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An approach to develop grey water footprint accounting

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ABSTRACT

Grey water footprint (GWF) is an indicator that represents the water quality issues embedded in producing a product in form of freshwater volume. This indicator converts the pollution loads to the equivalent volume of freshwater with respect to the assimilative capacity of the receiving water body. This study develops the method of accounting multiple-pollutant GWF with ecological perspective. For demonstrating the developed methodology, original samples were taken from trout farms in the Kabkian River, south-western Iran, and the pollution exports are calculated in first step. In the second step, river is modelled for determining the local-oriented water quality standards. Finally, total multiple-pollutant GWF is determined. Here, equations are developed for considering dissolved oxygen (DO) in accounting GWF due to the critical role of this parameter in aquaculture and fish production. In addition, a state-of-the-art coefficient is introduced to alter the formulation for including the environmental issues of receiving water body in accounting GWF. This can provide a framework for considering Eutrophication, saline intrusions, minimum environmental flow and DO deficit of river, in addition to the risks of micropollutants in water footprint assessments. Nevertheless, the results of case study show that GWF is nitrogen-related for trout farming. It equals 195 m^3/ton but it may fluctuate depending on the local development strategies and their consequences on the environmental issues. Consequently, the proposed methodology can broaden the prospect of the application of GWF and enhance the role of environmental capacity in this indicator.

1. Introduction

Grey water footprint (GWF) is an indicator that adds water quality issues in accounting the water footprint of products. This indicator refers to an equivalent volume of freshwater required for assimilating the pollution loads discharged to the water body during the process step (Hoekstra et al., 2011). It adds to blue and green water footprint to ultimately show the total water embedded in producing the products. However, its quantification is based on quite different methodology which has some potential for development to broaden its application.

The assimilative capacity of receiving water body is typically determined by using natural background concentrations and the existing ambient water quality standards (AWQS). Nonetheless, AWQS may vary from one basin or intended use to another. It can be spatially variable as a matter of differences in land-uses and ecosystems (Wu et al., 2016). In addition, AWQS may be modified during the time due to the variations of features and methods in census and monitoring (Zhao et al., 2018). Waste load allocation (WLA) policies are also reliant on determining locally-oriented water quality standards (Jamshidi et al., 2015, 2016; Monfared et al., 2017). The objectives and limitations of WLA like the economic incentives and outcomes (Imani et al., 2017), pollution mitigation strategies (Incera et al., 2017), and equity of stakeholders (Feizi Ashtiani et al., 2015) can push decision-makers forward determining agreeable AWQS. All these issues point to this fact that water quality standards can be case-specific and consequently GWF of products should be accounted with respect to the local requirements or in regional scales (van Vliet et al., 2017).

GWF expresses an idea of rephrasing the environmental impacts in form of water volume for integrated decision-making. This is originated from the fact that pollution worsens the problem of water scarcity as it makes water bodies unusable for some purposes (Pellicer-Martinez and Martinez-Paz, 2016). Since pollution consists of different pollutants, such as heavy metals or nutrients, it can add up the disparities in GWF accounting. This is addressed as a main shortcoming of GWF in addition to the variable AWQS (Liu et al., 2017). Thus, some researchers have recently focused on simulation techniques for standardization of water quality and multiple-pollutant GWF accounting. Here, nitrogen (N) and phosphorous (P) are chiefly addressed in croplands for managing their adverse environmental impacts (Mekonnen and Hoekstra, 2015, 2018). For example, Chukalla et al. (2018b) realized that N-related GWF is significant in irrigated croplands and is correlated with the application of blue water. So, they proposed a method that uses a simulation

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technique to reach a trade-off between two concepts of water quantity and quality in maize production. They also proposed best management practices (BMPs) to reduce nutrients discharges to the water body (Chukalla et al., 2018a). Likewise, Hu et al. (2018) found that N mostly dominates hydrological pollution in GWF assessment of food and crop production in China and consequently proposed an integrated methodology using simulation techniques. Liu et al. (2018) used a grid-based crop model to estimate P-related losses in crop cultivation through erosion. Herrebrugh (2018) pointed on heavy metals of industrial effluents in GWF accounting, while Bosman (2016) altered an equation to include pH in related calculations. These studies imply that still more research can be implemented for accounting multiple-pollutant GWF with respect to other water quality parameters or emission sources.

