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# Simulating run-off of Abbandans in Mazandaran province using SWMM model to increase their capacity through harvesting rainwater

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**Abstract**

Abbandans are man-made reservoirs constructed by excavating and creating borders of soil dykes around them. Dredging Abbandan is done to increase storage capacity and provide greater flexibility in water allocation during droughts. For this purpose, the catchment run-off for different return periods was calculated using the SWMM model. Subsequently, the Abbandans’ conditions were examined to change their dimensions to increase the volume. The increase in Abbandans' volume was investigated by increasing its depth and utilizing the genetic algorithm. One model is presented that maximizes agricultural net benefits. Various allowable dredging ratios are used in the model for the case study. According to the results, for return periods of the 2, 5, 10, 25, and 50 years, 5.4%, 8.3%, 12.1%, 29.9%, and 37.4% of precipitation at the Abbandan upstream was transformed into run-off, respectively. Increasing the cultivated area or planting second crops can be considered as additional management practices for optimizing water usage. Based on the results, dredging and improving of all Abbandans in the region will cause the collection of run-offs from rainfall events up to a 50-year period. The model shows that the maximum net financial benefit for agricultural increases as the ratio increases. It reaches its highest value (on average $8□1010) when the ratio is 0.5. Also, the area of cultivated fields irrigated by the Abbandan increased from 124 to 193 hectares.

## 1. Introduction

The sustainability of water resources is a critical issue in the context of increasing water demand for agricultural, industrial, and domestic use, as the world will need about 60% more food (Yearbook, 2013) to feed 9.5 billion people in 2050 (until 2013). This issue has become more challenging due to the depletion of water resources Singh and Panda (2012) due to urbanization, pollution, and the effects of climate change. Providing irrigation is critical to achieving food security for a growing global population Singh and Panda (2012) and sustaining livelihoods. This is especially important in arid and semi-arid regions, where water resources are critical for economic development. It should be noted that supplying the water required for high-consumption agricultural products including rice, as the main food of the majority of the world's population, is a challenging task. Population density, in addition to the high water requirement of some agricultural products including rice, efficient approaches in water conservation, and optimal use of

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water resources such as rivers, underground water, and reservoirs have become important issues for researchers and responsible authorities (Hadizadeh *et al*., 2018). Lack of water supply and excessive exploitation in Iran, especially in paddy fields, have shown the urgent need to improve the efficiency of using this important resource in paddy fields (Ebrahimian *et al*., 2020). In addition, the results of research conducted by FAO in 93 developing countries show that water supplies are decreasing in these countries, and Iran is one of those countries (Ali *et al*., 2010).

In Iran, the sum of the precipitation varies throughout the years, and also in different seasons, which causes problems for various industries including the food and agriculture industries, which have caused great economic losses for these sectors. (Hadizadeh, *et al*., 2018). Mazandaran Province possesses around 8.7% of Iran’s renewable water resources. Renewable water accounts for about 10 billion m$^3$, and the global water request for the paddy farms of Mazandaran Province is about 4 billion m$^3$. While the usual surface water flow to the province is about 33% of the total water, this volume of water supplies about 75% of the water needs in the paddy fields (Statistics, 2018). Considering the direct employment of over 300,000 purchasers in the rice area and its overall IRR (Iranian Rial) income of VND 45,000 billion, it can be assumed that rice development is the core of Mazandaran economy (Statistics, 2018).

It is also very important to pay attention to the effective management of water supply, reduction of underground water, protection of surface water, better efficiency of energy consumption, and increase in productivity. Reducing water consumption and implementing water management plans in the agricultural sector is the main solution to these problems (Hu *et al*., 2014).

In the recent years, water supply networks have faced environmental changes, agricultural development, and population growth (Goes *et al*., 2016). However, semi-arid and arid regions (such as Iran) usually suffer from water resource shortages that require more innovation (Qasemipour and Abbasi, 2019). As a result, water demand in these regions is increasing sharply for the infrastructure, industrial, and agricultural sectors. In each region, according to the climatic characteristics, topography, and soil conditions, creative and optimal methods have been used to exploit water resources (Deyhool *et al*., 2016).

In the northern provinces of Iran, the effective solution for water optimum usage is the construction of Abbandan. Abbandan are man-made wetlands constructed by excavation and borders of soil dykes around them. These hydro-structures have significant contributions to farmland irrigation in the Mazandaran Province. Considering that in some regions, such as the north of Iran, most of the rivers and streams are seasonal, and some of them are out of reach or eventually flow into the sea, the construction or modification of Abbandan in their vicinity can save great proportions of water optimally. This volume of stored water can be used to increase agricultural production and farmers' income. These Abbandans are used as one of the main water resources for providing required water for paddy fields, especially under drought conditions. In the current conditions of the Abbandan operation, run-off, and other local water sources are not sufficiently collected by the Abbandan. However, as the Abbandan is approaching its optimal irrigation functions and water is more needed for agricultural uses (Su, 2003), there is an imminent need to promote the functions of the existing Abbandans. One of the ways for such promotion is to increase their storage capacity by dredging. Therefore, the optimal management and operation of Abbandan along with the other water resources and also developing and constructing them play an essential role in the optimum usage of rainfall and providing more water to agricultural fields in water shortage conditions.

On the other hand, due to the randomness and variability of the rainfall phenomenon due to the spatial and temporal conditions and the existence of different rainfall return periods, it is not possible to collect all the rainfall by Abbandan. For example, if an Abbandan only can store the volume of runoff resulting from 2 years of rainfall, in case of rainfall for higher return periods, it is not possible to store the resulting runoff due to the lack of capacity of the Abbandan. Therefore, conditions should be provided so that these structures can be used efficiently and even, if possible, run-off storage for different return periods should be provided. Constructing a new Abbandan will be able to increase water storage for irrigation. However, when it is compared with the method of dredging the existing Abbandan, constructing a new Abbandan is not easily accepted by the public because of environmental protection and lack of land. Dredging Abbandan is done to gain a larger storage capacity and to allow more flexibility in water allocation during drought. In addition, it is more practical in terms of engineering.

Regarding the role and importance of Abbandan and rainwater harvesting, numerous studies have been done so far, some of which will be mentioned below. Fang *et al*. (2012) concluded that reservoirs around agricultural lands are very important in harvesting local rains in dry years. Also they presented two optimization models with the objective function of minimizing water withdrawal and maximizing economic profit, and the results showed that the existence of Abbandan is very important in optimizing the mentioned objectives in drought periods. Asgari *et al*. (2015) studied the economic evaluation of increasing the water potential of water sources by dredging and improving Abbandan in the Alborz Dam catchment area. The results showed that the dredging and improvement of 11 existing Abbandan with an area of 240 ha had about 354,046 cubic meters of earthwork, which increased the capacity of the Abbandan by 2.3 million cubic meters. On the other hand, according to the calculations, the increase of each cubic meter of water cost an average of 1900 IRR. If the incomes from fish breeding or the conversion of dry farming to paddy fields are considered, the economic advantage of carrying out dredging and Abbandan improvement projects will be significant.

In the research work of Ejlali *et al*. (2016), during the two years of 2010 and 2011, by examining satellite images related to the Mazandaran Province and observing the distribution map of Abbandan, they selected a range of Sajadrod catchment basin with 40 Abbandan. Then they estimated the production performance and income of paddy fields fed by Abbandan. By choosing 4 Abbandan as a sample, three plots were examined for each Abbandan and the results were used for all Abbandan in the project area. The results showed that the dredging and improvement of all Abbandan in the region from 1 to 2 meters will result in the development of 222 to 443 hectares of paddy fields.

Mahmoud *et al*. (2014) studied the potential of rainwater harvesting in the city of Khartoum, Sudan, and its use as a tool for managing urban run-off. They concluded that harvesting rainwater can be considered an alternative source of water to deal with the phenomenon of drought.

