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1 **Developing a Non-Cooperative Optimization Model for Water and Crop Area Allocation Based**
2 **on Leader-follower Game**

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24 **Abstract**

25 In this paper, a mathematical model for conflict resolution among a diverse set of agricultural water users in
26 Golestan province, Iran, is developed. Given the bi-level nature of the distribution of power in the current problem,
27 a combination of Leader-Follower game and Nash-Harsanyi bargaining solution method is employed to find
28 optimal water and crop area allocations. The Golestan Regional Water Authority is the leader in this setting,
29 controlling the total water allocations; and the agricultural sectors are the followers, competing over the allocated
30 water. Two objectives for the leader are (i) maximizing profits, and (ii) maximizing share of green water in total
31 agricultural production through selecting more efficient crop patterns. The followers' objective is merely
32 maximizing obtained benefits for the selected crop patterns. Virtual water concept is also factored into the related
33 objective functions, and the water allocation problem is solved considering spatio-temporal crop pattern along
34 with a dynamic water pricing system. This involves using a hybrid optimization structure as a new approach to
35 solving two level optimization problems. The results show that the leader's income is independent of total water
36 allocation and is only affected by crop pattern and crop area, two factors which drive water price too. The
37 followers' benefit also depends on crop pattern and crop area, as they influence the crop yield, cost and water
38 price. Finally, green water plays a key role in selecting the optimal crop pattern and crop area.

39

40 **Keywords:** Green water; Leader-followers Game; Agricultural water allocation; Agricultural benefit; Nash
41 bargaining model; NSGA-II multi-objective optimization model

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45 **1. Introduction**

46 Water shortage is a global problem, which is more pronounced in arid and semi-arid areas (Sadegh et al. 2010).
47 While prolonged droughts, change in ratio of snow to rain, global warming, and increased number of dry days all
48 played some role in this issue, population growth and economic development and subsequent rise in water demand
49 aggravate the problem (AghaKouchak, 2015). Agricultural sector as the largest consumer of water around the
50 globe endures highest socio-economical loss from water scarcity, manifested in the reduction of crop yield
51 (Khanjari Sadati et al., 2014). Su et al. (2014) introduced “Virtual Water Trade” as an effective strategy to improve
52 sustainable use of water resources, which can also be employed as a strong tool to effectively allocate water
53 resources at regional scales. The concept of virtual water was originally introduced by Allan (1998) to account
54 for the water consumed in food production, and recently any product in general, which is in turn traded in regional
55 and global markets. The concept of virtual water and other related fields such as virtual water trade, virtual water
56 flow and water footprint have been extensively studied in the literature (Yang and Zehnder, 2007; Liu and
57 Savenije, 2008; Verma et al., 2009; Faramarzi et al., 2010; Velázquez et al., 2011; Konar et al., 2013; Chen and
58 Chen, 2013; Zhang et al., 2014; Su et al., 2014; Zhang et al., 2016; Ababaei and Etedali, 2017; Srinivasan et al.,
59 2017; Wang et al, 2017). Different methods have also been applied to optimize the water-food nexus (e.g.
60 Faramarzi et al., 2010; Su et al., 2014; Zhang et al., 2016).

61 Increasing water consumption and withdrawal due to population and economic growth, as well as increasing
62 awareness for environmental protection have led to intense competition over the already stressed water resources
63 (Sadegh and Kerachian, 2011; Taher Kahil et al. 2015). This highlights the significant role of governmental
64 entities and watershed managers as decision-makers on how to allocate water (C. Johansson et al., 2002; O. Orubu,
65 2006; Hanak and Lund, 2012; Farhadi et al. 2016; Hu et al. 2016). The relationships between different water users
66 can be effectively defined within the framework of Non-Cooperative game theory models. In this type of games,
67 the interactions between players (stakeholders) are based on their strategic goals (Carraro et al., 2007). When
68 players make decisions in different levels (power layers), a specific non-cooperative game, namely “leader-
69 follower” or “Stackelberg” game can be applied (Tharakunnel et al. 2009, Jorgensen et.al 2010, Safari et al. 2013,
70 Kicsiny et al. 2014, Taher Kahil et al. 2015, Hu et al. 2016). The application of leader-follower game in the field
71 of optimal water allocation was first considered by Barbier and Bhaduri (2003, 2008). Ever since, the leader-
72 follower game has been used in water resources management literature. For example, Bhaduri and Liebe (2012)
73 evaluated the scope and sustainability of cooperation between two countries with the common basin using a
74 Stackelberg static model, and Safari et al. (2013) developed a model for optimal water allocation to various users

75 based on a leader-follower game. In the latter study, Iran Water Resources Company was considered as the leader
76 and three water consumers as followers. Being of a single-objective nature, they used genetic algorithm to solve
77 the water allocation model. Another example is the conjunctive allocation of surface- and ground-water resources
78 by Parsapour-Moghaddam et al. 2015, using a single-player game with non-cooperative behavior by consumers
79 of surface- and ground-water resources.

80 Hu et al. (2016), by presenting a two-level optimization model, introduced the basin executives as upper-level
81 and farmers as lower-level decision makers. They converted the multiple objectives of their study into a weighted
82 single objective model and solved it by the weighted-sum method. Zhang et al. (2016) presented an optimization
83 model based on the concept of virtual water to increase the productivity of agricultural water consumption for
84 different scenarios. The objective function used in their research is to minimize the blue water consumption. The
85 impact of green water, as well as the possibility of intervention by the government and watershed authorities in
86 the water allocation process in the region are, however, not considered. In another study, Galan-Martin et al.
87 (2016) developed a multi-objective optimization model (objectives including sustainable food production and
88 environmental protection) and solved it by applying the epsilon constraint method, without any regard for the role
89 of the state and the watershed administrators. Furthermore, researchers such as Chen et al. (2017) used leader-
90 follower models in the field of water pollution. They presented a bi-level interaction model in which the
91 environmental sector and water users are defined as the upper- and lower-level decision makers, respectively. By
92 comparing this model with one-level models, they noted the significant performance of two-level models.

93 While significant strides have been made in this field, the impact of virtual water trade has not yet been
94 considered, to the best of authors' knowledge, in a leader-follower game framework to allocate water to consumers
95 and resolve potential conflicts. Also most models in the literature are either single-objective or are converted into
96 single objective form (weighted average of multiple objectives). In the model presented in this study, the leader
97 has two objective functions, namely maximizing profits and maximizing share of green water in agricultural
98 production, and the proposed method forms a Pareto front between the two objective functions. Strategic planning
99 for employing virtual water to reduce crop water demands in joint groundwater-reservoir irrigation systems is
100 also not fully explored, which we will address in this paper. Moreover, we define water price as a dynamic
101 variable, which is vital to preventing a surge in cultivation area and water demand, and achieve self-sufficiency
102 in crop production. Regional self-sufficiency is defined as a specific level of crop production that can supply the
103 annual consumption for that crop in the region. The concept depends on population, crop yield and crop demand
104 per capita.