Fish farming is a water user that directly benefits from clean water because the production yield is dependent upon the water quality (Wezel et al., 2013). However, as Vanham (2016) argued, water footprint studies mostly consider the agricultural, industrial or domestic applications of water, while aquaculture is not incorporated separately in GWF accounting. In a few studies on assessing water footprint of fish farms, Perez-Rincon et al. (2017) compared the water footprint of three species in Columbia regarding three pollutants of total suspended solids (TSS), biochemical oxidation demand (BOD), and ammonia. They found that trout has the most direct pollution with the highest weighted GWF (%) exceeding 15 thousands m^3/ton. Conversely, Pahlow et al. (2015) estimated the average weighted GWF of fish farming by their feed ingredients about 166 m^3/ton. By considering the uncertainties in water footprint accounting of fish production in marine and freshwater ecosystems of China, Yuan et al. (2017) also found that GWF is about 440 m^3/ton. Later, Wickramasinghe et al. (2018) used eight pollutants to calculate GWF of fish production. However, in all approaches dissolved oxygen (DO) is neglected, while this factor is critical for aquaculture. This can be due to the fact that DO is an indicator for managing water resources and is not a pollutant as such. However, it is influenced by other pollutants like nitrogenous and carbonaceous BOD (Kocer et al., 2013).

This study introduces an integrated methodology for accounting multiple-pollutant GWF for trout production by addressing all aforementioned research shortcomings. Although this method follows the standard equations of GWF assessment, it uses original samplings, simulation and WLA to determine locally-oriented AWQS instead of hypothesized global limitations. It also includes DO as a key factor in accounting multiple-pollutant GWF. These innovations in methodology are associated with some alterations in equations to build a foundation for further studies in water footprint assessments. Most significantly, this research originally discusses an amending coefficient that can include some environmental concerns within GWF equations.

2. Materials and method

2.1. Methodology

The proposed methodology has three consecutive steps (See Fig. 1). First, samples are taken to originally estimate the water quality in river in addition to the inlet and outlet of trout ponds located along the streamline. Here, pollution exports are calculated for a set of pollutants as described in part 2.2. Second, a simulation tool is used to locally set the required limits of water quality parameters, like DO, total nitrogen (TN), and chemical oxygen demand (COD) as described in 2.3. This section is aimed on developing a generic method for setting the maximum allowable concentrations of pollutants with respect to the local specifications of river basins instead of hypothesizing standards based on global assumptions. For example, the natural assimilative capacity of the receiving water body and the economic limitations of emission sources are included here in defining water quality baselines. This approach can develop the method of GWF accounting with respect to the regional capacities and economic, environmental or social requirements. Afterwards, the standard equations of GWF accounting are developed in third step to broaden its applicability for presenting other environmental and ecological issues within water footprint assessment. The multiple-pollutant GWF of trout production is calculated finally to verify the general applicability of these alterations in GWF accounting. The details of the third step are explained in Section 2.4.

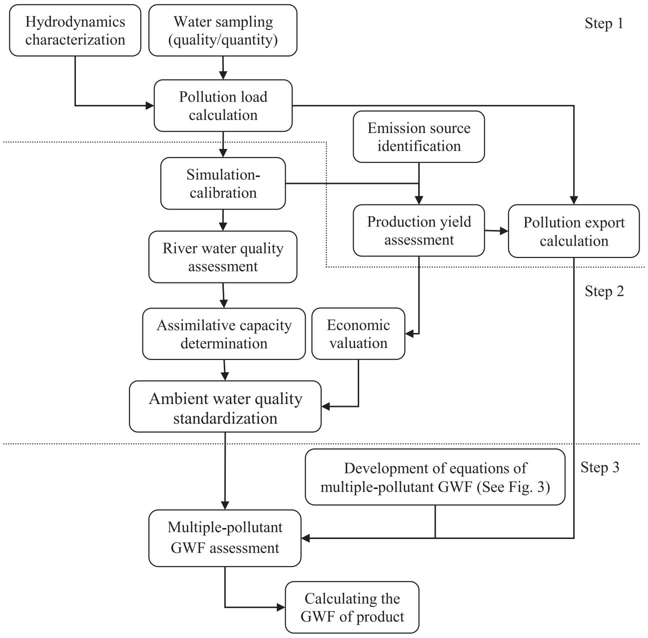

Fig. 1. Flow diagram of methodology and research steps.

The proposed methodology is verified in Kabkian River, south western Iran. The basin is rather small and mainly provides water for trout farms having low-income in average. Other land-use land-cover (LULC) of this area is pastures and paddy fields (Fig. 2). The lack of economic incentives in this area has made decision-makers to consider more flexible AWQS. For this reason, Kariman et al. (2018) has previously determined the economic value of water in this basin for WLA, which their analytical results and methodology are considered for water quality standardization in this study.

