.3 | 10.0| 11.6| 5.2 | 35.1| 9.4 |
| Parameter value | 151  | 97   | 172  | 186 | 140   | 190 | 221 | 163  | 110 | 255 | 189 | 241 | 203 | 200 |
| Farm 2     | 27.1 | 28   | 0.47 | 2.9 | 5.9–6.4 | 20.1 | 0.5 | 0.11 | 2.9 | 3.8 | 2.5 | 5.5 | 60.6 | 8.3 |
| Parameter value | 15   | 230  | 180  | 179 | 140   | 130 | 238 | 188  | 74  | 122 | 240 | 250 | 255 | 161 |
| Farm 3     | 27.0 | 31   | 0.68 | 0.3 | 2.6   | 19.2 | 0.4 | 0.06 | 6.1 | 3.8 | 13.4 | 44.5 | 7.8 |
| Parameter value | 165  | 248  | 116  | 176 | 230   | 185 | 246 | 85   | 156 | 123 | 178 | 246 | 12  | 95 |
| Farm 4     | 27.2 | 44   | 0.56 | 2.7 | 4.8–3.2 | 19.2 | 0.8 | 0.07 | 5.5 | 3.3 | 14.0 | 3.3 | 5.8 | 44.5 | 7.7 |
| Parameter value | 148  | 255  | 161  | 185 | 190   | 185 | 166 | 111  | 141 | 105 | 238 | 250 | 10  | 101 |
| Farm 5     | 26.1 | 28   | 0.71 | 2.9 | 5.9–6.4 | 19.4 | 0.8 | 0.07 | 3.1 | 5.9 | 2.9 | 5.5 | 19.4 | 7.2 |
| Parameter value | 192  | 201  | 109  | 181 | 140   | 150 | 155 | 112  | 42  | 32  | 252 | 55  | 55  | 6.6 |
| Farm 6     | 27.2 | 26   | 0.69 | 2.7 | 5.9–6.4 | 19.6 | 0.8 | 0.07 | 1.6 | 1.0 | 0.6 | 3.2 | 14.5 | 7.5 |
| Parameter value | 115  | 190  | 114  | 184 | 140   | 150 | 155 | 112  | 42  | 32  | 252 | 55  | 55  | 6.6 |
| Farm 7     | 27.2 | 29   | 0.78 | 2.9 | 5.9–6.4 | 20.1 | 0.5 | 0.09 | 3.1 | 17.2 | 1.9 | 5.1 | 31.8 | 7.4 |
| Parameter value | 146  | 232  | 87   | 180 | 140   | 130 | 223 | 139  | 80  | 255 | 243 | 282 | 180 | 71 |
| Farm 8     | 27.0 | 31   | 0.97 | 2.9 | 5.9–6.4 | 20.1 | 0.5 | 0.09 | 3.4 | 14.0 | 3.3 | 5.8 | 44.5 | 7.8 |
| Parameter value | 166  | 253  | 38   | 180 | 140   | 130 | 233 | 151  | 87  | 255 | 232 | 252 | 24  | 112 |
| Farm 9     | 26.6 | 21   | 0.53 | 3.0 | 5.5   | 18.5 | 0.6 | 0.07 | 0.9 | 0.5 | 0.5 | 3.1 | 75.1 | 6.7 |
| Parameter value | 190  | 113  | 158  | 177 | 160   | 190 | 196 | 113  | 23  | 17  | 252 | 32  | 255 | 74 |

3.2. GIS-Based Multi-Criteria Evaluation (MCE) with Ordered Weighted Averaging (OWA) Technique

The OWA combination procedure aims at the identification and prioritization of areas on the coasts of Mazandaran Province (depth of 20 to 50 m) for marine aquaculture. Five decision strategies were deployed in the present study. Each strategy is related to a specified value of ORness and the relationship between tradeoff and Risk (Figure 11, Table 6). OWA allows the control of the MCE status in both the risk and the tradeoff. In other words, it permits the control of the risk level assumed in the proposed MCE, and the effects of factor weights (tradeoff weights) on the final suitability map (Figure 11). The OWA weights which are shown in Table 6 were used to make various scenarios to control the trade-off and risk levels. These scenarios are as follows:

- **Scenario a**

  In this scenario, the risk level is between AND and OR; and the level of tradeoff is full. Consequently, and based on Table 6, the following order weights are specified. Here, weight is distributed or dispersed evenly among all factors without taking into account their rank-order position from minimum to maximum for any given location. This scenario is similar to the WLC method (Figure 13).