Akter and Ahmed (2015) evaluated the feasibility of using rainwater harvesting systems in the Chittagong City of Bangladesh with an average annual rainfall of 3000 mm. This city faces both water shortages and floods in a given year. They concluded that the use of rainwater harvesting systems can reduce floods by 26% and help provide urban water by up to 20 liters per day per person.

In the previous research work, the capacity of Abbandan has been increased regardless of the return period. As mentioned before, choosing a return period experimentally does not provide the possibility of storing run-off from other rains with return periods higher than the selected return period. With heavy rains or storms, the effective capacity of Abbandan is often reduced due to sedimentation. Dredging can not only remove the sediment accumulation to restore the original capacity but also obtain an additional capacity greater than the originally designed. On the other hand, the dredging of dams may not cause any change in the landscape of agricultural land, which will reduce social, economic, and environmental problems. By increasing the capacity of the Abbandan capacity, more water can be provided to agriculture through the optimal operation and management of the Abbandan irrigation system. This study tries to investigate the problem of dredging the Abbandans of an irrigation system belonging to the Haraz catchment located in Amol city of the Mazandaran Province in Iran to increase the storage capacity by using optimization programming. In this research work, the volume of water storage and the net profit of agriculture due to the dredging of Abbandan have been taken into consideration. In the present research work, different return periods were considered, and according to them, the Abbandans were improved and increased in height. With such improvements, the Abbandans have the optimal effective capacity, so the Abbandan irrigation system will entail maximal agricultural net benefits.

## 2. Materials and Methods

### 2.1. Studied area

The research work was performed in Northern Iran, in the Haraz catchment in Amol County of the Mazandaran Province. The Haraz River catchment leads from the north to the Caspian Sea, from the west to the Chalus River basin, from the south to the northern foothills of the Alborz mountain, and from the east to the Babolrood River basin. And geographically, it is located in a range between longitudes 26' and 51˚ to 36' and 52˚ east and latitudes 45' and 35˚ to 41' and 36˚ north. Due to favorable temperatures and sufficient rainfall (average rainfall is 789.2 mm), the hills of this region are filled with woods up to an altitude of around 1500 m where the sea water can touch. However, the higher altitudes sustain natural pastures. Agriculture is the most important economic activity of the people living in the villages of the area, and more than half of its agricultural lands are covered with rice fields. Figure (1) shows the studied area and the location of the studied Abbandan.

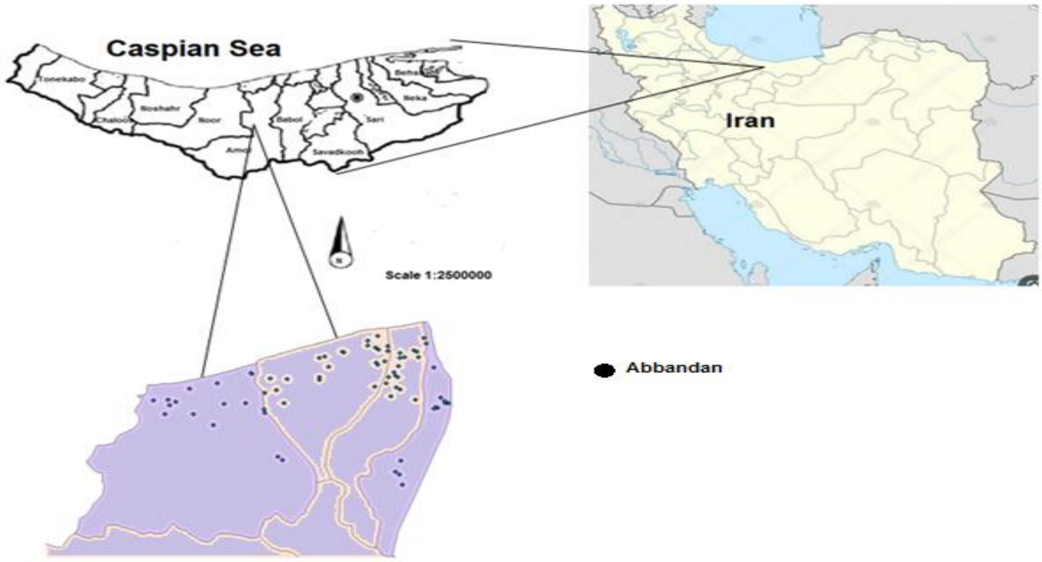

**Figure 1.** (a) The plan view of Dez watershed, Dez Reservoir, (b) Sedimentation rate and reservoir capacity of dams in Iran (a).

## 2.2. Condition of Abbandans for studied area

This study selects 14 Abbandans at the Haraz catchment in Amol County of the Mazandaran Province as an example. The Abbandans of the province were built to provide agricultural water. Their location is suitable for traditional and modern water extraction facilities from public water channels. The statistics of Abbandans, such as irrigation area, catchment area, and initial capacity, are listed in Table 1.

**Table 1.** Statistics of Abbandans in the studied area.

| The name of Abbandans | Initial capacity ($m^3$) | Area with full storage (ha) | Irrigation area (ha) | Catchment area (ha) |
|---|---|---|---|---|
| **5 hectari** | 73476 | 5 | 25 | 1.1 |
| **Abbandan bozorg** | 368018 | 10 | 90 | 4.1 |
| **Abbandan kochak** | 108620 | 6 | 75 | 3.4 |
| **Ab ni Abbandan** | 71824 | 5 | 25 | 1.1 |
| **Bene kenar** | 116285 | 8 | 40 | 1.8 |
| **Binamad** | 235131 | 45 | 120 | 2.3 |
| **Chemagh endon** | 39557 | 5 | 50 | 5.5 |
| **Kadgar mahale** | 99631 | 6 | 100 | 4.6 |
| **Kamangar kola** | 149645 | 10 | 50 | 2.3 |
| **Kooseh Abbandan** | 3636473 | 230 | 780 | 35.7 |
| **Marzango** | 267437 | 34 | 300 | 13.7 |
| **Mask Abbandan** | 101637 | 6 | 30 | 1.4 |
| **Panjgiri** | 88565 | 5 | 25 | 1.1 |
| **Pikle** | 13641 | 3 | 20 | 0.9 |

## 2.3. Introducing simulation model (SWMM)

Among the technical capabilities of this model, there are cases including the capabilities of simulating the hydrological-hydraulic situation and water quality in urban and non-urban areas, the possibility of estimating the peak flow of floods in different rainfalls, the possibility of evaluating the effects of delay-storage reservoirs on the intensity of floods and their equivalent water level, the ability to simulate the effect of bridges, culvert, spillways, dividers, pumps, and other related hydraulic structures, the possibility of solving equations in steady state and non-steady state, the possibility of estimating the volume and duration of flooding (if the intensity of the flood exceeds the capacity of the conduit) and the ability to simulate the state of flow in the floodplain in a free state and flooded conditions (Sin *et al.*, 2014). This model simulates a storm event based on the rainfall hyetograph, meteorological input data, basin system, and drainage network to produce the output hydrograph (Sin *et al.*, 2014). In this model, each catchment is divided into smaller sub-catchments and simulated as a non-linear reservoir. In this method, the inflows come from precipitation or upstream sub-catchments. Outputs are evaporation, infiltration, and surface run-off.

The capacity of this reservoir (non-linear reservoir) is equal to the maximum depression storage, which includes the maximum surface storage created by the holes, surface moisture, and an interception. When the depth of water in the reservoir exceeds the depression storage $d_p$ , the surface run-off is formed, which forms the outflow. This flow is obtained by Manning's equation. The water depth on the surface of the sub-basin (d) concerning time is obtained by differential numerical solution of the water balance equation. Since the role of factors such as evaporation and transpiration and other factors in flood formation is limited and can be neglected, the effect of evaporation has been neglected in this study. In this model, Horton's method is used for water infiltration in the soil. The parameters of Horton's infiltration equation were obtained using the soil permeability information of the region and related tables from the SWMM software guide (Rossman, 2010). For more information about the SWMM model, refer to the reference Sadeghi *et al*. (2022) SWMM is often used by consulting engineers to help meet the unique design needs of urban and regional planning projects. Fig. 2 shows the model's represented processes and their interactions.