105 In the current research, a two-level optimization model is developed with the presence of executive managers
106 in top-level and the agricultural sectors in low-level as leader and followers, respectively. The leader's objective
107 functions are (i) maximizing the profit gained from selling water to the followers, and (ii) maximizing ratio of
108 “green water to total water” consumption through strategic planning and crop selection. The followers’ objective
109 functions are to maximize their benefits through adopting different crop patterns. To prevent intensive increase in
110 cultivation area for some crops and to ensure self-sufficiency in crop production, the model is designed to adapt
111 water price dynamically in different sectors for each crop. For solving the proposed optimization model, a multi-
112 objective genetic algorithm (NSGA-II) approach is combined with an internal GA optimization model that
113 maximizes the benefit of the followers. In the following sections, the proposed methodology, results, discussions
114 and conclusions are discussed.

115 **2. Methodology**

116 The purpose of this study is to optimize agricultural water allocation, while satisfying the goals of basin’s
117 executive manager with superior power over the agricultural sectors in the decision making process. Two defined
118 objectives for the basin manager are (i) maximizing the profit gained from selling water to agricultural sectors,
119 and (ii) maximizing the ratio of “green water to total water” consumption through selecting more efficient crop
120 patterns in different sectors (three sectors in this study). Both objectives are affected by the crop pattern and the
121 crop cultivation area. In our model, 10 crops that maximize the leader’s objective functions out of 16 crops are
122 chosen to be planted, which may vary in different sectors. Selection of these 10 crops must guarantee maximum
123 benefit for each of the three sectors (followers). Furthermore, by maximizing the ratio of “green water to total
124 water” consumption, crop per drop productivity would improve. It can lead to increasing cultivation area and
125 consequently yielding higher profit.

126 Another parameter that has a key role in determining the objective values of the leader and followers is the
127 price of water. In the proposed methodology, the price of water is considered as function of the cultivation area
128 for each crop, such that minimum water price is associated with the cultivation area and pattern that assure self-
129 sufficiency in each sector. The so-called ideal cultivation area in this study depends on population, crop yield and
130 crop demand per capita in each sector. Farmers that choose to diverge from the ideal cultivation area, for any
131 reason like crops price, yield, etc., are penalized by the leader through higher water price. Therefore, the water
132 price for each crop is a function of cultivation area of that specific crop and can vary dynamically in different
133 sectors for each crop.

134 Considering the multi-level nature of the problem at hand, with the basin administrator (leader) in a higher
 135 level than agricultural sectors (followers), it is logical to apply a non-cooperative leader-follower game to model
 136 the system. To resolve the related optimization problem, a combined genetic algorithm (GA) structure is applied.
 137 While an internal GA optimizes the objective of followers, a multi-objective genetic algorithm (MOGA) as an
 138 outer loop, optimizes the leader's objectives.

139 In non-cooperative single leader-multi followers game, the followers decide simultaneously for their movement
 140 without any knowledge about each other's strategies, and based solely on the leader's total water allocation to the
 141 system and their perception of other players' behaviour. The objective function of the followers is defined based
 142 on non-symmetric Nash-Harsanyi function (Harsanyi and selten, 1972), in which each follower's function takes
 143 a power proportional to its influence in the bargaining process. In this study, it is assumed that the more population
 144 the sectors (followers) have, the more powerful they are in bargaining. Therefore, to calculate each sector's power
 145 factor, its population is divided by the total population of all sectors.

146 The allocated water to each of the three sectors are the leader's decision variables, while the follower's decision
 147 variables include cultivation area coefficient for each crop, as well as crop patterns in the three sectors. There are
 148 4 and 6 types of dominant crops for winter and summer, respectively, and hence the number of possible crop
 149 patterns among 16 suitable crops for each sector is equal to 2,940.

150 In each iteration, the internal GA structure (for the followers) randomly chooses three crop patterns among the
 151 2,940 alternatives including 10 crops for each sector. Then it randomly selects 30 cultivation area coefficients as
 152 the followers' decision variables. Therefore, the total number of followers' decision variables is 33. It is also
 153 assumed that the cultivation area for a given crop is calculated by the multiplication of the total allocated water to
 154 each sector (the leader's decision variables) by the crop's cultivation area coefficient (Safari et al., 2014). By
 155 solving the model, a Pareto front curve with various solution points is formed. Fig. 1 shows the different steps for
 156 modelling the proposed methodology. The multi-objective optimization model is formulated as:

$$f(1) = \text{Maximize} \sum_{i=1}^3 \sum_{c=1}^{10} (X_i \cdot AC_{ic} \cdot r_{ic}) \quad (1)$$

$$f(2) = \text{Maximize} \frac{\sum_{i=1}^3 \sum_{c=1}^{10} (X_i \cdot AC_{ic} \cdot y_{ic} \cdot VWC_{green-ic})}{\sum_{i=1}^3 \sum_{c=1}^{10} (X_i \cdot AC_{ic} \cdot y_{ic} \cdot VWC_{green-ic}) + \sum_{i=1}^3 \sum_{c=1}^{10} (X_i \cdot AC_{ic} \cdot y_{ic} \cdot VWC_{blue-ic})} \quad (2)$$

157

158 Where X is allocated water to each sector (MCM), AC is allocation coefficient and r is water price for each crop
 159 at each sector (\$), respectively. Also y is crop yield (ton per hectare), VWC_{blue} is blue virtual water content (m³/kg)
 160 and VWC_{green} is green virtual water content (m³/kg), respectively. i and c are indices for sectors and crops,
 161 respectively. In equations (1) and (2), $f(1)$ is the benefit function (\$) and $f(2)$ is the green water rate function. The
 162 objective functions are subjected to the following constraints:

$$Area_i \leq \text{Maximum Area}_i \quad (3)$$

$$\sum_{i=1}^3 X_i \leq T.A.W \quad (4)$$

..... Internal GA

$$f_{followers} = \text{Maximize} \prod_{i=1}^3 B_{f_i}^{\omega_i} \quad (5)$$

Subject to:

$$Area_i \leq \text{Maximum Area}_i \quad (6)$$

$$\sum_{i=1}^3 \omega_i = 1 \quad (7)$$

163

164 Where $Area$ is cultivation area (hectares), $T.A.W$ is total available water (MCM), B_f is followers' benefit (million
 165 dollars) and ω denotes followers' power coefficient.

