Determining the economic value of surface water quality improvements to trout farmers

Ashraf Sadat Kariman, Lida Salimi and Shervin Jamshidi

ABSTRACT

Water quality exerts certain effects on fish farming. This study determined the economic value of strategies for improving surface water quality to trout farmers, with such economic valuation regarded as a decision-making approach for further development. For this purpose, the Kabkian River in southwest Iran was sampled and simulated using QUAL2 K. Here, the dissolved oxygen (DO) profiles of the river under four waste load allocation (WLA) scenarios were obtained. The economic value of water under each of the scenarios was estimated with respect to the net incomes of farmers, DO deficit, and probable losses due to water degradation. Analytical results indicated that the WLA scenarios only slightly increased the economic value of water which minimally compensates for treatment costs. Therefore, implementing strict standards and using advanced technologies for wastewater treatment are uneconomical approaches. Despite the profits generated by increased water allocation for developing fish farms, this strategy is also unfavorable because it degrades the self-purification potential of rivers and reduces the economic value of water in vulnerable areas. The findings indicated that the optimal solutions are to recycle fish farm discharges and implement moderately intensive treatment that preserves water quality and stabilizes the economic value of water at US$0.027/$m^3$.

Key words | dissolved oxygen, economic value, fish farming, river, water quality

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INTRODUCTION

As a natural resource, water has numerous applications, such as use for drinking and sanitation, irrigation and food production, energy generation, industrial fabrication, recreation, and ecosystem conservation. Each application presents a value that reflects the importance of water to society, including its enabling of economic activities and societal functions related to health and its potential value as a resource (Weerdmeester *et al.* 2016). In sanitation, for example, the value of water is indiscernible on the basis of health expenditures, but it can be clearly calculated in energy generation or industrial production (Reneses *et al.* 2016).

An increasing number of scientific studies regard economic value as an objective in modeling and decision-making for water allocation (Giannoccaro *et al.* 2016; Graveline 2016; Maas *et al.* 2017). Qureshi *et al.* (2016) used this concept to identify economic crops for irrigation. Kauffman (2016) calculated the economic value of the Delaware River Basin to show that this water body is worthy of investment and that its value should be considered in decision-making and restoration policies. Economic valuation has also been directed toward water quality. Viscusi *et al.* (2008) estimated the economic value of water with respect to its quality and found that water quality degradation over a period of 6 years in the USA equals an economic value of US$20 billion. Dodds *et al.* (2009) reported that eutrophication in lakes annually costs US$2.2 billion to the properties located in lake vicinity in the USA, but also suggested that further research be

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conducted on fish populations for improved cost estimations. Dehnhardt (2017) classified the concepts of economic value analysis for water quality improvements and calculated the total benefits of different scenarios on river development in Germany. What is inferred from the concepts is that the economic valuation of water quality improvements should be conducted on the basis of policies that are suitable for user requirements. Such an approach was adopted by Crutchfield *et al.* (2016), who reported that the economic value of drinking water with respect to nitrate concentrations can be calculated on the basis of customers' willingness to pay for measures to reduce adverse health exposure.

Quality may likewise affect the economic value of water for fish production because it affects both production efficiency and treatment cost. If the quality of water in streams and rivers diminishes, aquaculture is harmed and fish populations decrease (Ma *et al.* 2012). These problems, in turn, reduce the market value of water to fish farmers. In a series of studies, Besson *et al.* (2016a, 2016b) concluded that temperature, dissolved oxygen (DO), and nitrogen constrain the production cycle, thereby affecting the economic profits of fish farmers. The authors recommended genetic improvements to solve the aforementioned problems. Lafferty *et al.* (2015) highlighted case studies to demonstrate the relevance of marine diseases on the growth of commercial species and the economic value of aquaculture. The examples emphasized the economic valuation of the quality of water for fish production with respect to the incomes of users for better decision-making.

Accordingly, the current study was aimed at identifying the relationship between surface water quality improvements in the form of waste load allocation (WLA) policies and the economic value of water quality to fish farmers. Specifically, we were interested in illuminating the extent to which WLA policies can increase the economic value of water to fish farmers. The other applicability is to draw a baseline for these emission sources which derives from both issues of self-purification potential of river and economic valuation. We determined the extent to which the use of wastewater treatment facilities and growth of fish farms are economical, particularly in rural areas inhabited by low-income stakeholders. To these ends, we chose the Kabkian River in Iran as a modeling case study.

