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Comments on the international consensus model for the water scarcity footprint (AWARE) and proposal for an improvement.

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Abstract

Life Cycle Assessment (LCA) provides a structured framework, addressing environmental impacts of human activities. LCA requires consensual and scientifically sound characterization factors to quantify impacts and allow comparisons. This is the objective of the AWARE model, recently published by an international consortium, which is now the reference for water impact in LCA. Looking back at the shape of the equation, linking human water use and water impact, we discuss the limits of the AWARE model and the associated cut-offs. They imply that all regions in a less than fair ecosystem condition are treated at the same level of severity, regardless of the extent of degradation. From this statement, we propose to define the impact by the ratio between the ecosystem demands and the remaining after human activities (DTR model). We use the marginal and average approaches, common approaches in LCA, to determine the corresponding characterization factors. Through a sensitivity analysis with respect to parameters used (total water availability, ecosystem demand, human consumption and area of the region), we show that the DTR-based characterization factors have the same properties than the AWARE-based ones between cut-offs. This article therefore provides a new alternative way of quantifying the impact of water use, in line with the AWARE model features, but without its validity limits and induced thresholds.

Keywords

Life Cycle Impact Assessment; Water Impact; Characterization factor; Marginal approach; Average approach;

1. Introduction

Life Cycle Assessment (LCA) is the generic and global approach dealing with environmental impacts of human activities. Led by an entire community of researchers and practitioners, LCA provides operational assessments of goods and services through a structured framework (Finkbeiner et al., 2006) and guidelines (e.g. European Commission 2013).

All comparisons need consensual criteria. Under the umbrella of UN environment, the Life Cycle Initiative leads collective works defining recommended Life Cycle Impact Assessment (LCIA) indicators (Frischknecht and Jolliet, 2016; Jolliet et al., 2018). As part of this, the Available WAter REmaining (AWARE) model has recently been published (Boulay et al., 2018), addressing water issues in LCA.

The AWARE model highlights the importance of considering consumption rather than withdrawal and takes into account spatial variability. It results from a massive and collective effort on behalf of the Water Use in LCA (WULCA) working group. The AWARE provides a consensual, operational and recommended indicator for addressing and comparing water impacts, and fully succeeds in this purpose.

The present article discusses the shape of the model, as well as associated limitations on its range of validity, which do not distinguish between regions that are more degraded than fair. A subsequent improvement is then proposed. This improvement follows the common practice in LCIA by (1) the definition of a relationship modelling the impact according to human intervention and (2) the use of marginal and average/linear approaches for determining the characterisation factor (CF). This improvement is mathematically sound, all the while satisfying the same expectations as the AWARE model.

2. Methods

2.1. The AWARE model

2.1.1. Origin

With the purpose of answering the following question, "What is the potential to deprive another freshwater user (human or ecosystem) by consuming freshwater in this region?"(Boulay et al., 2015, 2018), the water impact is logically addressed as first approach using the ratio between the water demand and the water availability (DTA) in a given area.

However, Boulay et al. (2015) also highlighted the limitation of the DTA. As the numerator and denominator have the same unit, this ratio is unitless. It does not offer any information concerning the quantity involved, and the DTA obviously cannot be used as a characterisation factor (CF). As an illustration, a 0.1 DTA value could either refer to a demand for 1 m^3 over 10 m^3 of availability in area A, or to a demand for 1 000 m^3 over 10 000 m^3 in area B. Nevertheless, the use of one same 1 m^3 of water in A or in B should not involve the same impact (if using DTA as a CF). The CF must address the "size" of the reserve. In another context, this was precisely the reason for justifying the square of the reserve in the abiotic depletion potential equation (ADP) described in Guinée and Heijungs (1995). This allows for this "size" to be taken into account in the CF.

2.1.1. Model

The WULCA group investigated several alternatives to overcome the DTA issue. The two most discussed alternatives were DTA$_X$ (which is roughly similar to the ADP without the same rational), which was finally not selected by the group, and the AWARE, which is detailed below.

Using a more synthetic notation than that of the initial publication, the AWARE characterisation factor (CF_{AW}) defined in Boulay et al. (2018) is the following:

$$\frac{1}{AMD} = \frac{a}{A - D_E - C_H} \tag{1}$$

$$CF_{AW} = \begin{cases} 0.1 \times \overline{AMD}, & AMD > 10\,\overline{AMD} \\ \dfrac{1}{AMD} \times \overline{AMD}, & 0.01\,\overline{AMD} \geq AMD \geq 10\,\overline{AMD} \\ 100 \times \overline{AMD}, & AMD < 0.01\,\overline{AMD} \end{cases} \tag{2}$$

The CF is based on the inverse of the availability-minus-demand (AMD, m^3/m^2.month). The variable a is the area of the region ("area" in Boulay et al. (2018), m^2), A the availability ("Availability", m^3/month), D_E the environmental water requirements ("EWR", m^3/month), C_H the human water consumption ("HWC", m^3/month), and $\overline{AMD}$

the global average AMD of freshwater ecoregions where $C_H + D_E < A$ ("$\text{AMD}_{\text{world avg}}$", m^3/m^2.month).