166

167 2.1. The NSGA-II Multiobjective Optimization Model

168 Non-Dominant Sorting Genetic Algorithm (NSGA-II) is a powerful optimization algorithm, proposed by Deb
 169 et al. (2002). This algorithm, which solves multi-objective optimization problems, has been widely used in the
 170 literature (Nikoo et al., 2011; Nikoo et al., 2012; Nikoo et al., 2014; Monghasemi et al., 2015; Alizadeh et al.,
 171 2017). Fig. S1 (Supplementary Information) explains in details the NSGA-II multi-objective optimization
 172 procedure.

173

174

175

176 2.2. The Leader – Follower Game

177 This method was introduced by Von-Stackelberg, as a non-cooperative game in 1934. The hierarchical nature
 178 of decision making in this game necessitates an equilibrium solution concept. In this game, the optimal move of
 179 the leader is subject to existing Nash equilibrium among followers. In other words, the leader is completely aware

180 about the followers' payoff functions before making a decision and can determine the equilibrium in followers'
 181 game. Similarly, for every leader's decision, the followers are able to calculate their equilibrium reaction in order
 182 to maximize their individual payoff function (Tharakunnel et al., 2009). The best move by the followers is
 183 associated with the strategy that maximizes their payoff. How to make this best move depends on the leader's
 184 decision that is clear to all followers, and also the solution method that is assigned by the leader. The followers
 185 can interact with one another based on non-cooperative, or hierarchical, behaviour (Safari et al., 2013). Since the
 186 followers compete over limited resources, they all should make simultaneous decisions without any knowledge
 187 about the others' moves. In this condition, it is rational that the followers consider one of the bargaining solution
 188 methods like the Nash-bargaining solution method. In this paper, a non-cooperative interaction is proposed among
 189 the followers (agricultural sectors) with different powers in the bargaining process. Therefore, a non-symmetric
 190 Nash-bargaining method can be used to define the followers' objective functions. Interested readers are referred
 191 to examples S1 and S2 (Supplementary Information) for more details.

192

Fig.1 Flowchart of the proposed non-cooperative optimization model for water and crop area allocation
 based on leader-followers game

193

194

195 **2.3. Non-symmetric Nash-bargaining Solution Method**

196 The symmetry assumption as one of the Nash axioms was criticized by some researchers because different
 197 players may not possess similar negotiating power (Matsumoto and Szidarovszky, 2016). This idea is the
 198 foundation of the non-symmetric Nash-bargaining method (Harsanyi and selten, 1972). The mathematical
 199 representation of this method describes the solution method by introducing a positive power vector ω ($\omega_1, \omega_2, \dots,$
 200 ω_n), where $\omega_1 + \omega_2 + \dots + \omega_n = 1$, as well as a unique solution function $\varphi(H, d)$, which is the unique solution for
 201 the following optimization problem:

$$196 \quad \text{Maximize } Z = (f_1 - d_1)^{\omega_1} \cdot (f_2 - d_2)^{\omega_2} \dots (f_n - d_n)^{\omega_n} \quad (8)$$

Subject to:

$$197 \quad f_i \geq d_i \quad (i = 1, 2, 3, \dots, n) \quad (9)$$

$$198 \quad f_1, f_2, \dots, f_n \in H \quad (10)$$

202

203 in which Z is the objective function for the Nash-based problem, f is the payoff function for each follower, and d
204 is the disagreement payoff vector.

205

206 **2.4. Water price function**

207 As mentioned before, in this study water price is a function of crop's cultivated area. It is assumed that the
208 minimum water price for each crop is associated with the ideal cultivation area, in which self-sufficiency is met
209 for each crop. This area is readily computed based on crop yield, crop per capita demand and population in each
210 region. A second degree polynomial equation can model this function:

$$P_w = a.Area^2 + b.Area + c \quad (11)$$

211

212 Where P_w is the water price, $Area$ is defined as cultivation area and a , b , c are equation coefficients.

213

214 **3. Case study**

215 Performance of the proposed methodology is examined for a specific part of Golestan province in Iran, which
216 includes an irrigation network named Narmab, supplying water to Minoo Dasht, Azad Shahr and Gonbad Kavoos
217 cities with maximum cultivable area of 2,000, 7,000 and 10,000 hectares, respectively. The network water demand
218 is supplied by Narmab reservoir (Fig. 2) and groundwater resources. The dam reservoir with a capacity of 115
219 MCM was constructed on Narmab River. Groundwater resources, consisting of 1,535 wells, 11 qanats, and 218
220 springs, also supply water to the agricultural sectors. The related aquifer characteristics such as average aquifer
221 thickness and storage coefficient are 95 meters and 5%, respectively. The aquifer transmissivity varies between
222 20 to 2,000 m² per day, and average annual precipitation is about 500 mm delivered mostly from January to April,
223 while average potential evapotranspiration is roughly 1000 mm (Golestan Regional Water Authority, 2010). The
224 current prolonged drought condition has led to significant stress on the water resources in the region, with
225 maximum extraction from surface and subsurface water resources being about 70 and 50 MCM, respectively. This
226 research considers two planting seasons (i.e. winter; from November to April and summer; from June to October)
227 for cultivation, as it is common in the study area with 16 possible crops (summer Rice, summer Cotton, Cucumber,
228 Soybean, Potato, Tomato, Mung bean, Water Melon, Corn, Pea, Wheat, Onion, Barley, Spinach, Canola and
229 Kidney bean).

230

Fig. 2 Location of the study area in Iran

231

232 Fig. 3 schematically presents the relationship between different players in the study area. Agricultural sectors as
233 Economical Actor push Water Company Authority to access more water through Parliamentary representatives
234 and other political powers in their region. However, supplying the environmental water demand is a very important
235 issue for environmental sectors such as Department of Environment and related NGOs. Therefore, they try to
236 force Water Company Authority not to allocate excess water to the agricultural sectors. Forming some
237 negotiations between the political and environmental actors is both possible and pragmatic.
238