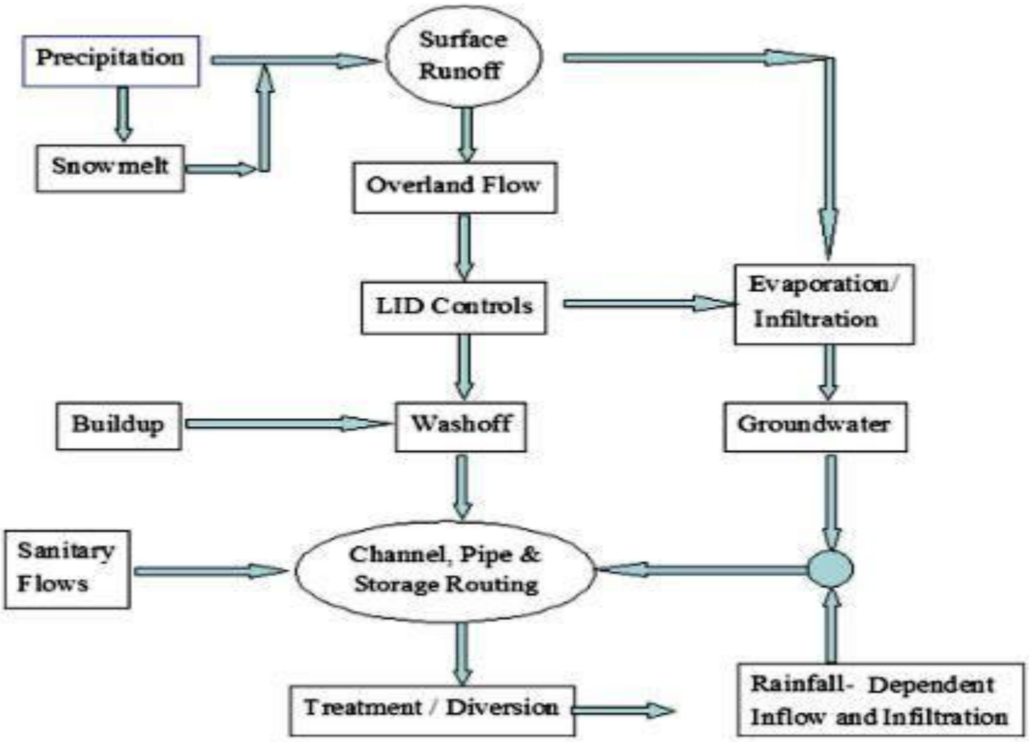

**Figure 2.** Processes considered in the SWMM model.

### 2.4. Simulation of studied area in the model

To determine the sub-catchment, the land use map and their slope were used and the boundaries of the sub-catchments were determined. Figure 3 shows the area of the sub-catchments of the region in the SWMM model. Boundary conditions at the outfall of the network are assumed to be free, because in the SWMM model, different types of boundary conditions can be changed depending on the user's choice. One of them is the selection of boundary conditions in a free manner, where the stages of water exit from the outlet of the network are determined by the minimum critical depth of the flow and the normal depth in the channel.

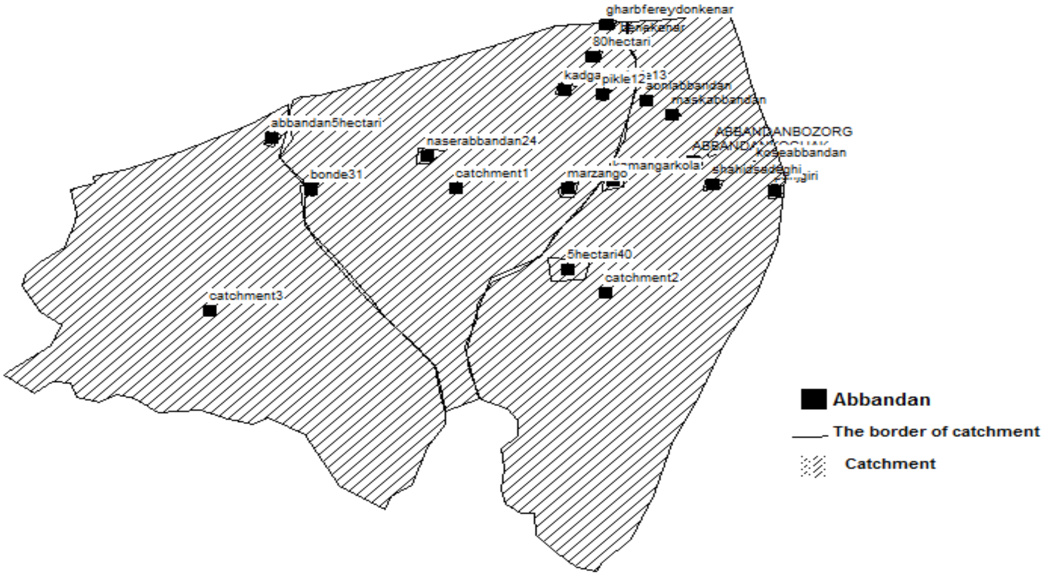

**Figure 3.** Scope of the studied area in the SWMM model.

## 2.5. Calculation of rainfall and design flood hydrograph

Rainfall is the main component in the quantitative simulation of rainfall-runoff. The volume and intensity of runoff are directly related to the size of the storm and its temporal and spatial distribution. In the SWMM model, to observe the spatial distribution of precipitation, each catchment is connected to a rain gauge, from which the data related to the time distribution and amount of precipitation are collected.

To prepare design flood hydrographs, the return period intensity curves of the nearest station adjacent to the studied area were used as shown in Figure 4. Then using the hydrological simulation of the sub-basins in the SWMM model, the design flood hydrograph was determined for the design precipitation at the outlet of each sub-catchment.