2.2. Sampling and tests

In order to estimate the pollution loads (ton/year) of fish farms and calibrate the modelling of water quality, 21 stations were located as checkpoints for 12-month sampling (2016–2017). 11 stations were selected in the application area as checkpoints of fish farm effluent discharges and 9 stations were located in streamline as shown in Fig. 2. The concentrations of BOD, COD, DO, ammonium (NH_4), nitrite (NO_2), nitrate (NO_3), TN, phosphate (PO_4), sulphate (SO_4), electro-conductivity (EC), and TSS in streamline, the influent (C_{in}) and discharges (C_{out}) of trout ponds were analyzed in 21 samples taken monthly. The annual average of differences between these concentrations ($C_{out} - C_{in}$) of a pollutant (i) were then multiplied by the annual average flow rates of their effluent discharges (Q) to calculate the added pollution loads (L_i) as Eq. (1) (ton/yr). L_i is used for calculation of pollution exports (P_{exp}) as Eq. (2) in order to present decision-makers with simple coefficients for pollution estimation and modelling. It can also be used for GWF accounting as explained in Eq. (4). Here, Y is the annual average yield of a product (ton/yr).

$$L_i = (C_{out} - C_{in})_i \times Q \tag{1}$$

$$P_{exp} = \frac{L_i}{Y} \tag{2}$$

It should be noted that water quality samples were analyzed in-site

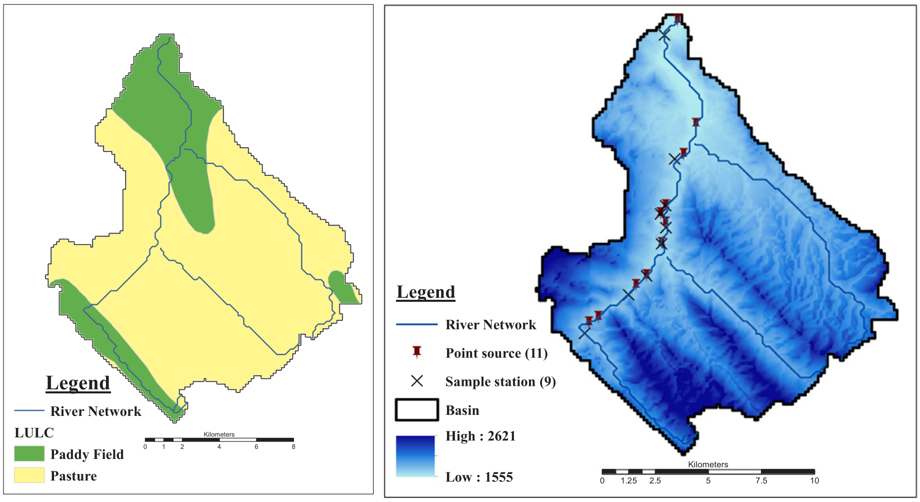

Fig. 2. Kabkian River basin with main LULC and the sampling locations.

for DO and EC and then tested in a laboratory for other required parameters in accordance with standard methods for the examination of water and wastewater (APHA, 2005).

It is also noteworthy that the trout ponds are assumed as black boxes in this study. Here, any process is addressed by the samples taken from influent and effluent. It is previously realized that a reduction in DO level of water entering to the ponds may increase the mortality ratio of trout farming in the study area as shown in Eq. (3) (Kariman et al., 2018). Consequently, the DO deficiency in the influent of trout farms (mg/L) can have adverse impacts on the annual average yield (%) of trout production (Y_t) which should be considered in GWF accounting of aquaculture products. Although this equation is case specific, it mainly emphasizes this idea that the yield of products, particularly aquaculture, may be changed due to low water quality.

$$Y_t = 129.7\ln(DO) - 171.2 \tag{3}$$

2.3. Modeling

The river was divided to 16 reaches for water quality modelling and simulation by QUAL2K (version 5.1) and the profiles of water quality parameters, such as DO, COD and TN, were extracted (Kannel et al., 2007). The hydraulic characteristics in addition to the specifications of headwater, pollution discharges, and initial conditions were included in modelling (Table 1). Calibration was also carried out using the auto-calibration tool of QUAL2K based on the samples taken from the 9 stations (Fig. 2). On the basis of the calibration, the aeration coefficients (K_a) of the river were calculated (Table 1). In this study, the optimal weighted root mean square coefficient of variation is 0.25 which shows about 75% accuracy in simulation. This is equivalent to the auto-calibration fitness function of about 4 (Kariman et al., 2018; Chapra et al., 2008).

Table 1
Hydraulic characteristics in consecutive segments of river.

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

2.4. GWF calculations

This study mainly follows a standard method introduced by Hoekstra et al. (2011) for accounting multiple-pollutant GWF as Eqs. (4)–(6).

$$GWF = \frac{\max(P_i)}{Y} \tag{4}$$

$$P_i = \frac{L_i}{D_f} \tag{5}$$

$$D_f = C_{max} - C_{nat} \tag{6}$$

Here GWF is the ratio of maximum freshwater required (m^3/ton) for assimilating a pollution load (P_i) per annual average yield of a product (Y). In accounting multiple-pollutant GWF, it is necessary to find P_i for any pollutant (i) first. This is the ratio of the pollution load discharged (L_i) to the dilution factor (D_f). D_f represents the assimilative capacity of the receiving water body which is reliant on two terms of natural (C_{nat}) and maximum allowable concentrations of a pollutant (C_{max}). C_{nat} equals the concentration of a pollutant in the receiving water if the interferences of human activities are eliminated, while C_{max} is the maximum allowable concentration estimated regarding the AWQS.