METHODS

Study area

The Kabkian River is a tributary of the Karoon River and is located in southwest Iran near Yasooj, Kohgiluye Province, where the average annual temperature is 12 °C. The land use types in the area are mainly paddy fields and trout farms, mostly brown species. The flow rate of the river ranges from 1.5 to 2 m^3/s. It is 21 km long and divided into two main zones: the upstream zone is populated primarily by fish farms that are directly connected to the river, whereas the downstream zone is occupied by paddy fields and residential areas such as villages. In the simulation, fish farms and rural areas falling within a perimeter of less than 200 m were clustered and regarded as point sources (P1 to P11), whereas paddy fields were treated as diffuse sources (NP1 to NP3). To estimate the overall pollution loads (ton/year) of the point and diffuse sources, we determined the concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and total nitrogen (TN) in discharges sampled over a year. The annual average concentrations of these parameters were then multiplied by the flow rate of effluent discharges equal pollution loads. The results are shown in Table 1.

Table 1 | Overall pollution loads of emission sources in the study area

Polluter	Location (km)	BOD (ton/yr)	COD (ton/yr)	TKN (ton/yr)	TN (ton/yr)
P1	20.5	50.5	79.2	0.31	5.42
P2	19.8	41	61.5	0.34	3.27
P3	19.6	25.2	53.6	0.48	4.50
P4	18.3	2.6	3.6	0.43	1.07
P5	17.6	25.2	43.2	0.17	4.06
P6	16.2	31.5	53	0.27	3.8
P7	15.8	34.7	58.3	0.31	4.21
P8	15.1	34.7	58.3	0.31	4.21
P9	10.4	15.1	21.4	2.52	6.31
P10	1.9	3.8	5.4	0.63	1.58
P11	0.5	33.1	56.1	0.11	9.73
NP1	[11–21]	4.5	6.8	0.03	14.8
NP2	[3.5–10.8]	7.1	10.7	0.05	23.2
NP3	[0–3.3]	2.3	3.5	0.02	7.53

Sampling and tests

To estimate the pollution loads and calibrate the modeling of water quality, we selected 11 stations as checkpoints for point-source effluent discharges and nine stations in river for 12-month sampling. The samples were analyzed online for DO concentration, pH, electroconductivity, and total dissolved solid concentration; the samples were then tested in a laboratory for other required modeling parameters in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA 2005). The threshold of water quality for WLA policy implementation in trout farming was derived from national standards (Shilat 2013), in which the minimum allowable DO concentration is 6 mg/L and the maximum allowable BOD, COD, nitrate, nitrite, ammonia, and sulfate concentrations are 5, 10, 400, 0.1, 0.03, and 50 mg/L, respectively.

Modeling

The river was divided into 16 reaches, and its water quality was simulated using QUAL2 K (version 5.1) to extract the DO profile (Kannel *et al.* 2007). The hydraulic characteristics, with specifications regarding headwater, pollution discharges, and initial conditions, were incorporated into the software (Table 2). Calibration was carried out using the auto-calibration tool of QUAL2 K for the samples taken from nine stations. On the basis of the calibration, the aeration coefficients (K_a) of the river were calculated (Table 2). The weighted root mean square coefficient of variation was 0.25, which is equivalent to an auto-calibration fitness function of about 4. The calculations were modeled using the Runge–Kutta method with 100 iterations (Chapra *et al.* 2008).

In the model, the Streeter–Phelps equation (Equation (1)) is used to draw the DO profile (Chapra 1997). Because Kocer *et al.* (2013) found that the effluent DO concentration of fish farms is sensitive to carbonaceous and nitrogenous BOD, the average DO concentration in fish ponds (D_f) is calculated using Equation (2):

$$D = D_{sat} - D_0 e^{-K_a t} + \frac{K_d \times L_{BOD}}{K_a - K_r}\left(e^{-K_r t} - e^{-K_a t}\right) + \frac{K_n \times L_N}{K_a - K_n}\left(e^{-K_n t} - e^{-K_a t}\right) \quad (1)$$

Table 2 | Hydraulic characteristics of the river's reaches

Reach no.	Length (km)	Slope (%)	Velocity (m/s)	Ka (d^{-1})
1	0.50	0.4	0.27	5.6
2	0.70	0.71	0.38	7.7
3	0.30	1	0.52	8.9
4	1.20	0.63	0.50	6.4
5	0.80	0.69	0.52	6.9
6	1.00	0.4	0.42	5.2
7	0.30	0.67	0.51	6.8
8	0.50	0.6	0.54	6.3
9	0.60	0.5	0.51	5.7
10	0.70	0.29	0.46	4.0
11	2.00	0.15	0.28	3.2
12	2.00	0.55	0.50	6.3
13	7.00	0.73	0.59	7.2
14	1.50	0.33	0.46	4.6
15	1.40	0.14	0.36	2.8
16	0.50	0.4	0.40	3.6