![Figure 13. Final aggregated suitability image (FASI) for scenario a.](image-url)
• Scenario b

In this scenario, full weight assigned to the first rank-order results (the minimum suitability score among all factors for every pixel) will be the same as the AND operation in Boolean MCE. Here, full weight is assigned to the factor with the minimum value. The order weights used for AND operation are shown in Table 6. In addition, such weighting leads to conditions with no tradeoff and low risk (Figure 14).

![Figure 14. Final aggregated suitability image (FASI) for scenario b.](image)

• Scenario c

In this scenario, full weight assigned to the last rank-order results (the maximum suitability score among all factors for every pixel) will be the same as the OR operation in MCE. The order weights used for OR operation are shown in Table 6. Moreover, such a weighting technique results in no tradeoff and high risk (Figure 15).

![Figure 15. Final aggregated suitability image (FASI) for scenario c.](image)

• Scenario d

In this scenario, for example, stakeholders and managers may be interested in a conservative or low-risk solution for identifying suitable areas for marine aquaculture. However, they also know that their estimates for how different factors should tradeoff with one another are important and should be taken into consideration as well. Then, a set of order weights that provides some tradeoff but maintains a low level of risk in the solution will be generated. Several sets of order weights exist that could be applied to achieve this. For low risk, the weight should be skewed to the minimum end. For some tradeoffs, weights are to be distributed across all ranks. The set of order weights is shown in Table 6 and the results of this scenario have been illustrated in Figure 16.
Figure 16. Final aggregated suitability image (FASI) for scenario d.

- Scenario e
In this scenario, these order weights determine an operation that takes place midway between the extremes of AND and the average risk position of WLC. Furthermore, these order weights set the level of tradeoff midway between the no tradeoff situation of the AND operation and the full tradeoff situation of WLC (Figure 17).

Figure 17. Final aggregated suitability image (FASI) for the scenario e.

- Scenario f
In this scenario, the risk level is exactly between AND and OR and the tradeoff level is average (Table 6). Figure 18 shows the results of this scenario.

Figure 18. Final aggregated suitability image (FASI) for scenario f.

3.3. Site Selection

The results of the application of the ZLS methodology for 3 scenarios a, b, and d are presented in Figure 19. The zones are then ranked in descending order by the value of their zonal land suitability to facilitate the decision process. According to available reports of the Iranian Fisheries Organization, studies done for marine aquaculture site selection
in the south of the Caspian Sea are applied by the weighted linear combination (WLC). The risk of this scenario is 50%. Since the fish culture in cages includes high-risk activities, models and methods should be used to determine the appropriate location with the least environmental damage. Three scenarios a, b, and d are important environmental scenarios with low risk. The more scenario b (AND) moves toward scenario c (OR), the more the amount of suitability and the number of the appropriate zone increases. Accordingly, scenarios a, b, and d were, respectively, introduced to zones 4, 8, and 11 as the end zones in each scenario. Nevertheless, scenarios e, c, and f have high-risk so they do not have favorable results.

![Figure 19.](image)

Figure 19. The final zones of site selection for scenarios: (a) AND, (b) MIDAND, (c) weighted linear combination (WLC).

Then, using the Extract function, the average value of each parameter and also the amount of utility (fuzzy number) in each of the 9 available farms were calculated. The results of this function are shown in Table 8.
### Table 8. Average value and fuzzy number of 14 factors in the selected sites.