In GWF accounting, the maximum P_i of multiple-pollutants is considered in final calculation. Therefore, different parameters should be sampled first as introduced in 2.2. Here, it is recommended that the annual average L_i of emission sources is used for calculations as it represents the normal pollution load of a product. This introduces GWF as a more comparable indicator and increases its applicability for different products with lack of data. In addition, the multiple-pollutant GWF should be accounted based on pollutants with small variations in samplings or significant change from the inlet to outlet of a production process statistically. As a result, L_i of pollutants with high standard deviations or high p-value (> 0.05) can be neglected, particularly if these parameters are not specific for the related products.

DO is not usually categorized as a pollutant. It is an indicator that shows the level of oxygen concentration of water rather than pollutions. Hence, its P_i cannot be calculated directly, whereas its deficiency is critical in water quality and may increase the losses of aquaculture (see

Eq. (3)). Consequently, Eq. (7) is originally developed in this study to consider DO as a pollutant in the multiple-pollutant GWF assessment of trout production. This equation is based on the fact that the organic compounds are typically found in polluted waters and they are mainly responsible for increasing the oxygen demand of water for related biological and chemical processes. For example, it is obvious that the DO content of water in rivers and lakes are adversely influenced by the concentrations of BOD, NH_4 and NO_2. Therefore, with respect to Streeter-Phelps equation (Chapra, 1997), it is recommended that the amount of added pollution of BOD, NH_4 and NO_2, that have direct impacts on DO deficit of river (Kocer et al., 2013), should be added up and divided by the dilution factor (D_f) of DO. Here, the dilution factor is the difference between the saturation level of DO (C_{sat}) and the minimum standard limit of freshwater (C_{min}). These two factors respectively represent C_{nat} and C_{max} in reverse order. Although, this equation can be used for accounting the GWF of any product with discharges to the receiving surface waters, it may be more applicable for aquacultures and fish products.

$$P_{DO} = \frac{(L_{BOD} + L_{NH4} + L_{NO2})}{C_{sat} - C_{min}} \tag{7}$$

In Eq. (7), L_{COD} can be used instead of the added loads of BOD, NH_4 and NO_2 only if the receiving water body is a lake, reservoir, or wetland. This is due to the fact that COD includes not-readily biodegradable compounds which have long-term impacts on DO concentration of water.

In addition, a state-of-the-art coefficient is included in GWF formula to convert any possible “embedded ecosystem damages” into equivalent freshwater volume as shown in Eq. (8).

$$P_i = \frac{L_i}{\omega D_f} \tag{8}$$

where ω is a dimensionless correcting factor ($\omega < 1$) that represents the recovery required by the receiving water body regarding its background quality. Here, ω is the minimum of five indicators defined as Eq. (9) that separately focuses on one subject in water resources. Here, if any indicator is higher than 1, it can be neglected as it means this type of recovery is not required.

$$\omega = \min(\omega_1 = \frac{\boldsymbol{Q_{act}}}{\boldsymbol{Q_{env}}}; \omega_2 = \frac{\boldsymbol{DO_{act}}}{\boldsymbol{DO_{std}}}; \omega_3 = \frac{(\boldsymbol{N_{req}\,or P_{req}})}{(\boldsymbol{N_{act}\,or P_{act}})}; \omega_4 = \frac{\boldsymbol{EC_{req}}}{\boldsymbol{EC_{act}}}; \omega_5 = \frac{\boldsymbol{MP_{req}}}{\boldsymbol{MP_{act}}}) \tag{9}$$

In which, ω_1 refers to the freshwater volume required for enhancing the current minimum flow of river (Q_{act}) to the minimum environmental flow required in receiving water body (Q_{env}). Q_{act} should be measured in the terminus or any critical points through a year. This may be influenced by high water allocations, unsustainable operation of dams, or even climate change (Jamshidi et al., 2019). ω_2 controls the basic conditions of aquatic life in surface waters. DO_{std} is the minimum of required DO in surface waters to preserve aquatic life. This is typically set between 5 and 6 mg/L. On the condition that surface water, which receives the pollution loads, contains DO less than 5 mg/L; it requires to be diluted virtually with some volume of freshwater to be rehabilitated in a way that the actual minimum level of DO (DO_{act}) increases to the environmental level (DO_{std}). This can broaden the application of GWF for preserving the aquatic and ecosystem services currently encounter DO deficiency ($DO_{act} < DO_{std}$). ω_3 mainly deals with Eutrophication problem in lakes. If a product is raised in a lake basin with Eutrophic condition, altering dilution is necessary for lake rehabilitation. Here, it can be recommended that current N or P level of lake (N_{act} *or* P_{act}), relating to their limiting role, should be reduced to some extent (N_{req} or P_{req}) that the lake trophic status enhances one degree. For example, a lake with Eutrophic condition needs only to be promoted to the Mesotrophic condition in which the differences are reflected in ω_3. ω_4 mostly point to the coastal areas or water-stress aquifers where overexploitation of groundwater may lead into salinity intrusion or, in the manufacturing process, desalination plants are working. Therefore, the EC level of water (EC_{act}) should be reduced virtually to the required levels (EC_{req}) for being compatible with the ecosystem or society who are the water user for drinking or agriculture. ω_5 refers to the micropollutants (MP) that may cause health risks. Products made in industries, agriculture, urban areas, or even aquacultures may discharge heavy metals, toxics, pesticides, herbicides, fungicides or even pharmaceutical compounds (Martínez-Alcalá et al., 2018). In accounting GWF, it is recommended that a virtual freshwater volume is allocated for considering the assimilative capacity required to reduce the concentrations of MPs (MP_{act}) to less than their risk free limits (MP_{req}).