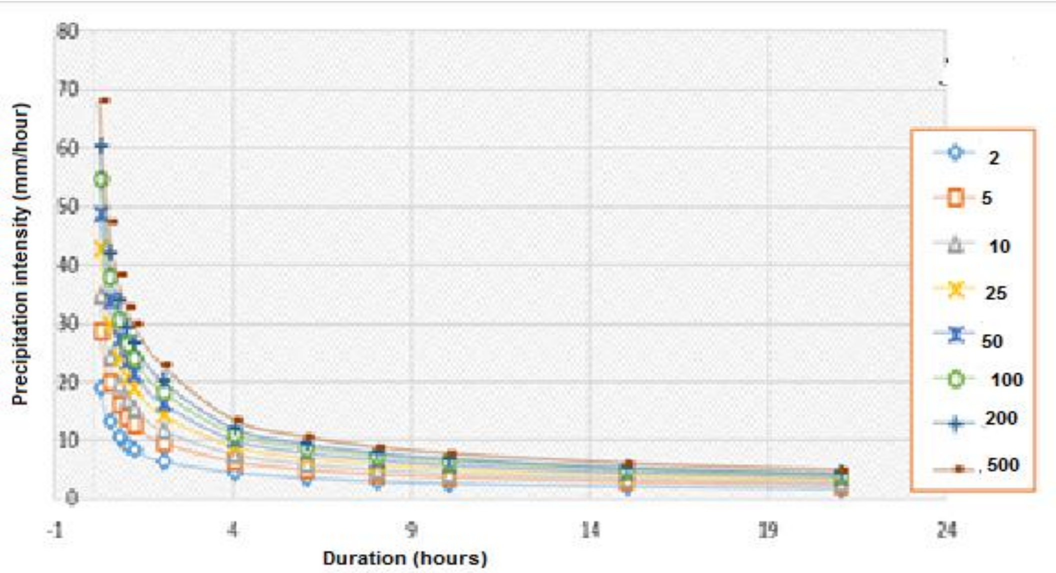

**Figure 4.** Intensity-duration-frequency curve of the short-term storm by Dr. Ghahraman's method in the Haraz basin.

The temporal distribution of rainfall or how the intensity of rainfall changes during the duration of rainfall is one the important and necessary information, which must be calculated and determined to prepare the hydrograph of the surface flows of catchment basins or to use mathematical models to convert precipitation into surface run-off of the basins. Since the influence of the temporal distribution of precipitation is significant on the maximum flood water and the shape of the corresponding hydrograph, it is very important to determine the appropriate pattern. Various methods have been developed to determine the temporal distribution pattern of precipitation. According to the available data, to perform rainfall-runoff calculations in the model and to determine the appropriate pattern of rainfall in the study area, the intensity-duration-frequency curves of the Haraz basin and alternating blocks method have been used. In this way, by using the mentioned curves, in a 24-hour rainfall, the amount of rainfall is determined in 10-minute to 24-hour intervals and the amount of rainfall in each selected time step is calculated. Then, the largest block of rain is placed at midnight (in the middle of the continuation of rain), and the next blocks are placed in order of magnitude, first on the right and then on the left of the largest block. For example, the rainfall hyetograph for a 2-year return period is shown in Figure 5.

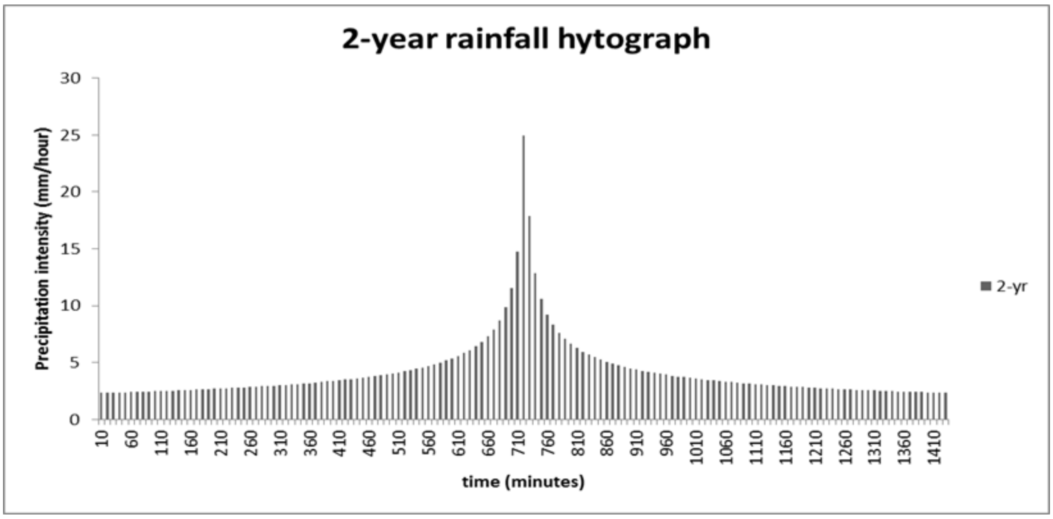

**Figure 5.** Rainfall hyetograph with a 2-year return period.

### 2.6. Optimization model for capacity changes of Abbandans with genetic algorithm

This study uses Genetic Algorithm (GA) program to seek optimal solutions. In the following, brief features of applied GA are explained:

**Chromosomes**

In GA terminology, a chromosome is a vector of variables to be optimized. Each chromosome represents a design alternative that can be potentially feasible or not. In the GA, each chromosome is composed of several genes, each of that represents a decision variable. In this algorithm, each gene is coded as a real number.

**Population**

GA starts to optimize the problem with an initial population of chromosomes that are randomly generated in the beginning. The chromosomes evolve through successive iterations, namely generations in GA Gen and Cheng (1999) deciding on the population size, $N_{pop}$ greatly depends on the problem size and its mathematical specifications. However, some preliminary sensitivity analyses and the user experiences on GAs are pretty substantial. For more details about the GA in water and wastewater engineering, the readers are referred to the optimization of water distribution networks of different researchers ((Simpson *et al.*, 1994); (Yagi *et al.*, 1998); (Wu and Simpson, 2001)).

**Objective functions**

This study establishes one model. The model is to have the maximal annual agricultural net benefit for the area. In the problems of operation of the reservoir system, where the aim is to supply the estimated demand downstream, the objective function can be defined according to the following relationship:

$$\max NB = \sum_{i=1}^{n} y_n \times A_i \times B_i \qquad (1)$$

$$B = (P - C) \qquad (2)$$

$$y_n = a_0 + a_1 Q + a_2 Q \qquad (3)$$

where NB is the value of the objective function in the problem to maximize profit, $A_i$ is the amount of cultivated area of each Abbandan, $B_i$ is the amount of net profit per unit of cultivated area, and i is the number of Abbandans. $P$ is the price for the rice and $C$ is the total cost. $y_n$ is the product performance, $Q$ is the water amount needed, $a_0$, $a_1$, $a_2$ are the coefficients related to the product performance function. When water is not distributed as planned, the profit from rice production decreases. The costs of paddy cultivation usually include various investments of paddy land, irrigation water, fertilizers and pesticides, labor, irrigation equipment, paddy seedlings, and financial loans. The objective function is to maximize the annual agricultural net benefit under the combination of water amounts needed.

**Model restrictions**

The limitations of the model include the limitations of the Abbandan storage volume and the cultivated area of each Abbandan, which are defined as follows:

$$V_{min} < V < V_{max} \qquad (4)$$

where V is the storage volume of the Abbandan and $V_{\text{min}}$ and $V_{\text{max}}$ are the minimum and maximum storage volumes of the Abbandan, respectively.

The cultivated area of each Abbandan must be less than the total cultivated area ($A_{\text{Total}}$), so it is defined as follows:

$$A_i < A_{Total} \qquad (5)$$

In general, if α is considered as a criterion that is defined in the specific range $\mathrm{A}_{\min} \leq \alpha \leq \mathrm{A}_{\max}$, the application of penalty functions is considered as the following relationships (6) and (7):

$$\mathrm{P}_{\max} = \lambda \max\left(\left(\frac{\propto}{\mathrm{A}_{\max}} - 1\right), 0\right) \qquad (6)$$

$$\mathrm{P}_{\min} = \lambda \max\left(\left(\text{١} - \frac{\propto}{\mathrm{A}_{\min}}\right), 0\right) \qquad (7)$$

In the above relationships, $\mathrm{P}_{\min}$ $\mathrm{P}_{\max}$are the constraints related to the maximum and minimum criteria, $A_{\text{max}}$ and $A_{\text{min}}$ are the maximum and minimum values defined for each parameter For example, it is defined for the minimum and maximum of storage volume of the Abbandan and the cultivated area of each Abbandan, and λ is the penalty parameter related to the desired criteria. The value of this parameter is estimated in an iterative process of trial and error with the help of experimental runs to increase the efficiency of optimization.

In this research work, to optimize the above problem, the genetic algorithm was used in MATLAB.

### 2.7. GA optimization parameters

The configuration of the GA was determined using several test implementations with random initial generations on the proposed model to achieve the fastest convergence seeking the optimal solutions. For this purpose, the optimization model was implemented with different values of parameters to find the most appropriate ones. These parameters are listed in Table 2.