| Sites | Parameters | MaxT | MinT | Bath | SSC | Chl-a | WH | WS | SIS | CV | DI | DT | DC | DB | DP |
|-------|------------|------|------|------|-----|-------|----|----|-----|----|----|----|----|----|----|
| A     | Parameter value | 26.7 | 7.3  | 48.5 | 0.9 | 2.6  | 5.4 | 16.2| 0.48| 0.08| 11.2| 9.0 | 10.6| 9.9 | 66.4|
|       | Fuzzy number  | 182  | 111  | 255  | 34  | 188  | 160| 190 | 246| 132| 255| 255| 194| 184| 255|
| B     | Parameter value | 26.4 | 7.4  | 48.8 | 0.7 | 2.8  | 5.6 | 18.4| 0.52| 0.07| 7.1 | 6.3 | 6.0 | 9.2 | 69.6|
|       | Fuzzy number  | 208  | 127  | 254  | 91  | 183  | 160| 190 | 235| 111| 183| 201| 220| 195| 255|
| C     | Parameter value | 26.4 | 7.4  | 46.3 | 0.8 | 2.9  | 5.7 | 18.6| 0.52| 0.09| 6.2 | 7.3 | 5.9 | 8.9 | 65.2|
|       | Fuzzy number  | 205  | 125  | 254  | 76  | 180  | 160| 190 | 239| 149| 160| 232| 221| 202| 255|
| D     | Parameter value | 26.6 | 7.7  | 49.0 | 0.6 | 2.8  | 5.9 | 18.8| 0.57| 0.08| 6.2 | 8.6 | 5.3 | 8.5 | 53.5|
|       | Fuzzy number  | 125  | 134  | 254  | 112| 183  | 160| 190 | 224| 131| 158| 254| 224| 209| 255|
| E     | Parameter value | 26.7 | 7.5  | 49.8 | 0.8 | 2.8  | 5.9 | 19  | 0.53| 0.09| 7.0 | 11.5| 6.2 | 9.3 | 50.0|
|       | Fuzzy number  | 184  | 128  | 254  | 82  | 182  | 140| 190 | 234| 149| 180| 255| 119| 194| 255|
| F     | Parameter value | 27.0 | 7.8  | 47.9 | 0.6 | 2.8  | 6.1 | 19.2| 0.51| 0.09| 6.8 | 15.9| 6.7 | 9.3 | 44.2|
|       | Fuzzy number  | 166  | 143  | 254  | 128| 182  | 140| 190 | 239| 138| 175| 255| 216| 193| 246|
| G     | Parameter value | 26.8 | 9.8  | 26.1 | 0.4 | 2.7  | 6.2 | 19.6| 0.37| 0.09| 5.5 | 8.9 | 11.1| 7.0 | 43.4|
|       | Fuzzy number  | 177  | 253  | 188  | 175| 183  | 140| 150 | 177| 142| 140| 224| 191| 233| 231|
| H     | Parameter value | 57.0 | 7.9  | 28.9 | 0.4 | 2.8  | 6.3 | 19.8| 0.70| 0.1 | 7.6 | 11.1| 3.2 | 4.0 | 40.0|
|       | Fuzzy number  | 160  | 179  | 236  | 188| 180  | 140| 150 | 192| 172| 195| 255| 236| 139| 230|
| I     | Parameter value | 27.0 | 7.7  | 49.6 | 0.4 | 3.0  | 6.4 | 20  | 0.64| 0.1 | 23.5| 5.5 | 4.7 | 7.7 | 24.0|
|       | Fuzzy number  | 166  | 157  | 254  | 186| 177  | 140| 150 | 208| 241| 255| 275| 228| 223| 119|
| J     | Parameter value | 27.1 | 7.6  | 49.2 | 0.4 | 2.9  | 4.8–5.4| 19.6| 0.47| 0.09| 10.4| 9.6 | 9.8 | 10.0| 10.8|
|       | Fuzzy number  | 156  | 152  | 254  | 173| 179  | 140| 150 | 248| 151| 249| 255| 199| 176| 28|
| K     | Parameter value | 26.8 | 7.7  | 47.1 | 0.5 | 3.1  | 1.8–3.7| 19.2| 0.52| 0.08| 10.0| 7.3 | 6.2 | 9.1 | 12.2|
|       | Fuzzy number  | 180  | 160  | 254  | 166| 174  | 210| 185 | 236| 122| 233| 218| 219| 198| 36 |

#### 3.4. Comparison of OWA Model’s Results with Existing Sites (ROC)

ROC is a summary of statistics obtained by several two-by-two contingency tables, based on a comparison of the simulated and reference images. In this study, simulated image was the Final Aggregated Suitability Image (FASI) of scenario a (WLC) and the reference image was existing aquaculture farms (9 farms) on the coasts of Mazandaran Province. In Figure 20, the amount of ROC was calculated as 0.69 and this showed that aquaculture sites in the coastal of Mazandaran province were selected correctly based on weighted linear combination method but according to the ROC (0.69), the position of these farms can still be transferred to areas more suitable with less risk.