Fig. 3 Interactions between different stakeholders (players) in the study area

239

240 **4. Results and discussion**

241 The proposed methodology, as schematically presented in Fig. 1, starts with gathering data and determining
242 parameters such as virtual water content (Green and Blue) of different crops in the region and the crop price
243 functions. The ideal cultivation area, that satisfies self-sufficiency for each crop, is also calculated to then be used
244 for water pricing. Subsequently, the developed NSGA-II multi-objective optimization model (NSGA-II MO) with
245 an internal GA optimization structure is executed. The NSGA-II MO model optimizes the leader's objective
246 functions, while the internal GA optimizes the followers' objective functions. NSGA-II MO has three decision
247 variables namely agricultural water allocation to each of the three agricultural sectors. The population size and
248 maximum number of generations in NSGA-II are set to 60 and 150, respectively. For internal GA, there exist 33
249 decision variables including 30 cultivation area coefficients (10 for each of the sectors) and 3 crop patterns (one
250 for each sector). The GA model assigns 330 chromosomes to the population size and 300 to the maximum number
251 of generations, with a two point crossover function with fraction value 0.8. Stopping criteria is defined based on
252 TolFun parameter of 1e-6 for StallGenLimit parameter value 50. For the NSGA-II model, since the number of
253 decision variables is small (3), it is expected that the number of solution points is small too. So the largest probable
254 value (1) is assigned to the Pareto fraction parameter to get the maximum number of solution points. Using an
255 Intel® Core™ i7 and CPU @ 2.4GHz processing system, the model's run took about 72 hours. By running the
256 model, a Pareto front that consists of 5 solution points is obtained (Fig. 4). Different solutions on the tradeoff
257 curve include the optimal values for agricultural water allocation to each sector, crop cultivation area and optimal
258 crop pattern in each sector. Also the agricultural benefit as a function of the cultivation area and the water price
259 are calculated. It should be noted that the water price appears both in the leader's objective function (maximization
260 of the leader's income) and the followers' (maximization of the followers' benefit).

261

Fig. 4 Pareto front solution points as a result of running multiobjective genetic algorithm

262

263 **4.1. Optimal agricultural water allocation**

264 Leader's decision variable is optimized through maximizing the leader's income and share of green water in
265 total agricultural water consumption, as the two leader's objectives. Fig. 5 shows the values of agricultural water
266 allocation to the different agricultural sectors for the 5 obtained solution points on the Pareto front. Alternative 3
267 is associated with the highest total agricultural water allocation, and the highest water allocation to sectors 1, 2
268 and 3 are related to alternatives 3, 5 and 4, respectively. This is due to the selected crop pattern for each sector.

269

Fig. 5 Agricultural water allocation to the different agricultural sectors (MCM)

270

271 Note that higher agricultural water allocations do not guarantee more profit for the leader (Table 1 and Fig.
272 5). For example, for alternatives 4 and 5 with agricultural water allocations of 100.11 and 102.72 MCM,
273 respectively, the obtained incomes are 12.3 million dollars (alternative 4) versus 8.8 million dollars (alternative
274 5). This is because of the selected crop patterns and the calculated water price, which are assigned to each crop in
275 different sectors based on its price function.

276

Table 1 Values of leader's objective functions and total water allocation for different alternatives

277

278 Table 2 presents total crop water consumption (green + blue water) calculated for different alternatives
279 associated with the values of maximum "green to total water" consumption ratio, agricultural water allocation and
280 irrigation efficiency (0.5). Comparing the alternatives in terms of "green to total" water consumption, alternative
281 5 with greater volume of green water is ranked more favourably in comparison with alternative 3, although
282 alternative 5 consuming more blue water. This stems from the crop patterns with different ability to extract soil
283 water content (green water) for alternative 5 compared to alternative 3.

284

Table 2 Total water consumption for different alternatives

285

286 **4.2. Optimal crop area**

287 As mentioned earlier, one of the decision variables that is optimized during the optimization process is crop
288 pattern, which can vary from one agricultural sector to another. Table 3 details the optimal crop patterns for
289 alternatives 4 and 5 as the least and most water consuming alternatives, respectively. Each crop pattern consists
290 of 6 summer and 4 winter crops (10 total), which are selected among 9 summer crops and 7 winter crops. In this
291 table, Spinach as a winter crop is not considered in any of the crop patterns calculated for different sectors.

292

Table 3 Optimal crop pattern in different agricultural sectors for alternatives 4 and 5

293

294

295 In addition to crop pattern, the cultivation area for each crop also plays a significant role in water consumption
296 in each crop pattern. Figs. 6 and 7 separately compare the total cultivation area for the two previously mentioned
297 alternatives (4 and 5) for summer and winter crops, respectively.

298

Fig. 6 Cultivation area comparison for summer crops for two alternatives 4 and 5

299

300

Fig. 7 Cultivation area comparison for winter crops for two alternatives 4 and 5

301

302

303 As depicted in Fig. 6, summer crops, excluding watermelon, have greater or similar cultivation area in
304 alternative 5 as compared to alternative 4. Also among winter crops (Fig. 7), wheat has a greater area for
305 alternative 4 than alternative 5, but canola with the same monthly water consumption and longer cultivation period
306 increases water demand (total water consumption, Table 2) for alternative 5. Note that crop area for canola in
307 alternative 4 and kidney bean in alternative 5 are 56 and 0 hectares, respectively.

308 Also total cultivation area for alternatives 4 and 5 are 24,018 hectares and 26,442 hectares, respectively (Table
309 4). Hence, alternative 5 is expected to have a greater amount of water consumption in comparison with alternative
310 4. As mentioned earlier, maximum cultivable area in sectors 1, 2 and 3 are 2,000, 7,000 and 10,000 hectares,
311 respectively.

312

Table 4 Cultivation area (hectares) for different agricultural sectors and alternatives

313

314 **4.3. Agricultural benefit**

315 Maximizing agricultural benefit is the objective of each agricultural sector (followers). Since all followers
316 make their decisions simultaneously, the Nash-Harsanyi bargaining method has been used to formulate their
317 objective functions. Fig. 8 shows the agricultural benefit for different sectors and alternatives, with alternatives 3
318 and 4 yielding the most and the least benefits, respectively. Total crop area for alternatives 3 and 4 are 30,245
319 hectares and 24,018 hectares, respectively (Table 4). In addition to several factors such as crop yield, crop price,
320 cultivation cost and water price, the total crop area is the main factor in the followers' benefit.

321

Fig. 8 Agricultural benefit (10^6 \$) for different sectors and alternatives

322

323 Fig. 8 also shows that comparing each sector, the benefit of alternative 3 is greater than that of alternative 4.
324 For alternatives 1 and 5 with almost the same total cultivation area (Table 4), the difference in benefit is about 12
325 million dollars, which is attributed to the crop patterns for alternative 1 that have lower water consumption (Table
326 2), lower costs (cultivation area and water price), and finally greater cultivation area for the more expensive crops
327 with greater yield (Table 5).