**Table 2.** Parameters set in GA.

| Parameter | Population size | Number of iterations | Mutation rates | Cross-over rate |
|---|---|---|---|---|
| Amount | 250 | 1000 | 0.02 | 0.9 |

## 2.8. Water demand

The water demand for paddy fields covers the periods for transplanting, active tillering, booting, and ripening (Chen *et al.*, 2008). Irrigation water demand is field water demand deducted by effective rainfall. In this study, the water demand for rice was calculated using CROPWAT8 software. Then with the help of the following relationships, the net irrigation requirement was obtained.

$$ET_C = K_C \times ET_O \quad (8)$$

$$NIR = ET_C - Re \quad (9)$$

ETC = Evaporation and transpiration of the plant

KC = Vegetation coefficient

$ET_O$= Potential evaporation and transpiration

NIR = Net irrigation requirement

Re = Effective rain

In estimating the water requirement of Abbandan catchment areas, which used the meteorological data of the Amol Agricultural Meteorological Station, the water requirement of one hectare of rice was estimated to be 859 mm per year. Considering the efficiency of 70%, the gross requirement of rice will be 1227 mm per hectare. Next, the water requirement of the second crop was also calculated, and the net requirement of each hectare of rice is 512 mm per year and the gross requirement is 730 mm per hectare. The costs and benefits of irrigation in agriculture are discussed, as well as the construction costs of Abbandan dredging.

Allowable dredging ratios, which are defined as the coefficient of the maximum allowable dredging volume and the current effective capacity for the Abbandans, are considered in the optimization model for 11 studied cases (0.0, 0.1, 0.2, … and 1.0). Case 1 is the simulation when no dredging is done to store the current Abbandan. The effective capacities of Abbandans for various allowable dredging ratios (0.1, 0.2, …, and 1.0) are used as the constraints in the programming, and the corresponding simulations are numbered as cases 2, 3, …, and 11. To the extent of pond dredging, it is decided according to the objective function.

## 3. Discussion and Results

According to the discussions, the information required for simulation has been entered into the SWMM model, and the model was implemented for rainfall with a return period of 2, 5, 10, 25, and 50 years and in unsteady mode, and the run-off hydrograph was calculated for each Abbandan, as well as the remaining run-off volume on each sub-basin for the mentioned return periods. For example, in Figure 6, an example of this hydrograph is shown for 3 Abbandan (Abbandan Bozorg, Abbandan Kochak, and Abni Abbandan) for a return period of 25 years. The total volume of run-off remaining on each sub-basin for return periods of 2, 5, 10, 25, and 50 years is shown in Table (3).

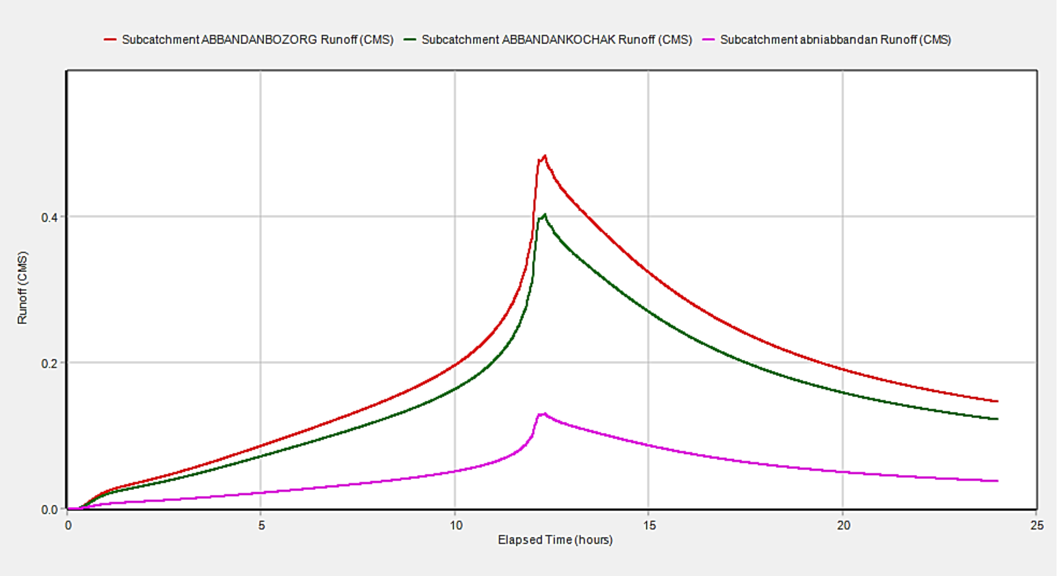

**Figure 6.** Run-off hydrograph for 3 Abbandans in the 25-year return period.

**Table 3.** Volume of residual run-off on the sub-basin of each Abbandans.

| **Name of water Abbandans** | **Run-off volume (m$^3$)** | | | | |
|---|---|---|---|---|---|
| | 2- YR | 5- YR | 10- YR | 25- YR | 50- YR |
| **5 hectari** | 150 | 2660 | 3370 | 4250 | 4900 |
| **Abbandan 5 hectari** | 90 | 1590 | 2020 | 2550 | 2940 |
| **Abbandan bozorg** | 840 | 10410 | 12980 | 16160 | 18510 |
| **Abbandan kochak** | 700 | 8670 | 10820 | 13470 | 15430 |
| **Ab ni Abbandan** | 150 | 2660 | 3370 | 4250 | 4900 |
| **Bene kenar** | 380 | 4630 | 5770 | 7180 | 8230 |
| **Binamad** | 700 | 12750 | 16160 | 20390 | 23520 |
| **Chemagh endon** | 470 | 5780 | 7210 | 8980 | 10290 |
| **Kadgar mahale** | 580 | 10630 | 13470 | 16990 | 19600 |
| **Kamangar kola** | 290 | 5310 | 6730 | 8500 | 9800 |
| **Kooseh AbbandanAbbandan** | 4540 | 82890 | 105040 | 132540 | 152870 |
| **Marzango** | 1740 | 31880 | 40400 | 50980 | 58800 |
| **Mask ab bandan** | 170 | 3190 | 4040 | 5100 | 5880 |
| **Panjgiri** | 150 | 2660 | 3370 | 4250 | 4900 |
| **Pikle** | 120 | 2130 | 2690 | 3400 | 3920 |

According to Table (3), in different return periods due to the lack of capacity of the Abbandan, a large amount of runoff will remain on the sub-catchments of the Abbandan and will remain unused. Therefore, the need to pay attention to the restoration and reconstruction of Abbandan and the collection of surface runoff and sewage as a reliable source of water can help the stability of these native structures. On the other hand, due to the water crisis, by renovating the Abbandan and increasing its capacity, run-off can be stored in non-agricultural seasons and used in agricultural seasons. In this study, it is important to find out the effects of changing the capacity of Abbandan by dredging.

Allowable dredging ratios, defined as the quotient of the maximum allowable dredging volume and the present effective capacity for the Abbandan, are assumed in the optimization model for 11 study cases

(0.0, 0.1, 0.2, …, and 1.0), and thus the Abbandan effective capacity is allowed to be changed. Case 1 is to find out the optimization simulation when there is no dredging conducted for the present Abbandan storage. The effective capacities of Abbandans for various allowable dredging ratios (0.1, 0.2, …, and 1.0) are used as the constraints in the programming, and the corresponding simulations are numbered as cases 2, 3, …, and 11. To the extent of pond dredging, it is decided according to the objective function.

In the following, the water requirement of rice should be calculated during both cultivation periods. After calculating the water requirement, it was assumed that the water requirement of the first cultivation period (April, May, June, and July) is fully supplied from the amount of water stored in the Abbandan and the amount of input and output during the cultivation period. For this reason, the amount of water required for the second cultivation should be stored and supplied in the region for more operations and second cultivation (months of August, September, and October). Figure 7 shows the amount of water required by different months of the first and second crop periods.