$$D_f = D - 0.5[(\alpha \times L_{BOD}(1 - e^{(-K_d t_p)})) + (\beta \times TKN(1 - e^{(-K_n t_p)}))] \quad (2)$$

where D is the concentration of DO (mg/L) in the examined water body; D_{sat} denotes the ultimate DO (mg/L) saturated in the river, determined on the basis of air temperature, air pressure, and water salinity content; D_0 represents the initial concentration of DO (mg/L) in the upstream zone of the river; K_d, K_n, and K_a are the coefficients related to organic (BOD) degradation, nitrogen oxidation, and aeration rate, respectively; K_r incorporates both organic degradation and the settling of suspended solids; and L_{BOD} and L_N refer to the concentrations of carbonaceous BOD and nitrogen (mg/L) that reduces DO, respectively. The coefficients of α and β are set to 2.67 and 4.57, respectively, following the recommendations of Chapra (1997). *BOD* and *TKN* are equal to their concentrations, and t and t_p are the travel times of water in rivers (reaches) and ponds, respectively. The latter is assumed to be 2 hours for a typical fish farm in the study area with an inflow of 0.1 m^3/s and an annual capacity of 55 tons of fish production.

Scenario definitions

This study investigated the effects of four water management policies on the economic value of water to fish farmers. In the first two policy scenarios, the imposition of total maximum daily loads is indicated as falling under WLA strategies. In the first scenario (S1), the baseline is 45% BOD and TKN removal from all pollutants, whereas in the second scenario (S2), the removal rate is 90%. These two scenarios focus only on the effects of water quality enhancement on the river and, consequently, on fish farm production. The third scenario (S3) is aimed at determining what may happen if, as in S1, effluents from fish farms are recycled and reused for paddy field irrigation or fish farm expansion. In this scenario, the potential volume of effluent for recycling in watersheds is assumed to be 0.5 m^3/s. In the fourth scenario (S4), the entire capacity of the river (1.2 m^3/s) is allocated for the development of fish farming in the study area. This strategy is termed 'full water allocation' in this work. The last two scenarios consider the effects of water quantity and quality on decision-making.

Economic value analysis

To determine the economic value of water to fish farmers and the role that its quality plays in total production, we developed questionnaires designed to identify the relationship between water quality (DO) and total fish production. These questionnaires were filled out by the owners of fish farms whose net incomes do not exceed 25% of total incomes as a matter of operating and maintenance costs. The farmers were asked about their production yields and annual losses (ton/year), their incomes and expenditures, feeding processes, and water consumption rates. Water consumption rate was determined by referring to flow meters installed at discharge points. The net production of the fish farms in the different zones of the river fell between 35 and 50 tons/year. The spatial variations in the total losses of the fish farms located along the river can explain the role of water quality in the water's economic value with respect to the total incomes of the fish farmers.

The economic value of water to fish farmers in each scenario is calculated using Equation (3):

$$EV_i = \frac{(dP + P_0)_i P_r}{Q_i} - C_i \quad (3)$$

where EV represents the economic value and equals the net income (US\$/m^3); P_0 is the current productivity of the fish farms; P_r denotes the market price, which equals a gross annual income of about US\$2,850/ton; Q is the average flow rate of each fish pond (m^3/year); and C refers to organic abatement costs. Equation (4) is used, as recommended by Jamshidi & Niksokhan (2016), to calculate the total costs of organic matter removal from the point sources of small catchments. The variable dP is the difference between total production capacity and present production capacity. This difference is calculated using Equation (5):

$$C = \omega(1.7x^2 + 0.9x + 0.1) + \gamma(-2.8y^3 + 4.1y^2 - 0.3y) \quad (4)$$

$$dP_i = (F.P_m - P_0)_i \quad (5)$$

where x and y are the BOD and nitrogen removal efficiency levels in S1 and S2 and is equal to 0.45. In S1 and S2, ω and γ equal 1, whereas in S3, these variables have a value of 1.5 and 0, respectively. This difference is due to the fact that in times of reuse, nitrogen removal is not necessary, but high aeration is required for increased BOD removal. This approach is recommended for estimating the cost functions of advanced treatments in times of recycling and reuse by Jamshidi *et al.* (2014). The variable P_m is the maximum production capacity of the fish farms and equals 55 tons/year. The variable F is the yield factor that considers both water quality and quantity issues in fish production and is calculated using Equation (6):

$$F = Y \times q \quad (6)$$

where Y represents losses in fish production due to low water quality and equals the ratio of P_i to P_m, and q indicates the potential production development as a matter of increased water availability. This potential production development equals the ratio of total available water for allocation to the current water allocation.