328

Table 5 Average agricultural benefit (\$/ha) for alternatives 1 and 5

329

330

331 In this table, the parameters "Cost", "Y.P" and "Water-price" are calculated as weighted average of the
332 cultivation area for each crop. Also the parameter "Water allocation" (m^3/ha) is calculated through dividing the
333 agricultural water allocation (Table 2) by the total cultivation area (Table 4) for each alternative.

334

335 **4.4. Agricultural water price**

336 The agricultural water price for each crop can vary in different sectors for a specific alternative. The water
337 price depends on the divergence from ideal cultivation area, "the area which satisfies the demand for that crop",
338 and the initial prices, which are set to \$0.05, \$0.0625 and \$0.075 for sectors 1, 2 and 3, respectively. The
339 parameters "ideal area" and "initial price" are used to determine the water price function for each crop. The

340 objective function also calculates the lowest water price associated with the ideal cultivation area for each crop.
341 As an example, the values of water price in different sectors for alternative 1 are compared to each other in Figs.
342 9 and 10, for the summer and winter crops, separately.

343

Fig. 9 Water price for summer crops in different agricultural sectors based on the results of alternative 1

344

345

Fig. 10 Water price for winter crops in different agricultural sectors based on the results of alternative 1

346

347 Among summer crops (Fig. 9), corn in sector 3 has the highest water price, because of higher divergence from
348 the ideal cultivation area (greater ratio of cultivation area to the ideal cultivation area, as in Table 6). Fig. 10
349 depicts the water price for winter crops. Spinach in sector 3 and pea in sector 2 have the highest water prices
350 among other crops. As illustrated in Table 7, the main reason for this behaviour is divergence from the ideal
351 cultivation area for these crops. It is worth mentioning that the higher water prices lead to less benefit for the
352 agricultural sectors, although this can lead to maximizing the leader's profit as one of its objectives. Hence, it is
353 rational that the model calculates some cultivation areas with a higher water price.

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Table 6 Ratio of cultivation area to the ideal cultivation area (hectares) for summer crops based on the results
of alternative 1

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Table 7 Ratio of cultivation area to the ideal cultivation area (hectares) for winter crops based on the
results of alternative 1

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358 These results are only comparable to that of Safari et al. (2014) to some extent, given the difference of adopted
359 methodology. Safari et al. (2014) optimized water price for different users (domestic, industrial and agriculture)
360 and crops using historical cultivation area for different crops. They, however, did not consider any water price
361 function for the users and crops. In addition, they did not optimize the cultivation area. In our study, both water
362 price function and crop area optimization have been considered. A key strategy to manage cultivation area to serve
363 regional needs for each crop is to set water price as a function of the ratio of cultivation area to ideal cultivation
364 area.

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366 **5. Conclusion**

367 In this study, a non-cooperative game theory model was developed to optimize agricultural water allocation and
368 crop cultivation area. Considering the bi-level decision making nature of the problem, a Leader – Follower game
369 was applied with Iran Water Resources Management Company as the leader and agricultural sectors as the
370 followers. Two defined objective functions for the leader are (i) maximizing profit gained from selling water to
371 the agricultural sectors, and (ii) maximizing the ratio of “green water to total water” consumption through selecting
372 the most efficient crop patterns. Since the followers’ behaviour is non-cooperative and they make their decisions
373 simultaneously, their objective functions, i.e. maximizing benefits for the selected crop patterns, are formulated
374 based on the Nash-Harsanyi bargaining solution method. The developed optimization model is solved by the
375 multi-objective genetic algorithm (NSGA-II) approach linked with an internal GA optimization model that
376 maximizes the benefit of the followers. The proposed methodology is applied to the Narmab irrigation network
377 in Golestan province in Iran to examine the model’s performance. The results show that the leader’s profit is
378 affected by crop pattern and crop area as two factors that also influence the agricultural water price. The alternative
379 with the highest total water consumption is not identical to the one for which the highest blue water was allocated
380 (Table 2), because the ratio of “green water to total water” consumption (i.e. leader’s second objective) affects
381 the total water consumption. This ratio plays a significant role in selecting the optimal crop pattern and crop area,
382 through which it also affects the followers’ benefits. Note that optimal crop pattern and crop area are functions of
383 crop yield, cost and agricultural water price. Future studies can develop a stochastic model to consider uncertain
384 parameters such as water availability and green water content (dependant on precipitation). Furthermore, an agent-
385 based model could be developed to account for the role of interactions among agents in determining crop pattern
386 and area allocation.

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502 **Table 1** Values of leader's objective functions and total water allocation for different alternatives

Alternative	Leader's Income (10 ⁶ \$)	Green-water/total water consumption	Total water allocation
1	11.9	0.361	97.67
2	11.7	0.363	98.05
3	10.2	0.371	107.12
4	12.3	0.340	100.11
5	8.8	0.411	102.72

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505 **Table 2** Total water consumption for different alternatives

Alternative	Obj.2 *	Agricultural water allocation (MCM)	Net irrigation (blue) water (MCM)	Green water (MCM)	Total water consumption (MCM)
1	0.361	97.67	48.83	27.59	76.42
2	0.363	98.05	49.02	27.94	76.96
3	0.371	107.12	53.56	31.59	85.15
4	0.340	100.11	50.06	25.79	75.84
5	0.411	102.72	51.36	35.84	87.20

506 *Obj. 2 is the maximum green water to total water consumption ratio

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508 **Table 3** Optimal crop pattern in different agricultural sectors for alternatives 4 and 5

Alternative	Crop															
	Summer Crops								Winter Crops							
	R	C ₁	C ₂	S ₁	P ₁	T	M	W ₁	C ₃	P ₂	W ₂	O	B	C ₄	K	
4	1,2,3	2	3	1,2,3	1	1,3	1,2,3	2,3	1,2	3	1,2,3	1,2	1,2,3	1,3	2	
5	2,3	1,2	3	2,3	1	1,2,3	1,2,3	1,2,3	1	3	1,2,3	1,2,3	1,2	1,2,3	-	

509 R: Rice, C₁: Cotton, C₂: Cucumber, S₁: Soybean, P₁: Potato, T: Tomato, M: Mung bean, W₁: Water Melon, C₃:

510 Corn, P₂: Pea, W₂: Wheat, O: Onion, B: Barley, C₄: Canola, K: Kidney bean

511 1: Minoo Dasht agricultural sector, 2: Azad Shahr agricultural sector, 3: Gonbad Kavoos agricultural sector

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Table 4 Cultivation area (hectares) for different agricultural sectors and alternatives