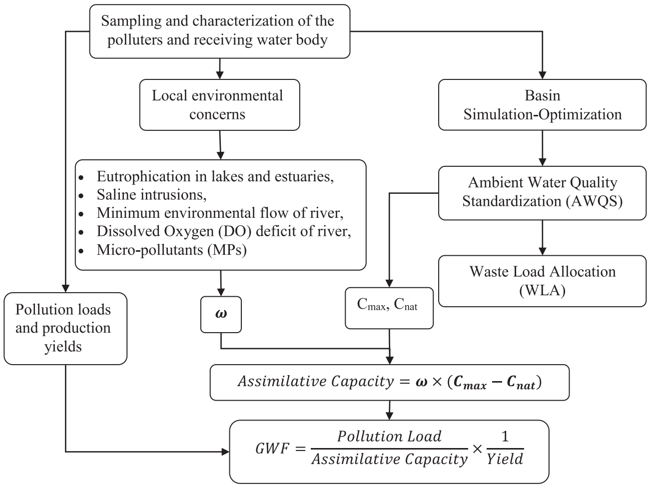

Fig. 3. Proposed methodology for calculating GWF.

In Fig. 3, the altered methodology for accounting GWF is outlined. Here, it is emphasized that the assimilative capacity should be derived locally for the receiving water body regarding its main environmental concerns (ω) and ambient water quality standards (AWQS).

3. Results

3.1. Application area

The Kabkian River is a tributary of the Karoon River in a mountainous region and is located in southwest Iran near Yasooj, Kohgiluye Province, where the average annual temperature of water is 12 °C. The land-use types in the area are mainly paddy fields and trout farms, mostly brown and rainbow species. The flow rate of the river ranges from 1.5 to 2 m^3/s. It is 21 km long and divided in two main zones: the upstream zone is populated primarily by fish farms that are directly connected to the river, whereas paddy fields can also be found in downstream zone (see Fig. 2). In water quality modelling, fish farms falling within a perimeter of less than 200 m were clustered and regarded as point sources (P1 to P11) shown in Table 1, whereas paddy fields were treated as diffuse sources (NP1 to NP3). Referring to the field surveys and questionnaires, the annual average yield (*Y*) of fish farming is between 28 and 40 ton for enterprises located alongside the river. Here, the annual mortality rate is reported 12% in average (Table 2). Besides, *Q* (Eq. (1)) is measured at the outlet of ponds by V-shaped weir that equals 0.18 l/s in average with standard deviation of 0.055.

3.2. Pollution exports

The sampling results show that water quality degrades in trout

Table 2
Fish farm identification in the study area by field surveys.

Trout ponds	Distance to headwater (km)	Q_{in} (l/s)	Annual production yield (ton)	Fish mortality (%)
P_1	0.5	0.3	28	2
P_2	1.2	0.38	35	3
P_3	3.5	0.45	40	5
P_4	4.2	0.38	35	10
P_5	6	0.3	28	10
P_6	7.2	0.45	40	12
P_7	7.7	0.43	35	15
P_8	8.2	0.55	40	25
P_9	11.5	0.4	30	15
P_{10}	14	0.55	40	20
P_{11}	20	0.43	35	15

ponds. Table 3 demonstrates the measured concentrations in average in association with calculated L_i and pollution exports (P_{exp}) in the study area. For example, it shows that producing one ton of trout can export 503 grTSS, 214 grN, and 399 grCOD to the river. DO is also reduced from 8.15 mg/L in average to 7.8 mg/L. Regarding the deviations of experimental results, TSS, PO_4 and SO_4 are rather fluctuating in C_{out} which their average differences with C_{in} are not statistically significant (p-value > 0.05). Therefore, the calculations of L_i and P_i are set on more reliable parameters that are also verified in WLA. Accordingly, COD is considered as more reliable factor comparing with BOD for WLA and environmental monitoring.