RESULTS AND DISCUSSION

Water quality analysis

The calibrated model can be used to draw the predicted DO profiles (Figure 1) under the different WLA scenarios. These profiles revealed that the upstream zone of the river exhibits relatively higher DO concentrations than does the downstream zone and is minimally sensitive to artificial aeration in fish farms, as similarly discussed by Jamshidi *et al.* (2015). However, degraded organic matter (BOD and TKN), coupled with pollutant discharge along the river, can gradually reduce DO content, as evidenced by the DO level being lower than 7 mg/L in the last 15 km of the river. This result also showed that the WLA strategies in S1 and S2 exert stable effects on the DO profiles of the river. The strategies may increase DO concentration by 14% and maintain concentration at levels greater than 7.2 mg/L. Compared with the strategies in S1, the recycling and reuse of treated effluents in S3 can slightly downgrade water quality because recycling may increase contaminant concentration through the entire chain of production. Nevertheless, recycling relatively reduces the requirement for more water allocation. This reduced requirement amplifies the robustness of river water quality against headwater variations in comparison with the sensitivity levels observed in the other WLA scenarios. Increasing the allocation of water for the development of fish farming (S4) dramatically reduces the self-remediation potential and dilution effect of the river, as predicted by the model. Consequently, the DO level decreases significantly in the upstream zone of the river but is gradually restored in the downstream zone.

Productivity analysis

The predicted DO profiles can draw attention to river zones that present a high potential for use in fish farming. The samples, the field studies, and the questionnaires gathered from the fish farm owners revealed that the DO deficit in tanks correlates with total losses. Equation (7) illustrates a logarithmic trend line that relates DO (mg/L) to the productivity (%) of fish farms. This logarithmic trend line was similarly observed by Mallya (2007) and Ellis *et al.* (2002). In the equation, P represents the productivity of fish farms (%) and D_f was previously defined in Equation (2):

$$P = 129.7Ln(D_f) - 171.2 \ (0 \leq P \leq 100) \tag{7}$$

Equation (7) shows that the potential for fish production in regions with low DO content is weaker than that in areas

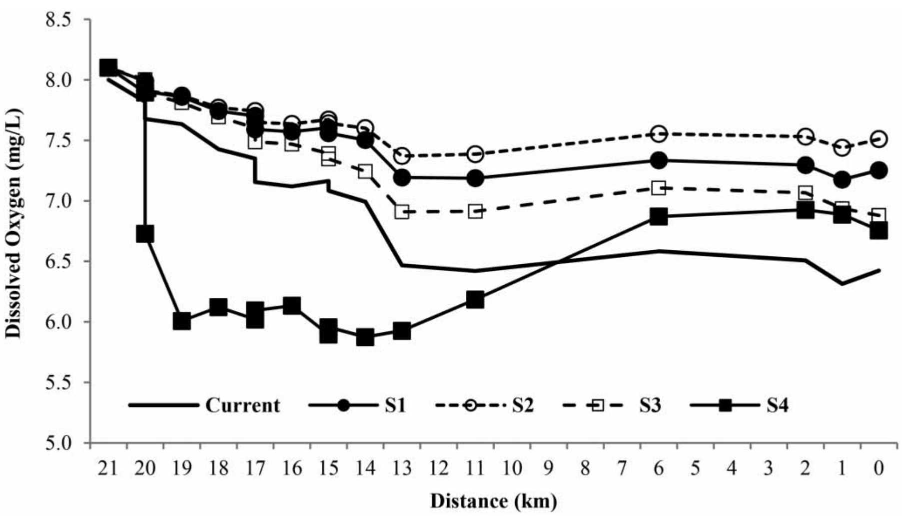

Figure 1 | DO profiles of the river under four management scenarios. S1: WLA with 45% organic matter removal; S2: WLA with 90% organic matter removal; S3: S1 with limited reuse; S4: S3 with full river water allocation.

with high water quality. This issue indicates that the losses (%) incurred by fish farms located along the river can be predicted with respect to the DO profile and that the economic value of water can be estimated.

Figure 2 combines the results of Figure 1 and Equation (7) for the four scenarios. The figure outlines the possible losses (%) incurred by fish farms under different environmental management strategies from a water quality perspective. The figure also shows that fish farms located at the first 5 km of the river experience losses of less than 20%, whereas fish farms located downstream encounter losses of up to approximately 35%.

Determining WLA is an efficient means of extensively reducing the losses incurred by fish farms and consequently increasing the economic value of water. For example, S1 and S2 can reduce average productivity losses from 25% to 12.6% and 10%, respectively. S3, however, may lead to relatively lower water quality and higher losses (16%). S4 clearly degrades water quality, reduces the self-purification potential of the river, and increases average losses to 32.8%. Losses vary from 26% to 46% from the end of the streamline to the middle because of the high water allocation to fish farms located upstream of the river and the effluent recharge downstream of the river. In S3 and S4, the total potential for fish production can be compensated by water recycling and reuse and full water allocation. These strategies may provide an opportunity to further develop fish farms in the area.