![Figure 20. ROC scenario of (WLC) with the existing aquaculture.](image)

#### 3.5. Results of Sensitivity Analysis

Table 9 shows the differences with the baseline model for each variable and every suitability score. Based on these results, an evaluation was made for the sensitivity of the models to the variations in the input parameters. Significant differences existed between the mean difference, percentage change, and ratio images in each scenario. The results of the sensitivity analysis in Table 9 showed that most of the parameters affecting the output location for marine aquaculture in the region were as follows: socioeconomic factors, water
quality, and physical–environmental parameters. The model was more sensitive to lower than higher values of the parameters.

### Table 9. Weighting sensitivity analysis.

| Sub Models          | Scenario | Interval Values | Difference Image | Percentage Change | Ratio Images |
|---------------------|----------|-----------------|------------------|-------------------|--------------|
| **Water Quality**   | 1        | +20             | 1.9              | 1.12              | 0.98         |
|                     | 2        | +10             | 1.06             | 0.65              | 0.99         |
|                     | 3        | +5              | 0.56             | 0.33              | 0.99         |
|                     | 4        | −5              | 0.64             | 0.17              | 1.003        |
|                     | 5        | −10             | 1.37             | 0.76              | 1.008        |
|                     | 6        | −20             | 3.01             | 1.67              | 1.01         |
| **Physical–Environmental** | 7 | +20             | 0.94             | 0.5               | 1.006        |
|                     | 8        | +10             | 0.52             | 0.30              | 1.003        |
|                     | 9        | +5              | 0.27             | 0.17              | 1.001        |
|                     | 10       | −5              | 0.31             | 0.21              | 0.99         |
|                     | 11       | −10             | 0.69             | 0.5               | 0.99         |
|                     | 12       | −20             | 1.38             | 1.5               | 0.98         |
| **Social–Economic** | 13       | +20             | 2.23             | 1.28              | 1.01         |
|                     | 14       | +10             | 1.28             | 0.67              | 1.006        |
|                     | 15       | +5              | 0.67             | 0.35              | 1.003        |
|                     | 16       | −5              | 0.81             | 0.45              | 0.99         |
|                     | 17       | −10             | 1.71             | 0.97              | 0.99         |
|                     | 18       | −20             | 3.05             | 1.77              | 0.98         |

As noted in Section 2.7, Cramer’s V coefficient was used to evaluate the correlation between the criteria and suitable sites for aquaculture. Figure 21 shows Cramer’s V coefficient values for each parameter. According to the figure, bathymetry and distance from the coastline were the most effective parameters and maximum temperature had the least impact on site selection of marine aquaculture in the coastal areas of Mazandaran Province.

![Cramer’s V coefficient for the criteria used in marine aquaculture site selection.](image)

**Figure 21.** Cramer’s V coefficient for the criteria used in marine aquaculture site selection.

### 4. Discussion

This study investigated the potential use of Ordered Weighted Average (OWA) for marine aquaculture site selection. Many factors affect marine aquaculture, including water quality, physical-environmental, and socioeconomic factors. Here, 18 criteria were simultaneously considered to allow the decision-makers to figure out the effects of every criterion in the operations of a marine aquaculture farm. Therefore, each criterion was standardized using fuzzy membership functions with regard to the desirable criteria for fish culture.

The fuzzy image for maximum temperature shows, the indexes of the east coast (as illustrated in Figure 1) are less desirable for fish farming than the west coast due to higher temperature and the temperature increases from the west to the east. Furthermore, the
The lowest suitability was obtained in indexes 6664 and 6763 by amounts of 45 and 43, and the most suitability was in indexes 6164 and 6263 by amounts of 198 and 191. Fuzzy picture of chlorophyll-a showed that the fuzzy number in index 6763 was equal to 56, which is an indication of high chlorophyll content and low utility value in this area. Gentle slope of the seabed and slower current velocity in Gorgan Bay and Miankaleh can cause high levels of chlorophyll in this area.