3.3. Setting water quality standards

Water quality simulation is a technique that enables decision-makers to deal with more computable data deprived from a set of authenticated equations and on-field samplings. This approach supplies decision-makers in water quality and environmental management with data required for optimization to attain a proper or nearly optimal multi-pollutant WLA. WLA draws a baseline as the satisfactory level of pollution removal for point-sources in an area with respect to the ecological, environmental or economic issues of that basin. For example, in Kabkian River basin, fish farmers have low income and river has high assimilative capacity for re-aeration. Accordingly, Kariman et al. (2018) showed that up to 50% removal of COD and TN in trout farm discharges can satisfy the minimum requirements of water quality in this basin. In addition, this limit can be achieved economically for fish farmers regarding their income and abatement costs to apply treatment systems. By this strategy, the simulation shows that the concentrations of COD and TN in river would be reduced below 1.55 mg/L (Fig. 4) and 20 mg/L (Fig. 5), respectively. In addition, this can enhance DO level of water which is more vital for trout farming. The proposed WLA policy can improve the minimum DO level of river from 6.3 mg/L to more than 7.2 mg/L (Fig. 6).

Regarding the simulation results, it can also be concluded that C_{max}

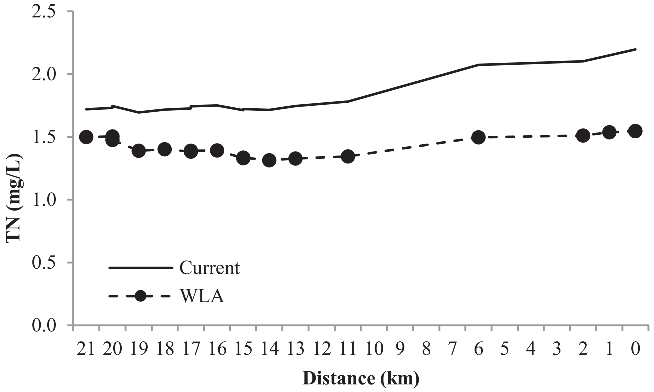

Fig. 4. TN profile of river in WLA attained by the simulation results.

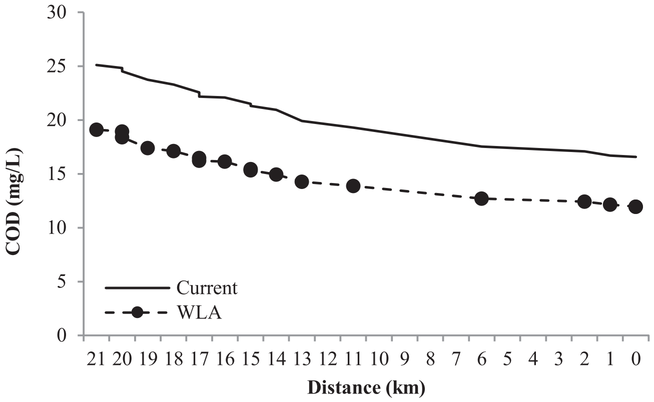

Fig. 5. COD profile of river in WLA attained by the simulation results.

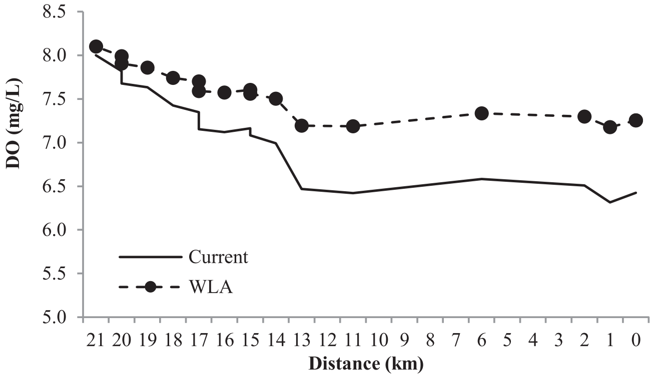

Fig. 6. DO profile of river in WLA attained by the simulation results.

Table 3
The sampled water quality and pollution export calculations.

Parameter	Unit	C_{in}	C_{out}	$C_{out} - C_{in}$	P-value	L_i (kg/yr)	P_{exp} (kg/ton)
TSS	mg/L	15 ± 3.8	18.1 ± 10.5	3.1	0.328	17.6	0.503
NH_4	mg/L	0.09 ± 0.015	0.17 ± 0.07	0.08	0.002	0.45	0.013
NO_2	mg/L	0.06 ± 0.03	0.15 ± 0.03	0.09	0.000	0.5	0.014
NO_3	mg/L	4.26 ± 0.98	4.98 ± 1.02	0.72	0.033	4.07	0.116
TN	mg/L	4.41 ± 1.05	5.72 ± 1.2	1.31	0.003	7.48	0.214
PO_4	mg/L	0.26 ± 0.08	0.34 ± 0.23	0.08	0.254	0.45	0.013
SO_4	mg/L	40 ± 2.4	46.9 ± 11.8	6.9	0.068	39.1	1.12
COD	mg/L	15.11 ± 3.5	17.57 ± 2.4	2.46	0.004	13.97	0.399
BOD	mg/L	8 ± 2	9.7 ± 1.8	1.7	0.007	9.65	0.276
DO	mg/L	8.15 ± 0.35	7.8 ± 0.65	−0.35	0.015	–	–
EC	µs/cm	421 ± 29	469 ± 42	48	0.002	–	–

Table 4
Steps of pollutant-related GWF calculation.