Figure 3 summarizes the estimations of total production potential on the basis of water quality and quantity. Interestingly, an increase in water allocation from 50% to 80% would reduce overall production potential by about 5 to 8 tons in fish farms located between 20 and 15 km from the terminus point in comparison with current conditions. Total productivity would also be insignificant downstream of the river, indicating that increasing the number of fish farms and allocating more water to these farms would not necessarily extend the incomes of residents because of the higher pollution discharges and possible losses caused by this strategy. Specifically, the average productivity of fish farms would decrease by about 11 tons because of water quality issues; increased water availability would elevate overall production by about only 15 tons.

Provided that fish farms remove 45% of organic matter from discharges (S1), overall productivity slightly increases, but this level remains unacceptable from an economic point of view. On average, the water quality degradation and full water allocation in S1 may lead to a 5 ton reduction in production; high water allocation provides an opportunity for fish farms to produce more than 18.5 tons of fish.

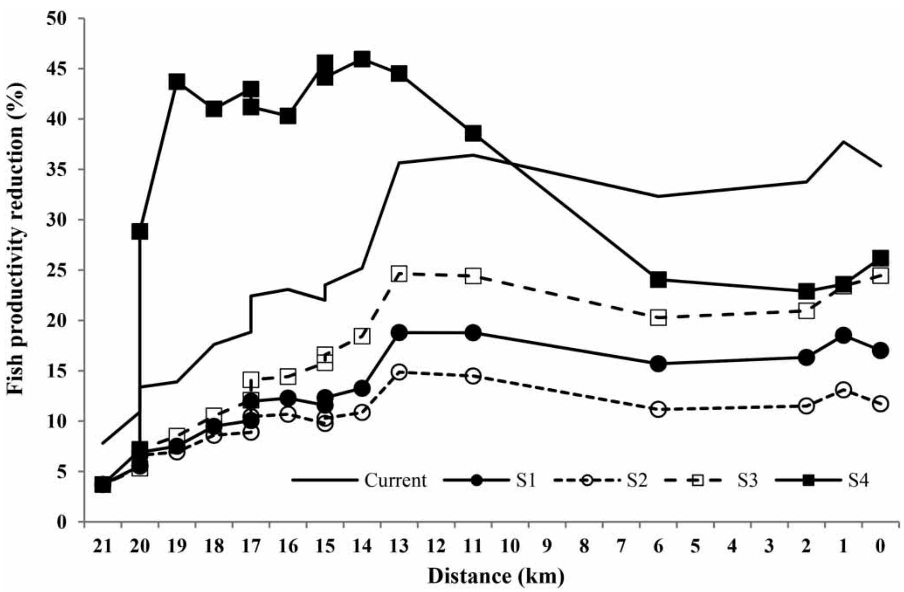

Figure 2 | Productivity reduction (%) profile determined on the basis of DO variations in the river water under four management scenarios. S1: WLA with 45% organic matter removal; S2: WLA with 90% organic matter removal; S3: S1 with limited reuse; S4: S3 with full water allocation.

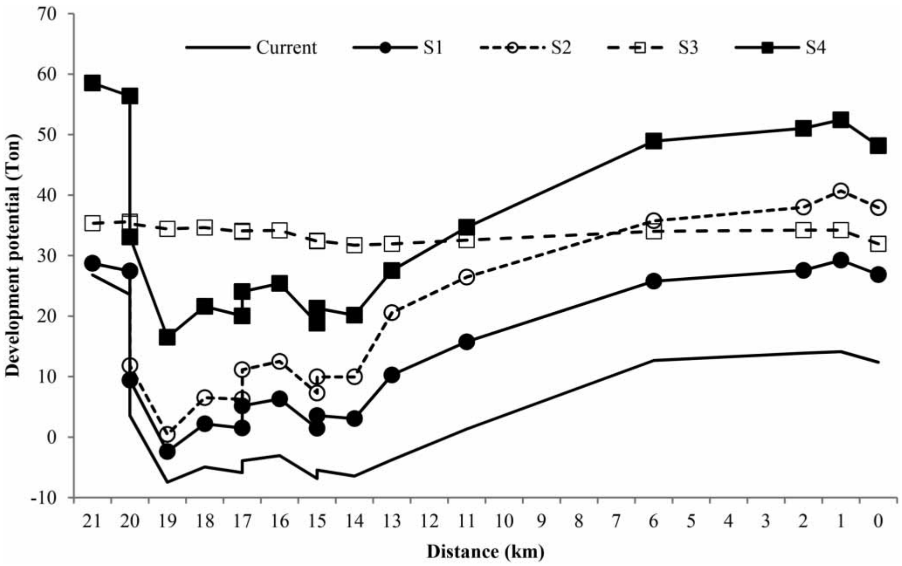

Figure 3 | Total production potential (ton) under different scenarios compared with the current status. S1: WLA with 45% organic matter removal; S2: WLA with 90% organic matter removal; S3: S1 with limited reuse; S4: S3 with full water allocation.