Alternative	Agricultural Sector 1		Agricultural Sector 2		Agricultural Sector 3		total
	summer crops	winter crops	summer crops	winter crops	summer crops	winter crops	
1	1999	1696	4150	6094	5288	6919	26147
2	1990	1762	3449	4787	4939	8869	25795
3	1992	2000	4188	6954	5337	9774	30245
4	1610	1966	3338	3699	5155	8251	24018
5	1929	1864	3801	6765	4852	7231	26442

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Table 5 Average agricultural benefit (\$/ha) for alternatives 1 and 5

Alternative	Cost*	Y.P*	Water-price	Water allocation (m ³)	Water-Cost	Benefit
1	273.72	3961.62	0.11	3735.39	419.30	3268.60
5	312.50	3387.08	0.08	3884.70	327.29	2747.29

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*Y, P and Cost are yield (kg/ha), crop price (\$/kg) and cultivation cost (\$/ha), respectively

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522 **Table 6** Ratio of cultivation area to the ideal cultivation area (hectares) for summer crops based on the results of

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alternative 1

Agricultural Sector	Crop								
	R	C ₁	C ₂	S ₁	P ₁	T	M	W ₁	C ₃
1	0.43	1.93	0	1.89	1.35	5.48	0	0	9.07
2	0.29	2.94	2.80	0	0.91	0	0	0.31	5.10
3	0.20	4.38	1.36	0	0	3.21	3.65	0	11.10

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R: Rice, C₁: Cotton, C₂: Cucumber, S₁: Soybean, P₁: Potato, T: Tomato, M: Mung bean, W₁: Water Melon, C₃:

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Corn

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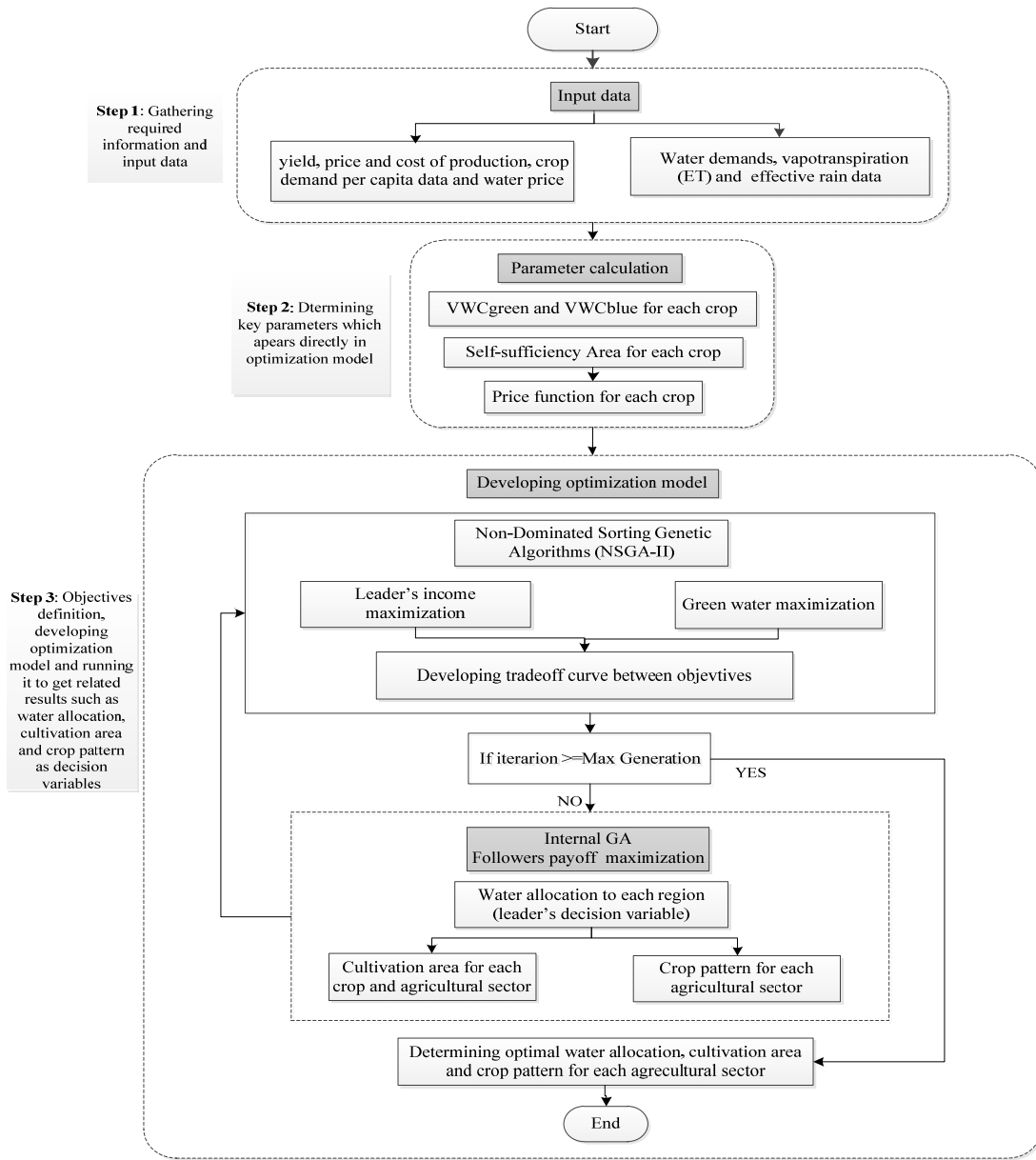
529 **Table 7** Ratio of cultivation area to the ideal cultivation area (hectares) for winter crops based on the results
 530 of alternative 1

Agricultural Sector	Crop						
	P ₂	W ₂	O	B	S ₂	C ₄	K
1	6.93	0.85	0	0	0	0.02	3.83
2	11.86	0.77	0	1.61	0	0.63	0
3	0	0.67	0	0	6.30	0.16	1.95

531 P₂: Pea, W₂: Wheat, O: Onion, B: Barley, S₂: Spinach, C₄: Canola, K: Kidney bean

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Fig. 1 Flowchart of the proposed non-cooperative optimization model for water and crop area allocation based



on leader-followers game



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Fig. 2 Location of the study area in Iran