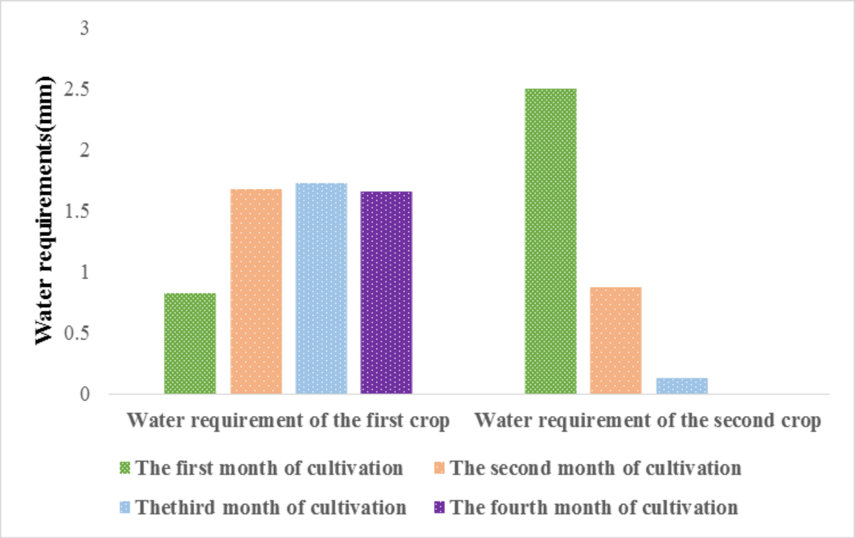

**Figure 7.** Water requirement of different months of both crop periods.

Considering the water requirement of rice in the second cropping period and other factors such as runoff volume, the optimal depth values were determined. The optimal depth in this research means that by dredging the Abbandan for various allowable dredging ratios (0.0, 0.1, 0.2, …, and 1.0), the water requirement of the entire cultivated area in the second cultivation period in the studied area will be provided. The amount of water required in the month of August is the highest amount of water required by rice in the months of the second crop period. It is very important to provide this amount of water after providing the water requirement of the first crop period.

According to the discussions, in the present research work, the wall of the Abbandan was reconstructed and its capacity was increased according to the volume of runoff and allowable dredging ratios. In this way, first, the volume of runoff was calculated in different return periods. As mentioned, the reason for choosing several different return periods is due to the randomness and variability of the precipitation phenomenon, that due to the spatial and temporal conditions and the existence of different return periods of precipitation, it is not possible to collect all precipitation by Abbandan. For example, if an Abbandan only can store the volume of runoff resulting from 2 years of rainfall, in case of rainfall for higher return periods, it is not possible to store the resulting run-off due to the lack of capacity of the Abbandan. Therefore, conditions should be provided so that these structures can be used efficiently and even if possible, run-off storage for different return periods should be provided.

Allowable dredging ratios, defined as the quotient of the maximum allowable dredging volume and the present effective capacity for the Abbandan, are assumed in the optimization model for 11 study cases (0.0, 0.1, 0.2, …, and 1.0), and thus the Abbandan effective capacity is allowed to be changed. Then the obtained secondary volumes are compared with the remaining run-off volume around each Abbandan. Accordingly, a decision will be made regarding the amount of dredging and increasing the height of the Abbandan. The simulation results are listed in Table 4, 5, 6, and 7, which consists of (a) Dredging volume, (b) Dredging expenses, (c) Secondary volume after increase, and (d) Agricultural net benefits. The results are illustrated in Figs. 8, which are agricultural net benefits for two of the Abbandan. As expected, the agricultural net benefit is increasing as the case number is increasing (see Fig. 8). The agricultural net benefit reaches the highest when Allowable dredging ratios = 0.5. As Allowable dredging ratios are increasing above 0.5, the agricultural net benefit is no longer increasing. This behavior is similar to other Abbandans. The total dredging volumes for various Allowable dredging ratios are shown in Fig. 9 for two of the Abbandan. The dredging expense is calculated according to the Price list for the year 2018 which estimated the expenses of bottom dredging and embankment height raising for the Abbandans. The expenses consist of three parts: (1) Direct expenses, (2) Indirect expenses, and (3) Engineering preparation expenses. Agricultural net benefits are obtained according to the introduced objective function.

**Table 4.** Simulation results (dredging volume).

| | Dredging volume ($m^3$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Case** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Allowable dredging ratios** | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| **5 hectari** | 0 | 11400 | 12560 | 12870 | 13261 | 11890 | 11520 | 24610 | 22320 | 30770 | 30520 |
| **Abbandan bozorg** | 0 | 100495 | 101539 | 102582 | 110549 | 105361 | 103236 | 104523 | 102325 | 282320 | 281001 |
| **Abbandan kochak** | 0 | 1056 | 1080 | 1120 | 1230 | 1095 | 1079 | 1182 | 1165 | 3133 | 3026 |
| **Ab ni Abbandan** | 0 | 972 | 1002 | 1025 | 1128 | 1003 | 1256 | 1502 | 2252 | 3992 | 3029 |
| **Bene kenar** | 0 | 2713 | 2815 | 2895 | 3024 | 2856 | 2752 | 2890 | 2736 | 3774 | 3652 |
| **Binamad** | 0 | 4280 | 4362 | 4450 | 4560 | 4263 | 4165 | 4589 | 4360 | 7641 | 7265 |
| **Chemagh endon** | 0 | 837 | 963 | 1002 | 1590 | 1005 | 968 | 1250 | 1560 | 3086 | 3050 |
| **Kadgar mahale** | 0 | 1186 | 1195 | 1296 | 1360 | 1197 | 1156 | 1260 | 1245 | 2147 | 2136 |
| **Kamangar kola** | 0 | 1243 | 1289 | 1350 | 2546 | 1285 | 1256 | 2896 | 2754 | 3251 | 3146 |
| **Kooseh Abbandan** | 0 | 6587 | 6589 | 6690 | 6820 | 6570 | 6452 | 6840 | 6690 | 7011 | 6984 |
| **Marzango** | 0 | 5678 | 5890 | 5960 | 6025 | 5870 | 5840 | 5980 | 5740 | 6023 | 5958 |
| **Mask Abbandan** | 0 | 1680 | 1750 | 1795 | 1852 | 1752 | 1686 | 1690 | 1563 | 1689 | 1672 |
| **Panjgiri** | 0 | 1378 | 1395 | 1452 | 1562 | 1365 | 1320 | 1469 | 1410 | 1520 | 1451 |
| **Pikle** | 0 | 788 | 790 | 805 | 896 | 752 | 732 | 789 | 754 | 799 | 746 |

**Table 5.** Simulation results (dredging expense).

| Dredging expense ($) |
|---|

| **Case** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Allowable dredging ratios** | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| **5 hectari** | 0 | 5869721226 | 6466991105 | 6626606331 | 6827927472 | 6122016261 | 5931507765 | 12671389419 | 11492296295 | 15843098432 | 15714376475 |
| **Abbandan bozorg** | 0 | 4859732151 | 4910217850 | 4960655192 | 5345922977 | 5095041934 | 4992281291 | 5054517972 | 4948227199 | 13652416348 | 13588632212 |
| **Abbandan kochak** | 0 | 4642033923 | 4747534694 | 4923369312 | 5406914513 | 4813472676 | 4743138829 | 5195912971 | 5121183258 | 13772246478 | 13301888874 |
| **Ab ni Abbandan** | 0 | 4791391718 | 4939274178 | 5052650731 | 5560380512 | 4944203594 | 6191345677 | 7403981852 | 11101043363 | 19678226068 | 14931199088 |
| **Bene kenar** | 0 | 12501375130 | 12971386285 | 13340022485 | 13934448357 | 13160312337 | 12681085277 | 13316982722 | 12607358037 | 17390412732 | 16828242527 |
| **Binamad** | 0 | 36008317880 | 36698196867 | 37438554805 | 38364002227 | 35865294187 | 35040804666 | 38607983820 | 36681370551 | 64284943206 | 61121595654 |
| **Chemagh endon** | 0 | 3330363330 | 3831708347 | 3986886567 | 6326496648 | 3998823353 | 3851602991 | 4973660887 | 6207128787 | 12278973998 | 12135732565 |
| **Kadgar mahale** | 0 | 20601344800 | 20757678782 | 22512093475 | 23623801794 | 20792419667 | 20080231525 | 21886757545 | 21626200907 | 37294340038 | 37103265171 |
| **Kamangar kola** | 0 | 21507743280 | 22303685509 | 23359174117 | 44053672076 | 22234473141 | 21732683475 | 50109754255 | 47652715200 | 5652351893 | 54435527240 |
| **Kooseh Abbandan** | 0 | 88266673320 | 88293473585 | 89646886976 | 91388904212 | 88038871066 | 86457655421 | 91656906863 | 89646886976 | 93948329535 | 93586525955 |
| **Marzango** | 0 | 29884179390 | 30999967701 | 31368388370 | 31710493277 | 30894704653 | 30736810081 | 31473651418 | 30210494839 | 31699966972 | 31357862065 |
| **Mask Abbandan** | 0 | 20901492650 | 21772388177 | 22332249587 | 23041407374 | 21797270906 | 20976140838 | 21025906297 | 19445852983 | 21013464932 | 20801961733 |
| **Panjgiri** | 0 | 4909834815 | 4970406072 | 5173497933 | 5565429594 | 4863515619 | 4703179939 | 5234069190 | 5023851298 | 5415782960 | 5169934918 |
| **Pikle** | 0 | 3815063044 | 3824745945 | 3897367704 | 4337939705 | 3640770824 | 3543941812 | 3819904495 | 3650453725 | 3868319000 | 3611722120 |