Production reaches 0.2 and 20.7 tons, respectively, in scenario S2. Therefore, a 90% removal of organic matter would be more promising for productivity potential, albeit this measure involves higher abatement costs. As determined using Equation (4), for instance, the organic abatement cost in S2 is 2.35 times higher than that in S1.

S4 similarly follows the productivity trend observed in the other scenarios but presents higher development potential. A comparison of Figures 2 and 3 revealed that the potential offered by S4 comes primarily from water allocation; low water quality inhibits the same potential for the upstream zone of the river. From an environmental protection perspective, S4 cannot be recommended as the best policy even though it is a more promising approach than S3.

Recycling and reuse with 45% organic matter removal (S3) not only drastically increases the development potential of areas with an average productivity of 75 tons but also stabilizes the development potential of fish farms located along the streamline (Figure 3). Water quality can also be improved (Figure 1). The optimal policy (i.e., S3) recommends that no further water allocation be carried out and indicates that recycling with 45% organic matter removal is an appropriate response to environmental and economic concerns.

Economic value analysis

The productivity analysis implied that river water quality has hidden economic value for fish farming. The water quality of the Kabkian River currently has an economic value of US$0.0375/m^3. If the river water is fully allocated for fish farming (1.2 m^3/s), the economic value increases only to US$0.0412/m^3 (9%), suggesting that increased water allocation may not necessarily lead to a higher water value. This limitation is due to the reduced water quality caused by high pollution discharges, the reduction in river flow rate, and the reduction in potential for self-purification. This finding also highlighted the areas with limited potential for development. For example, areas located 13 km from the middle of the river, between 7 and 20 km from the terminus point, would probably achieve a negative economic value through full water allocation. This result points to the fact that the sustainable spatial distribution of fish farms depends on both river water quality and quantity. The economic value of water and environmental standards should be scrutinized prior to selecting fish farm locations. Otherwise, low income from fish farming may increase the entropy of systems given that owners may change their land uses or illegally increase the volume of tanks and water consumption (Imani *et al.* 2017).

Moreover, following the WLA strategies in S1 and S2 may not restore the economic value of water because of consequent high abatement costs. The net income in S1 is limited to US$0.0023/m^3 on average, and that in S2 becomes negative at –US$0.06/m^3 (Figure 4). These findings confirmed that environmental conservation policies implemented through conventional structural methods (e.g., construction and operation of wastewater treatment plants) require considerable investment. Such investment is unsustainable and eliminates economic incentives. Fish farms should therefore either modify their processes for discharging organic loads (i.e., minimize such discharge) or use clustered land-based and economic units for effluent treatment. Phytoremediation systems in the form of filter strips (Imani *et al.* 2017) and constructed wetlands (Turcios & Papenbrock 2014) are recommended for this purpose. In addition, incentive-based strategies are also encouraged to economically support farmers and increase their incomes. Such strategies can be further analyzed with respect to innovative approaches, such as microalgae-based technologies for food and energy production (Castine *et al.* 2013; Posadas *et al.* 2015) or water quality trading frameworks that can be financially supported through taxes and fund reallocations (Feizi Ashtiani *et al.* 2015).

The calculations showed that with recycling and reuse (S3), the economic value of water only slightly decreases to US$0.027/m^3 because these strategies disregard investment in high nitrogen removal (Figure 4). Nevertheless, the total value of the potential of watersheds for fish production (S4) amounts to only US$0.028/m^3, implying that recycling and reuse must be incorporated into WLA policies for the study area to increase the willingness of fish farmers to pay for environmental conservation strategies. Recycling and reuse would be sufficient for the development of fish farming in the study area. By contrast, increasing water allocation for production development is neither economically efficient nor recommended.