Parameter	C_{max} (mg/L)	C_{nat} (mg/L)	D_f (mg/L)	L_i (kg/yr)	P_i (m^3/yr)	P_i-related GWF (m^3/ton)
NH_4	0.3	0	0.3	0.45	1500	43
NO_2	0.1	0	0.1	0.5	5000	143
NO_3	0.9	0.2	0.7	4.07	5814	166
TN	1.3	0.2	1.1	7.48	**6800**	**195**
COD	12	5	7	13.97	1996	57
DO	8.1	10	1.9	10.6	5579	159

They are bold because they are the maximum value as mentioned in Equation 4.

for TN and COD should be set on 1.3 and 12 mg/L, respectively. These are the minimum concentrations of TN and COD profiles in Figs. 4 and 5, respectively which can respond to the demands of both fish farmers and the environment. These AWQS have also been previously verified with respect to the economic value assessment (Kariman et al., 2018). For DO, C_{max} equals the highest level of DO profile of river which is 8.1 mg/L (Fig. 6).

C_{nat} can be estimated through simulation by eliminating the whole pollution discharges, including point and non-point sources. Yet, for an area that originates from a reservoir upstream, any possible polluters at headwater should also be removed because C_{nat} mainly follows the headwater characteristics in this condition. Therefore, C_{nat} for TN and COD are found respectively 0.2 and 5 mg/L, while C_{nat} of DO represents the saturation level of water which equals 10 mg/L (Woynarovich et al., 2011).

3.4. GWF assessment

By calculating the dilution factor regarding COD and TN parameters, and having the added pollution loads (Table 3), GWF can be calculated. As shown in Table 4, GWF is TN-related and equals 195 m^3/ton. This is comparable with the results of accounting GWF of fish farming carried out by other researchers (Pahlow et al., 2015; Yuan et al., 2017). It is also noteworthy that the DO-related GWF is calculated about 159 m^3/ton by Eq. (6). This is slightly different from TN-related GWF and points to the fact that DO may have the opportunity for being the focal indicator in accounting GWF in lower N-polluted areas.

In case of fish farm development in the study area (developed scenario), obviously more water will be allocated to the fish ponds upstream. This certainly reduces the self-purification and assimilative capacity of river for pollution abatement. Therefore, it is probable that pollutant concentrations increase and DO level decreases by these circumstances. However, regarding the framework of analyzing GWF, these impacts may not change its value unless the fish yield is also influenced in higher pollutant levels.

Provided that fish ponds become double in quantity, as a development strategy in the study area, the base flow of river reduces in upper reaches. It can reduce the assimilative capacity of river and consequently the DO content of river reduces from 7.5 mg/L to 6.2 mg/L in average (Fig. 7). This reduction in DO content can result in more than 25% mortality per Eq. (3). Therefore, the overall GWF may no longer remain 195 m^3/ton because the annual yield of fish ponds should be multiplied by 0.75 while P_i remains constant. As a result, the modified value of GWF is 260 m^3/ton. It is noteworthy that GWF calculations in larger scales or for other agricultural and industrial products, may not be influenced by a change in water quality significantly. Industrial fish farms may also use technologies for water treatment and recycling to keep the water quality of influent at the proper level. However, for conventional fish farm enterprises in small and local scales, this study points to a shortcoming in GWF calculation that should not be ignored.

In this study, ω_2 (Eq. (8)) can be addressed in the scenario of developing fish farms. Although increasing water allocation for fish farming reduces DO level (Fig. 6), this reduction is not significant that diminishes DO_{act} (5.87 mg/L) below DO_{std} (5 mg/L). Therefore, ω_2 and consequently ω (Eq. (7)) remains 1. In two examples, if DO_{act} was 4.5 and 2.5 mg/L, ω would be calculated as 0.9 and 0.5, respectively. This means that previously assessed GWF in the second scenario (260 m^3/ton) would be increased to 289 m^3/ton and 520 m^3/ton, respectively. It is obvious that in high water allocations that have influences on river capacity, ω_1 or ω_2 may not remain 1 and a modification would be required in GWF assessment.