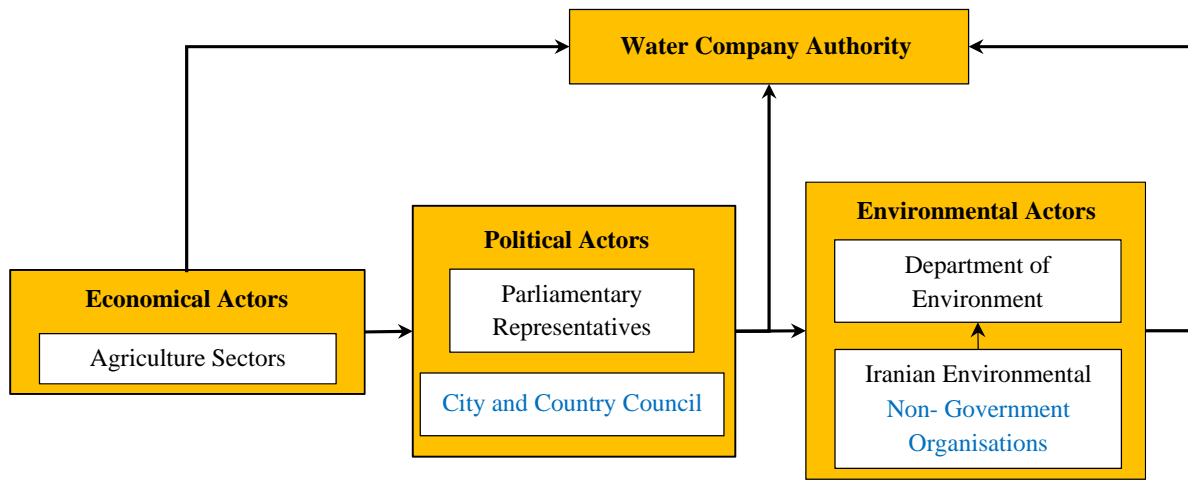
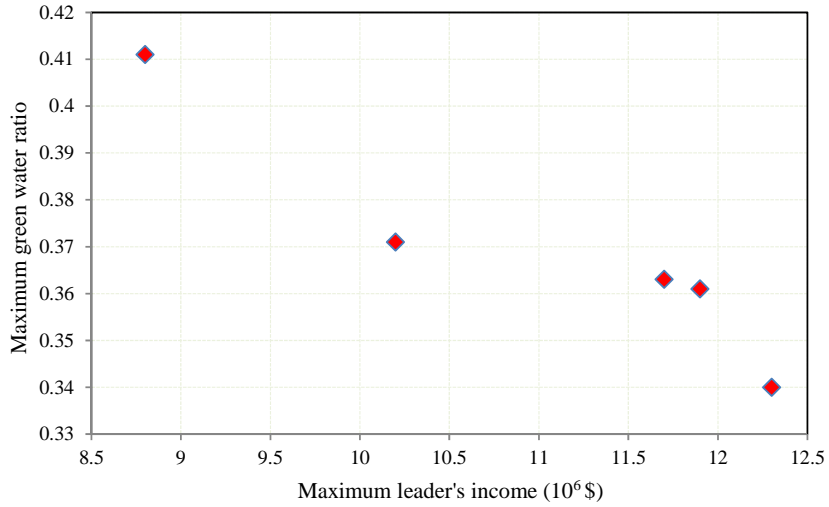


Fig. 3 Interactions between different stakeholders (players) in the study area



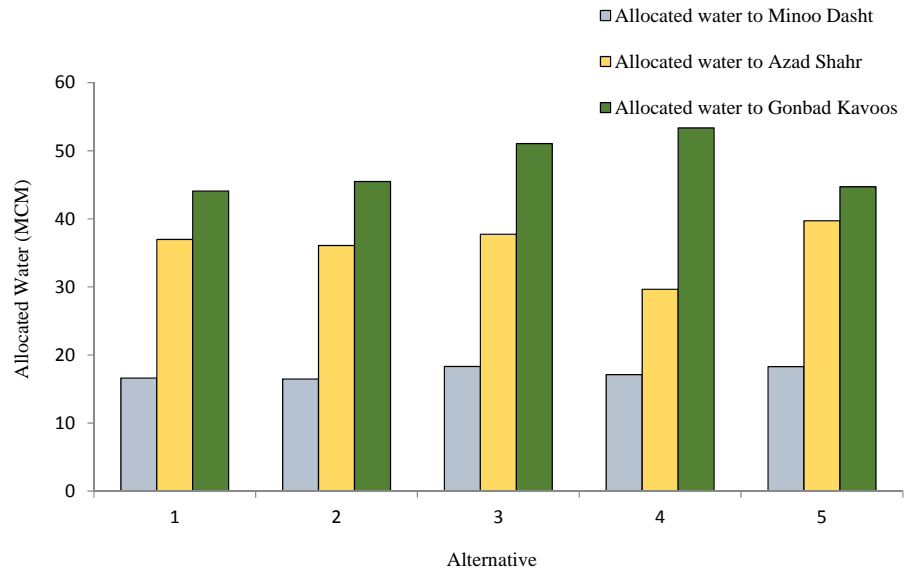
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Fig. 4 Pareto front solution points as a result of running multiobjective genetic algorithm

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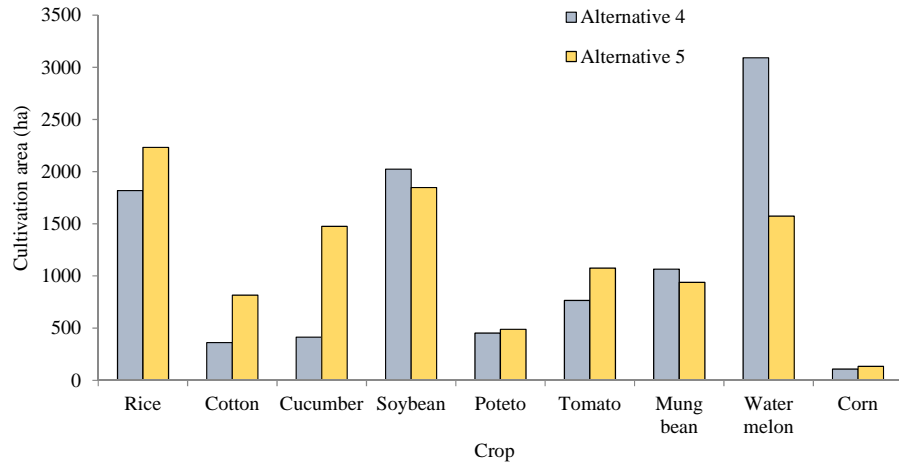
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Fig. 5 Agricultural water allocation to the different agricultural sectors (MCM)