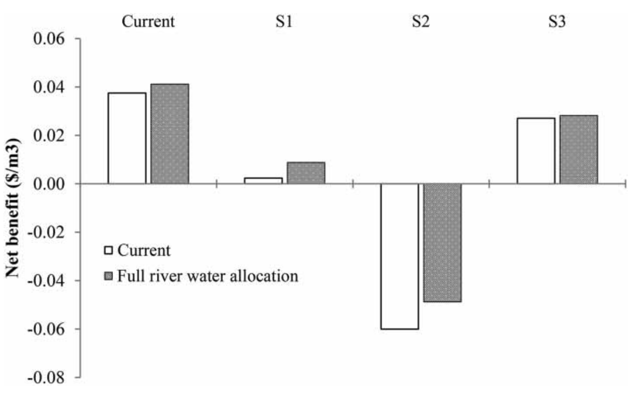

Figure 4 | Economic value of water in different scenarios in current and future horizons. S1: WLA with 45% organic matter removal; S2: WLA with 90% organic matter removal; S3: S1 with limited reuse.

The analysis indicated that water quality improvements and, therefore, environmental management approaches consider both positive and negative economic values. For example, using a WLA policy grounded in a quality perspective increases the economic value of water for fish farming to US$0.043/m^3 (+0.0055) in S1 and US$0.045/m^3 (+0.0075) in S2. These strategies require facility investments of US$0.041/m^3 and US$0.105/m^3, respectively. These values suggest that a robust WLA is one that considers both environmental and economic issues in decision-making. Additionally, strict standards or advanced treatment strategies are not necessarily sustainable from an economic perspective, unless they are coupled with incentives.

CONCLUSION

In this research, the economic value of water to fish farmers under different WLA policy scenarios was calculated with respect to the effects of DO deficit on trout harvest, wastewater treatment, and operating costs. The results showed that DO deficit inhibits the growth of trout and increases overall losses in the harvesting process, thereby limiting the incomes of farmers who are seeking the highest possible benefits. Nevertheless, water quality improvement policies do not necessarily translate to economic profits. For example, the farmers operating in the study area are not wealthy enough to afford high-tech wastewater treatment plants. To consider both affordability and the incomes of fish farmers, we introduced the economic value of water as a tool for decision-making on water allocation and further development. Through this method, we found that an analysis of self-purification potential through surface water quality modeling is required prior to WLA implementation. Such analysis can highlight vulnerable areas and provide a baseline as the total maximum daily load. Our findings also verified that the added value of products harvested under high water allocation would not be significant because of the degradation in water quality and the deterioration of self-purification potential. Thus, the most sustainable solutions for fish farm development are recycling and reuse of discharges, removal of 45% organic matter, and moderately intensive treatment. This policy, to some extent, preserves the environment, reduces abatement costs, provides opportunities for increased production, and ultimately increases the economic value of water.

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REFERENCES

APHA 2005 *Standard Methods for the Examination of Water and Wastewater*, 24th edn. American Public Health Association, Washington, DC.

Besson, M., Aubin, J., Komen, H., Poelman, M., Quillet, E., Vandeputte, M., Van Arendonk, J. A. M. & De Boer, I. J. M. 2016a Environmental impacts of genetic improvement of growth rate and feed conversion ratio in fish farming under rearing density and nitrogen output limitations. *Journal of Cleaner Production* **116**, 100–109.

Besson, M., Vandeputte, M., Van Arendonk, J. A. M., Aubin, J., De Boer, I. J. M., Quillet, E. & Komen, H. 2016b Influence of water temperature on the economic value of growth rate in fish farming: the case of sea bass (Dicentrarchus labrax) cage farming in the Mediterranean. *Aquaculture* **462**, 47–55.

Castine, S. A., McKinnon, A. D., Paul, N. A., Trott, L. A. & de Nys, R. 2013 Wastewater treatment for land-based aquaculture: improvements and value-adding alternatives in model systems from Australia. *Aquaculture Environment Interactions* **4** (3), 285–300. doi:10.3354/aei00088.

Chapra, S. C. 1997 *Surface Water Quality Modelling*. McGraw-Hill, Boston, MA, 378 pp.

Chapra, S., Pelletier, G. & Tao, H. 2008 *QUAL2 K: A Modeling Framework for Simulating River and Stream Water Quality*. Department of Ecology and Tuft University, Medford, MA.

Crutchfield, S. R., Cooper, J. C. & Hellerstein, D. 2016 *The Benefits of Safer Drinking Water: The Value of Nitrate Reduction*, Economic Research Service Agricultural Economics Report Number 752, 62 pp.

Dehnhardt, A. 2017 Value of water quality improvements. In: *German–American Frontiers of Engineering*, 31 March–2 April, Evendale, OH.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Schloesser, J. T. & Thornbrugh, D. J. 2009 Eutrophication of U.S. freshwaters: analysis of potential economic damages. *Environmental Science and Technology* **43** (1), 12–19.

Ellis, T., North, B., Scott, A. P., Bromage, N. R., Porter, M. & Gadd, D. 2002 The relationships between stocking density and welfare in farmed rainbow trout. *Journal of Fish Biology* **61** (3), 493–531.