For socio-economic factors, increasing and decreasing Liner functions were used because there is a direct relationship between the distance factor and fuzzy number. In distance from the coastline factor, indexes 6663, 6763, and 6767 had the lowest suitability levels of 37, 49, and 46, respectively, since the suitable depth was in a farther distance from the coastline in the east.

Wave height and wind speed factors were standardized by using S-shaped function and the three factors of seabed slope, bathymetry, and current velocity were standardized by linear symmetric function in physical and environmental submodule. In bathymetry, a fuzzy image in indexes 6764 and 6763 had the lowest utility levels of 45 and 62. Bathymetry results correspond with the results of distance to the coastline and seabed slope. The maximum amount of wave height and wind speed were, respectively, 4 to 5 m and 16 to 27 m/s according to the studies by References [26,33]. The east and west coast indexes had less suitability since the wave height and wind speed were more than optimal in central indexes 6263, 6364, and 6463. Based on previous studies, the optimal seabed slope for marine aquaculture was 0.5% to 2% [16,25,26]. In indexes 6663, 6664, 6763, and 6764, the seabed slope was less than 0.2% on the east coast and Gorgan Bay and it began to increase toward the west coast. In this paper, the weight has been done on the basis of the review of past studies. According to Table 5, among water quality factors, most weights were assigned to the temperature. Several studies such as the study of Pérez et al., 2005, and the other studies [16,31] showed that water temperature has the highest value among environmental factors. Among the socio-economic factors, more amounts of weight were dedicated to factors such as distance from industrial areas, distance from tourist areas, distance from the coastline, distance from the protected areas, and distance from the city with the values of 0.31, 0.28, 0.19, 0.13, and 0.07 [16,23,25]. Among the physical–environmental factors, more amounts of weight were dedicated to factors such as seabed slope, bathymetry, wave height, wind speed, and current velocity with the values of 0.31, 0.25, 0.20, 0.12, and 0.09.

One of the major barriers in site-selection analyses using multi-criteria evaluation procedures is weighting. Weightings should be in accordance with the priorities of decision-makers as far as possible [44]. After the weights are assigned, a sensitivity analysis should be performed to investigate their effects on the overall results. In this study, when parameters contained varied weights, significant changes were observed in terms of suitable aquaculture areas. Most of the parameters affecting the output location of marine aquaculture in the region were, respectively, as follows: social-economic, water quality, and physical–environmental parameters; and the model was more sensitive to lower than higher values of the parameters.

Not only was the weight of each factor used but also the OWA weights which are shown in Table 6 were used to generate various patterns to address the trade-off and risk levels. Scenario b or AND is related to the AND operator and provides a risk averse solution. Based on this scenario, the most suitable areas for marine aquaculture are located in indexes 6163, 6463, and 6563 (Figure 19a). The legends in Figure 14 indicate a measure of aquaculture suitability in which the possibility ranged on a scale between 1 and 68. The value of 1 for the ANDness in Table 6 reveals that the solution is coincident with the AND while the value of 0 for the ORness shows that the solution is the most distant from OR. The trade-off measure of zero indicates no trade-off.

Scenario d increases the risk level and provides an area suitable for marine aquaculture. In Table 6, the value of 0.64 is shown for the ANDness while the value of 0.36 is presented for the ORness and this solution pattern allows a trade-off equal to 0.47. This scenario
is midway between AND and the conventional weighted linear combination (WLC) in triangular decision space. The suitability for aquaculture, as shown in Figure 16, increased compared to scenario a. The legends in Figure 16 indicate a measure of aquaculture suitability in which possibility ranged between 181 and 7. Considering the ZLS results provided for this scenario, the most suitable areas for marine aquaculture site-selection are located on indexes 6163, 6263, 6463, and 6563 (Figure 19b).