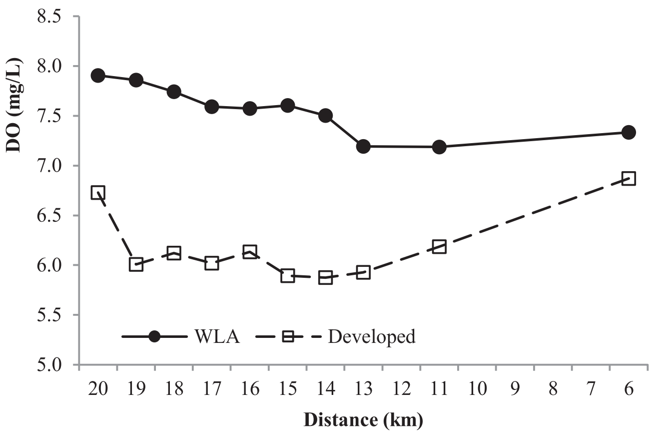

Fig. 7. Impact of fish farm development in comparison with WLA scenario.

4. Discussion

The definition of the assimilative capacity (D_f) only based on the differences of C_{max} and C_{nat} can introduce a misleading implication in GWF. For example, in regions and areas that pay high attention to the quality of their water resources and environment, C_{max} is usually determined closer to C_{nat} and consequently GWF is increased. It implies that virtual water of a product can be increased due to the environmental protection policies as it can be increased by blue and green water consumptions. This paradox can also mislead the policy makers in virtual water trading. It can push countries toward policies in which water quality standards are less controlled for justifying their virtual water exports. They can also find justifications for importing the virtual water from regions with lower water quality standards, mainly the developing countries. All these problems originate from a shortcoming in GWF that ignores the role of environmental minimum flows and the dilution required for recovering water resource per se. In other word, the meaning of C_{nat} in higher water allocations may be differed due to the impacts of human activities and development strategies on changing the basic environmental flow and water quality (Liu et al., 2016). Therefore, basins with lack of environmental flow for protecting the assimilative capacity of river are “virtually” in need of some freshwater transmitted from other basins. For example in this study, allocating higher blue water from Kabkian Basin to develop fish farms has lead into a reduction in DO level of river. It can put the aquatic life at risk and lessens the assimilative capacity of river. Therefore, any extra fish production can increase the water stress in this area which should be accounted in GWF.

Some alterations in accounting GWF are proposed in this study to include DO and ecological concerns in GWF calculations. Eutrophication, saline intrusions, minimum environmental flow and DO deficit of river, in addition to the micropollutants are five environmental concepts that are addressed in accounting GWF. The developed methodology and related alterations are new steps toward higher sustainability, applicability and accuracy of GWF. These alterations can also open a new discussion and research area for scientists to define a more sustainable framework for determining ecological indicators within GWF. It also covers two main shortcomings of GWF addressed by Liu et al. (2017). As previously argued by Pellicer-Martinez and

Martinez-Paz (2016), the foundation of accounting GWF is well constructed. However, in complex matters, as multiple-pollutant GWF of fish farming, related equations are in need of some alterations. It is also noteworthy that the proposed methodology and alterations differ with the efforts of Lovarelli et al. (2018). They proposed a pollution water indicator (PWI) separate from GWF formula to consider more pollutants, as pesticides, and environmental impacts on soil in crop cultivation, whereas alterations are included here within the standard method. In addition, these alterations have the potential to support the global food market for considering the economic incentives in trades of products with lower ecological damages (Hoekstra, 2018). It also has the potential to develop studies on accounting GWF with wastewater reuse perspective (Martínez-Alcalá et al., 2018).

5. Conclusion

This research emphasized that GWF accounting is dependent on the local characteristics of receiving water body such as the assimilative capacity, emission sources and AWQS. Using hypothesized or not-adjusted water quality standards seems not efficient enough for reporting the GWF of products. Therefore, a methodology is developed for calculating the multiple-pollutant GWF of trout farming and discussed some major findings. First, the pollution export coefficients of nine pollutants were estimated in trout farming. For instance, an average N footprint of a product was estimated 214 grN/ton. Second, this approach employed water quality simulation technique for defining WLA and AWQS. Accordingly, 50% pollution removal was set for meeting environmental demands in the study area. In this framework, C_{max} and C_{nat} were also defined locally-specified through simulation instead of hypothesizing. Third, due to the characteristics of the aquaculture, equations were developed to include DO level of water in fish production yield assessment and accounting multiple-pollutant GWF in association with TN and COD. This point of view highlighted the inevitability of surveying the impacts of water quality on the productivity of products, particularly in development strategies. Finally, this study provided a new exploration on how GWF accounts the ecological damages occurred to the receiving water bodies. Eutrophication, minimum environmental flow, DO deficit for aquaculture, saline intrusion and micropollutants are introduced as five ecological indicators. Therefore, this study showed that Y, C_{max}, C_{nat} and D_f are case specific parameters for accounting GWF of products and a coefficient (ω) should be defined for dilution factor to include the environmental concerns of receiving water bodies in form of the equivalent freshwater volume. These alterations can broaden the application of GWF with local environmental perspectives. However, further researches are required to verify or develop these alterations in other cases.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105477. These data include Google maps of the most important areas described in this article.

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