**Table 6.** Simulation results (secondary volume after increase (m$^3$)).

| | **Secondary volume after increase (m$^3$)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Case** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Allowable dredging ratios** | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| **5 hectari** | - | 102092 | 112480 | 115256 | 118758 | 106480 | 103166 | 220393 | 199885 | 275558 | 273319 |
| **Abbandan bozorg** | - | 400362 | 404521 | 408676 | 440416 | 419747 | 400281 | 416409 | 407652 | 1124734 | 1119479 |
| **Abbandan kochak** | - | 113048 | 115617 | 119899 | 131675 | 117223 | 115510 | 126536 | 124716 | 335397 | 323942 |
| **Ab ni Abbandan** | - | 99424 | 102492 | 104845 | 115380 | 102594 | 128473 | 153636 | 230352 | 408333 | 309830 |
| **Bene kenar** | - | 137732 | 142910 | 146971 | 153520 | 144991 | 139711 | 146717 | 138899 | 191596 | 185402 |
| **Binamad** | - | 423767 | 431885 | 440598 | 451490 | 422083 | 412380 | 454361 | 431687 | 756542 | 719314 |
| **Chemagh endon** | - | 55074 | 63364 | 65930 | 104620 | 66128 | 63693 | 82249 | 102646 | 203056 | 200687 |
| **Kadgar mahale** | - | 122653 | 128883 | 1319151 | 143927 | 121530 | 127705 | 182997 | 171601 | 234079 | 227343 |
| **Kamangar kola** | - | 187568 | 188991 | 204964 | 215086 | 189307 | 182823 | 199271 | 196898 | 339551 | 337812 |
| **Kooseh Abbandan** | - | 5675643 | 5885682 | 6164214 | 1162525 | 5867418 | 5735002 | 13223380 | 125749996 | 14844340 | 14364901 |
| **Marzango** | - | 562607 | 562777 | 51404 | 582507 | 561155 | 551076 | 584216 | 571404 | 598821 | 596515 |
| **Mask Abbandan** | - | 153940 | 159687 | 161585 | 163347 | 159145 | 158332 | 162127 | 1555620 | 163293 | 161531 |
| **Panjgiri** | - | 147013 | 153138 | 157076 | 162064 | 153313 | 147538 | 147888 | 136774 | 147800 | 146312 |
| **Pikle** | - | 60428 | 61173 | 63673 | 68496 | 59857 | 57884 | 64418 | 61831 | 66654 | 63629 |

**Table 7.** Simulation results (agricultural net benefits ($)).

| | **Agricultural net benefits ($)*10$^{10}$** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Case** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

| **Allowable dredging ratios** | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **5 hectari** | 1.8 | 1.95 | 2.1 | 2.25 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| **Abbandan bozorg** | 6.8 | 7 | 7.2 | 7.3 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 |
| **Abbandan kochak** | 3.85 | 4.1 | 4.25 | 4.5 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 |
| **Ab ni Abbandan** | 1.8 | 1.9 | 2 | 2.21 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| **Bene kenar** | 4.5 | 4.89 | 5 | 5.2 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| **Binamad** | 3.56 | 3.95 | 4.1 | 4.3 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 |
| **Chemagh endon** | 3.5 | 3.95 | 4.2 | 4.5 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 |
| **Kadgar mahale** | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| **Kamangar kola** | 3.5 | 3.8 | 4 | 4.3 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 |
| **Kooseh Abbandan** | 30 | 32 | 35 | 39 | 41 | 41 | 41 | 41 | 41 | 41 | 41 |
| **Marzango** | 19 | 21 | 25 | 28 | 31 | 31 | 31 | 31 | 31 | 31 | 31 |
| **Mask Abbandan** | 1.5 | 1.9 | 2.1 | 2.5 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| **Panjgiri** | 1.8 | 2 | 2.1 | 2.2 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 |
| **Pikle** | 1 | 1.2 | 1.5 | 1.7 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |