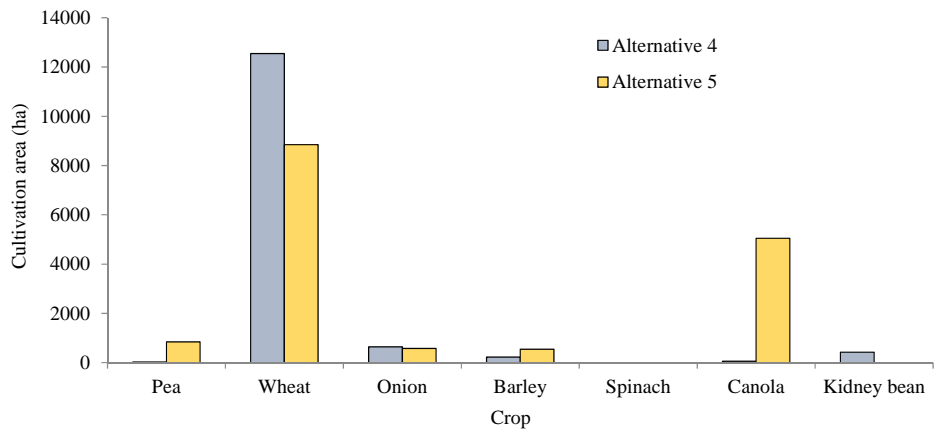
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Fig. 6 Cultivation area comparison for summer crops for two alternatives 4 and 5

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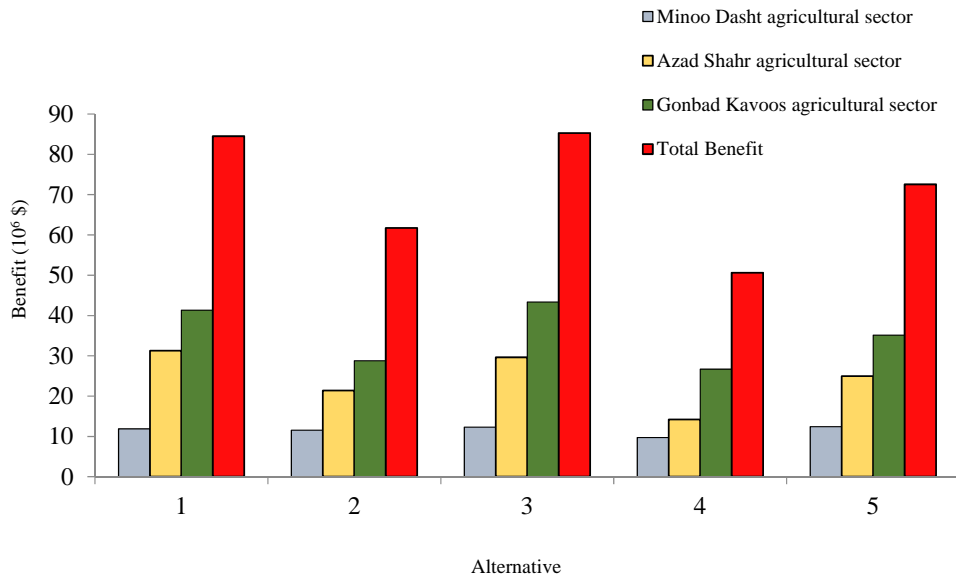
Fig. 7 Cultivation area comparison for winter crops for two alternatives 4 and 5

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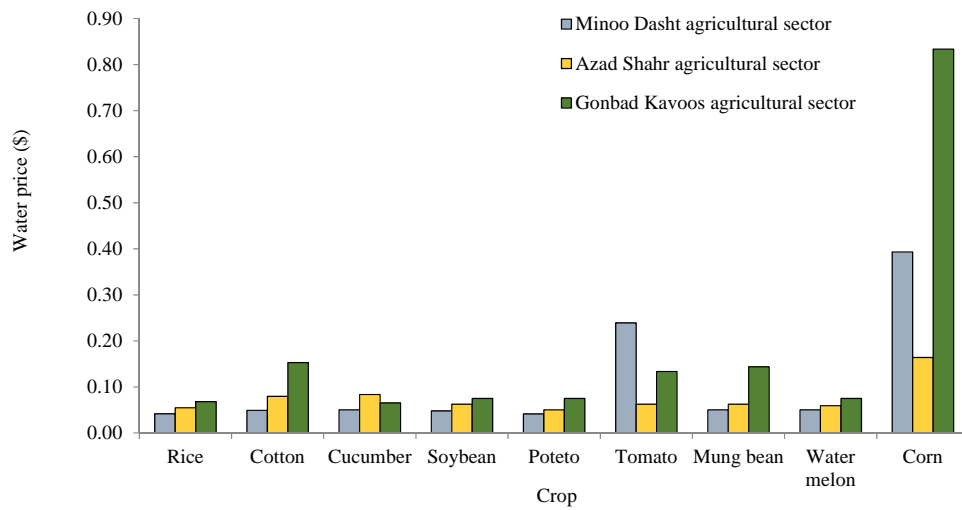


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Fig. 8 Agricultural benefit (10^6 \$) for different sectors and alternatives

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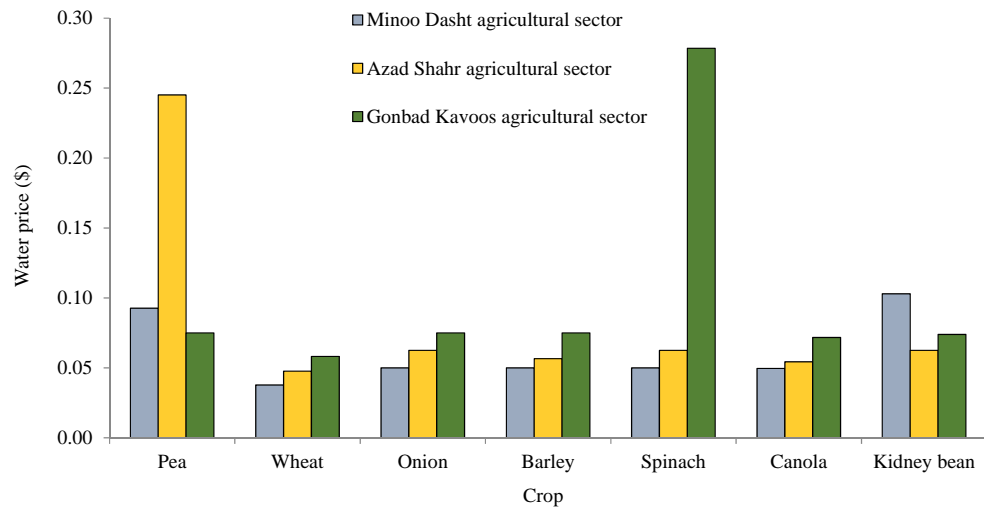
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Fig. 9 Water price for summer crops in different agricultural sectors based on the results of alternative 1

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Fig. 10 Water price for winter crops in different agricultural sectors based on the results of alternative 1