Feizi Ashtiani, E., Niksokhan, M. H. & Jamshidi, S. 2015 Equitable fund allocation, an economical approach for sustainable waste load allocation. *Environmental Monitoring and Assessment* **187**, 522.

Giannoccaro, G., Castillo, M. & Berbel, J. 2016 Factors influencing farmers' willingness to participate in water allocation trading, a case study in southern Spain. *Spanish Journal of Agricultural Research* **14** (1), e0101. Available from: http://revistas.inia.es/index.php/sjar/article/view/7827/2732.

Graveline, N. 2016 Economic calibrated models for water allocation in agricultural production: a review. *Environmental Modelling & Software* **81**, 12–25.

Imani, S., Niksokhan, M. H., Jamshidi, S. & Abbaspour, K. C. 2017 Discharge permit market and farm management nexus: an approach for eutrophication control in small basins with low-income farmers. *Environmental Monitoring and Assessment* **189**, 346.

Jamshidi, S. & Niksokhan, M. H. 2016 Multiple pollutant discharge permit markets, a challenge for wastewater treatment plants. *Journal of Environmental Planning and Management* **59** (8), 1438–1455.

Jamshidi, S., Niksokhan, M. H. & Ardestani, M. 2014 Surface water quality management using an integrated discharge permit and the reclaimed water market. *Water Science and Technology* **70** (5), 917–924.

Jamshidi, S., Niksokhan, M. H., Ardestani, M. & Jaberi, H. 2015 Enhancement of surface water quality using trading discharge permits and artificial aeration. *Environmental Earth Sciences* **74** (9), 6613–6623.

Kannel, P. R., Lee, S., Kanel, S. R., Lee, Y. S. & Ahn, K. H. 2007 Application of QUAL2Kw for water quality modeling and dissolved oxygen control in the river Bagmati. *Environmental Monitoring and Assessment* **125** (1–3), 201–217.

Kauffman, G. J. 2016 Economic value of nature and ecosystems in the Delaware River Basin. *Journal of Contemporary Water Research and Education* **158** (1), 98–119.

Kocer, M. A. T., Kanyilmaz, M., Yilayaz, A. & Sevgili, H. 2013 Waste loading into a regulated stream from land-based trout farms. *Aquaculture Environment Interactions* **3**, 187–195.

Lafferty, K. D., Harvell, C. D., Conrad, J. M., Friedman, C. S., Kent, M. L., Kuris, A. M., Powell, E. N., Rondeau, D. & Saksida, S. M. 2015 Infectious diseases affect marine fisheries and aquaculture economics. *Annual Review of Marine Science* **7**, 471–496.

Ma, Z., Song, X., Wan, R. & Gao, L. 2012 A modified water quality index for intensive shrimp ponds of *Litopenaeus vannamei*. *Journal of Ecological Indicators* **24**, 287–293.

Maas, A., Dozier, A., Manning, D. T. & Goemans, C. 2017 Water storage in a changing environment: the impact of allocation institutions on value. *Water Resources Research* **53** (1), 672–687.

Mallya, Y. J. 2007 *The Effects of Dissolved Oxygen on Fish Growth in Aquaculture.* Final project, the United Nations University, Reykjavik, Iceland, 30 pp.

Posadas, E., Muñoz, A., García-González, M. C., Muñoz, R. & García-Encina, P. A. 2015 A case study of a pilot high rate algal pond for the treatment of fish farm and domestic wastewaters. *Journal of Chemical Technology and Biotechnology* **90**, 1094–1101.

Qureshi, M. E., Ahmad, M. D., Whitten, S. M., Reeson, A. & Kirby, M. 2016 Impact of climate variability including drought on the residual value of irrigation water across the Murray–Darling Basin, Australia. *Water Economics and Policy*. doi:10.1142/S2382624X15500204.

Reneses, J., Barquin, J., Garcia-Gonzalez, J. & Centeno, E. 2016 Water value in electricity markets. *International Transactions on Electrical Energy Systems* **26** (3), 655–670.

Shilat 2013 *Regulations and Criteria of Fish Farming in Kohgiluyeh Province.* Fisheries Organization, Iran.

Turcios, A. E. & Papenbrock, J. 2014 Sustainable treatment of aquaculture effluents – what can we learn from the past for the future? *Sustainability* **6** (2), 836–856.

Viscusi, W. K., Huber, J. & Bell, J. 2008 The economic value of water quality. *Environmental Resource and Economics* **41**, 169–187.

Weerdmeester, R., Rausa, A., Mulder, M., Kuzmickaite, V. & Krol, D. 2016 *The Value of Water.* WssTP water version 2030, WssTP, Brussels, p. 4.

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