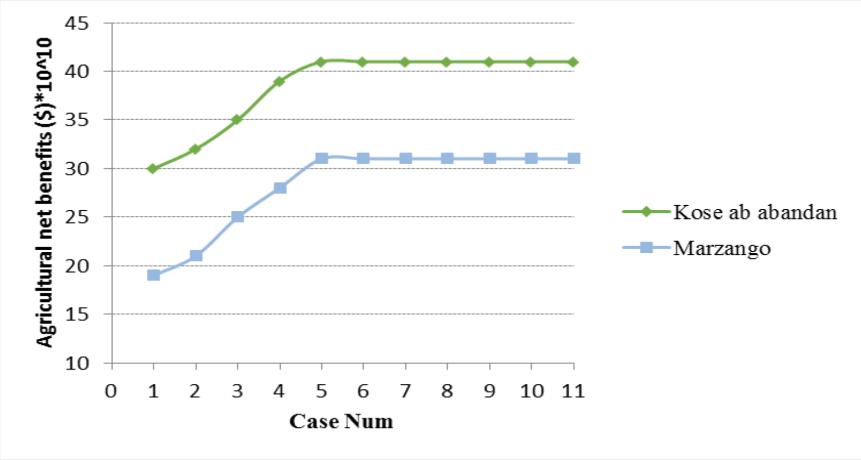

**Figure 8.** Agricultural net benefits.

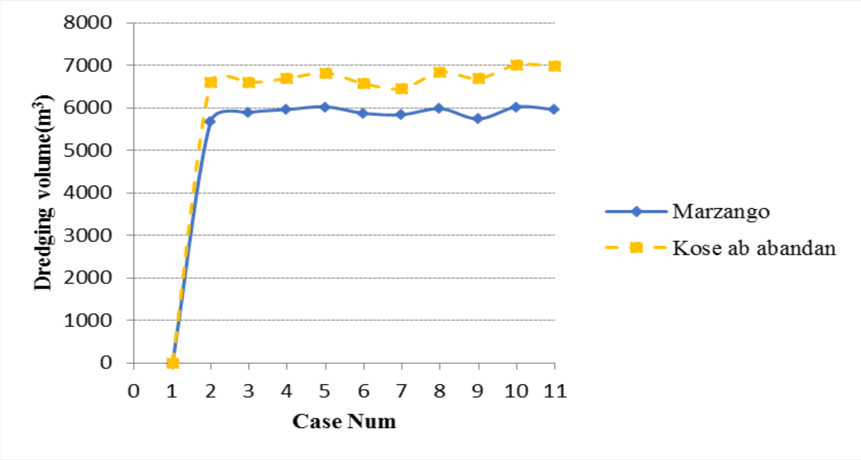

**Figure 9.** Total dredging volume for two Abbandan.

According to Figure 9, the trend is similar to those discussed above because agricultural net benefit also reaches the highest after Allowable dredging ratios = 0.5. The lowest dredging volume appears when Allowable dredging ratios = 0.8. This behavior is similar to other Abbandans. Therefore, it is inferred that there exist Abbandans that have a better dredging effect with the agricultural net benefit as the objective. It is known that the dredging expense is proportional to the dredging volume. Thus, the Allowable dredging ratio = 0.8 is the optimal case for dredging and increasing the capacity of Abbandan. Because in this case (number 9) (allowable dredging ratios = 0.8), the agricultural net benefit is maximum and dredging expense is minimum. Finally, according to the Allowable dredging ratios = 0.8, the optimal depth of Abbandans and the second volume of them are calculated. After determining the depths of each Abbandans and determining the amount of available water or the amount of water stored in the Abbandans, using the genetic optimization algorithm, the amount of cultivated area of each Abbandans was calculated. The simulation results are listed in Table 8.

**Table 8.** Amount of increase in the amount of depth of Abbandan and development of the cultivated area.

| Name of Abbandans | Amount of depth increase (m) | Development of cultivated area (Ha) |
|---|---|---|
| **5 hectari** | 2.00 | 9.6 |
| **Abbandan bozorg** | 2.70 | 39.1 |
| **Abbandan kochak** | 3.00 | 58.7 |
| **Ab ni Abbandan** | 3.30 | 14.9 |
| **Bene kenar** | 3.40 | 23.6 |
| **Binamad** | 3.60 | 1.6 |
| **Chemagh endon** | 1.70 | 43.4 |
| **Kadgar mahale** | 4.30 | 84.3 |
| **Kamangar kola** | 3.00 | 28.9 |
| **Kooseh Abbandan** | 3.65 | 281.4 |
| **Marzango** | 2.10 | 257.1 |
| **Mask Abbandan** | 3.50 | 15.9 |
| **Panjgiri** | 3.50 | 13.4 |
| **Pikle** | 0.55 | 13.9 |

For a better comparison, Figure 10 shows the water requirements of the first and second crops, as well as the current volume and the secondary volume of some samples of Abbandan after improvement. According to Figure 10, it is not possible to provide the water demand with the current volume. Therefore, according to the amount of run-off remaining in each area around the Abbandans and the calculated optimal depths, the secondary volume is calculated for each Abbandans, which will be able to receive the incoming run-off and also provide the water requirement in both cultivation periods.

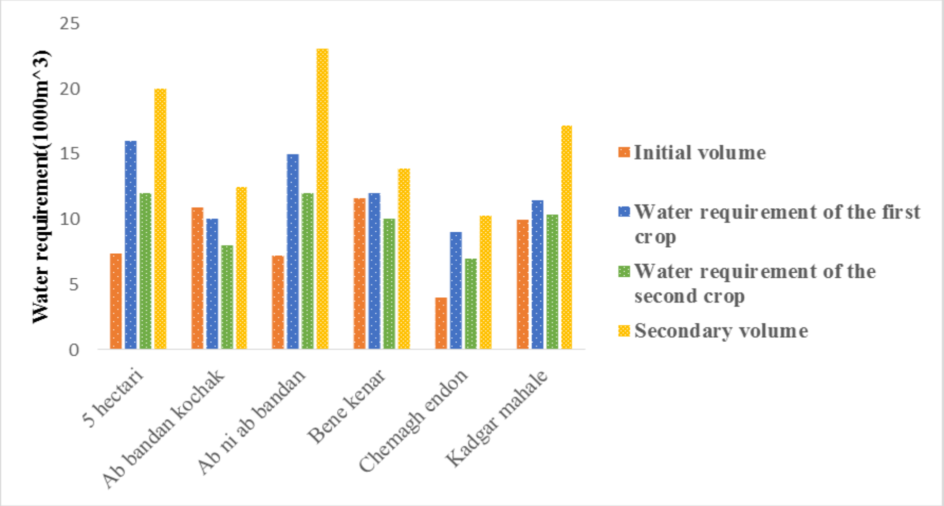

**Figure 10.** Values of water requirement and optimal volumes.

The results obtained above show that with the existing conditions of farm management, increasing the volume of water will lead to the development of the paddy field. However, the potential capacity of Abbandan with dredging and improvement at higher depths will be greater and will increase the cultivated area and increase the water allocation for the same existing paddy fields. As a result, it will increase the economic profit and the income of farmers in the region. On the other hand, due to the increase in the price of rice and the justification of the economic conditions in recent years, the second crop has been considered due to the increase in the income of farmers in the region. By bringing the lands under cultivation for the second time, it is possible to increase the cultivation coefficient of the region. By increasing the volume of water storage in Abbandan, the need to use and pump underground water is also reduced, and the production cost is reduced too, it also prevents the reduction of underground water quality. This increase in volume also results in other uses. Most of the waters of Abbandans in the country are used for fish breeding in agricultural and non-agricultural seasons, and fish breeding can be developed after the improvement and restoration of the Abbandan.

According to the results of the research, increasing the capacity of Abbandans will have other advantages in addition to expanding the area under cultivation and providing the possibility of second cultivation. It is expected that the following goals will be achieved with the implementation of the repair and improvement project of the mentioned Abbandans:

A) Supplying the required water for a part of the agricultural lands of the villages.

B) Revival of fish farming in Abbandans due to the increase in water volume created.

C) Preventing the digging of surface and shallow wells in the agricultural land of the village.

D) Creating employment for some young people in the region.

Increasing the entertainment and tourism plan.

## 4. Conclusion

In this research work, by observing the distribution map of Abbandans in the Mazandaran Province, a range of Haraz catchments with about 14 Abbandans were selected. For this purpose, the catchment run-off for different return periods was calculated using the SWMM model, Then, the conditions of the Abbandans were examined to change its dimensions to increase the volume. The increase in the volume of Abbandans was investigated by increasing the depth of its and using the genetic algorithm. One model is presented that maximizes agricultural financial net benefits. Various allowable dredging ratios are used in the model for the case study. According to the results, in the 2, 5, 10, 25, and 50 years return periods, 5.4, 8.3, 12.1, 29.9, and 37.4% of precipitation at the Abbandan upstream were transformed to runoff, respectively. Therefore, the capacity of the Abbandans could be increased as much as overflowed water in different return periods. Based on the results obtained, dredging and improvement of all Abbandans in the region area will cause the collection of runoff from rainfall up to the return period of 50 years. The model displays that the maximum agricultural financial net benefit increases as the ratio increases and it reaches the highest value when the ratio is 0.5. Also, the area of cultivated fields irrigated by the Abbandans increased from 124 to 193 hectares on average. By increasing the effective storage capacity of the Abbandans, the ability of the Abbandans to store and allocate water from main or auxiliary sources can be increased. Improving the capacity of Abbandan, can not only help satisfy water demand but also can save water for the Reservoir or obtain agricultural net benefits. Allowable dredging ratios provide Abbandans the flexibility for the dredging volume in the programming. To maximize the net profit of agriculture, the water demand is the most important factor in considering the priority of Abbandan volume dredging. This study follows the present conditions of the irrigation system to establish the optimization model for realizing the effects due to the changes in Abbandan's effective capacity. This study has focused on Abbandan volume dredging only. If the engineering planning is focused on the water transfer and intake facilities in addition to Abbandan volume dredging, it is expected that more water will be conserved through the optimal operation. However, the agricultural sector has low competitiveness and usually cannot afford the high costs of land acquisition and engineering construction. It is suggested that a financial analysis needs to bring water users from other sectors, particularly the industry, to cover the expenses.

## Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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