Scenario a (WLC) and f (AVG) are in the middle of the risk continuum which is neither risk averse nor risk-taking solutions. The slight difference between the AVG and WLC solutions is that trade-offs are allowed in the former (Table 6). Figures 13 and 18, by comparing the corresponding maps, suggest that scenario f produces a larger area for marine aquaculture. Based on scenario a, the most desirable areas for marine aquaculture are located on indexes 6163, 6164, 6363, 6463, and 6563 (Figure 20c). In Table 6, with the value of 0.5 for the ANDness and the ORness, also this solution pattern allows a trade-off equal to 1 for scenario a (WLC).

According to Figure 17, Scenario e falls between the WLC and the OR, in which trade-offs are allowed to some extent, and scenario c (OR) (Figure 15) is in the opposite extreme from the AND solution. A very large spatial extent could be assigned to the suitable areas for marine aquaculture with this alternative which includes all of the areas. Finally, the OR solution is observed at the extreme of the continuum, which suggests almost the entire area as suitable for aquaculture (Figures 15 and 17).

Since the fish culture in cages includes high-risk activities, models and methods should be used to determine the appropriate location that has the least environmental damage. So, scenarios c and e have high-risk and do not have a good result. The legends in Figure 15 indicate a measure of aquaculture suitability in which possibility ranges between 247 and 255. In Table 6, the value of 0 for the ANDness suggests that the solution is coincident with the OR while the value of 1 for the ORness suggests that the solution is the most distant from AND. The trade-off measure of 1 indicates no trade-off.

Evaluating and Comparing the Existing Aquaculture Farms and Selected Sites in the Area of Study

It is necessary that the average value and the suitability (fuzzy number) for each parameter are determined in every 9 existing farms and 11 selected sites in order to evaluate and analyze the existing aquaculture farms on the coasts of Mazandaran Province. There is index 6563 in farm 1 and all parameters in this farm have good condition and fuzzy number, except the bathymetry factor in other factors is more than 100. It is recommended that the location of farm 1 is transferred away from the coastline to a more appropriate bathymetry.

Farm 2 is on the coast of Babolsar in index 6563. Based on all the parameters, it has a favorable situation but this farm is near two landfills in Fereydoon Kenar and Babolsar, so the fuzzy number in distance to industry factor is 74. The location of farm 2 should be transferred away from the coastline to a more appropriate bathymetry.

Farm 3 is on the coast of Noshahr in index 6363. Fuzzy number for distance to coastal protected factor is of the lowest amount of 12. This farm is located 7 km from Alborz protected area. In addition, the current velocity and minimum temperature factors are lower than the standard level. In this farm, the amounts of these two factors for current velocity and minimum temperature are, respectively, equal to 0.06 m/s and 7.6 °C.

Two farms 4 and 9 in indexes 6363 and 6163 in OWA have various scenarios because based on constraints images, farm 4 is located in Noshahr harbor scope and farm 9 in Ramras harbor protected scope, with a value of zero.

Farms 5 and 6 are located in Chaluos and Tonekabon coastal areas (index 6263). The suitability of the minimum temperature factor is low. In addition, socio-economic factors in this index have very low suitability.

Farms 7 and 8 are located on the coast of Tonekabon in indexes 6263 and 6163. Both farms in all parameters have low suitability except the suspended solid and distance to industry factor. According to what was mentioned, farms 1 and 2 have the best situation and the highest suitability.
5. Conclusions

An important factor for successful marine aquaculture and for the sustainable development of the industry is proper site selection. The present paper proposes the OWA methodology as a site selection technique for fish culture along the coasts of Mazandaran Province. A robust interactive toolset is provided by the OWA approach for adjusting trade-offs and compensation between criteria which makes possible a rapid investigation and interpretation of alternative scenarios and relationships between criteria. Other advantages of this approach are: the ability to integrate heterogeneous datasets such as quantitative and qualitative criteria using expert opinion, criteria selection flexibility for different study areas or different problems under consideration, implementation of one or more decisions, the flexibility to change the relevance level of criteria, and the freedom in the development of several modeling scenarios for acceptable levels of decision risks. Since the fish culture in cages is a high-risk activity, this methodology has been shown to have a significant potential to shed the decision-making complexities in real-world applications.

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