2.2. AWARE limitations

Operationalization of the CF requires consequent work and the WULCA taskforce was committed to collecting all the necessary spatial information in order to determine the variables of the model at a global scale. The human consumption C_H was then used as the (satisfied) human demand. The ecosystem demand D_E was also spatially quantified, but using the environmental water requirement. The definition is therefore different: D_E does not quantify the current consumption by the ecosystem but, rather, the (requested) ecosystem demand, because the ecosystem can only receive what has been left to it. The state of the ecosystem can be categorised under pristine, good, fair or poor conditions (Pastor et al., 2014; Smakhtin et al., 2006). D_E "evaluates minimum water requirements as a fraction of the available flow to maintain freshwater ecosystems in "fair" conditions with respect to pristine flow" (Boulay et al., 2018).

A and C_H are estimations of current flows, and $C_H \leq A$. However when a too high human appropriation of water leads to a poor condition ecosystem (i.e. when $C_H > A - D_E$), equation (1) produces a negative result and obviously cannot be used. This is the case with 13% of the global area and up to 33% of world water consumption at a monthly level as indicated in Boulay et al. (2018). In addition, when the ecosystem state reaches a fair condition (when C_H is close to $A - D_E$) equation (1) tends to infinity. Equation (1) therefore needs to be bounded in definition of the CF in equation (2). The WULCA taskforce decided to spread the CF_{AW} over 3 orders of magnitude, between 0.1 and 100 times the global average. The upper boundary (when $AMD < 0.01\,\overline{AMD}$) excludes 5% of world consumption in addition to the previous 33%. As mentioned by Boulay et al.

(2018), the lower boundary ($AMD > 10\,\overline{AMD}$) does not have a significant effect (<1% of world consumption) as high AMD result from low C_H.

Due to these boundaries, the inverse of the AMD in CF_{AW} is only used for 87% of the world area and 62% of world consumption at a monthly level. The AWARE provides accurate information, expressing the remaining water with respect to the world average for most places. However, it is worth considering a way to overcome this limitation by proposing a relationship that maintains this validity over the whole world and not only for 62% of its water consumption.

2.3. New proposal

2.3.1. Demand-to-remaining

As aforementioned, the present study deals with requested-environmental and fulfilled-human demands. Each should now be addressed separately because of their differences in meaning. First, the initial ideas of the demand-to-availability and availability-minus-demand are considered. The $\frac{D_E}{A-C_H}$ ratio is defined as the demand (requested by the ecosystem) to availability (minus the effective human appropriation), more simply named the demand-to-remaining (DTR). This ratio, considering both ecosystem demand and human consumption, provides useful and straightforward information representing the current state. An. arbitrary value of 1 indicates the ecosystem is in a fair condition. A value of 10 implies the ecosystem needs 10 times more water in order to reach a fair condition. Values less than 1 suggest that the conditions are rather good. With this ratio, the state of the ecosystems can be compared, although their surface matters too. For a surface area twice as large, the corresponding impact should be twice more severe, and the DTR ratio therefore has to be multiplied by the area.

This leads to the following water impact (I_w, m^2), which expresses an area degraded to fair conditions:

$$I_w = a\frac{D_E}{A - C_H} \tag{3}$$

2.3.1. Unit change in the model

The demands and availability are expressed in m^3/month. Flows instead of quantities are consistent with the notion that freshwater is viewed as a flow resource in the classification proposed by Sonderegger et al. (2017). However, the associated elementary flows defined in the life cycle inventory are commonly expressed in terms of quantity (a volume of water, sometimes dated at a given month). This flow (m^3) is a part of C_H, although C_H is defined as a flow rate (m^3/month).

This aspect is not an issue in the AWARE model because the CF is expressed in the world average equivalent and its initial unit no longer appears. As this is not the case when the CF is defined from the DTR, the issue still remains for marginal and average approaches (see below). It can be solved, as equation (3) can be easily defined using demands and availability that are not expressed in terms of flow rate (m^3/month), but in terms of quantity (m^3) for the given timespan (i.e. m^3/month × 1 month). This simply ensures a unit consistency for the definition of CF and does not modify the reasoning and the numerical values used.

2.3.2. Characterisation factors

Mainly two approaches have been used in LCA to derive CFs, representing a marginal or average change (Hauschild and Huijbregts, 2015). The Life Cycle Initiative guideline recommends using marginal CF when the system under study concerns less than 5% of the issue (Frischknecht and Jolliet, 2016; Verones et al., 2017), while the average CF addresses large changes.

The marginal CF ($CF_{DTR,ma}$, m^2/m^3) is the partial derivative of a model of the relationship between the impact and the inventory flow (the marginal change of the impact with respect to a marginal change in the inventoried flow).

$$CF_{DTR,ma} = \frac{\partial I_w}{\partial C_H} = a \frac{D_E}{(A - C_H)^2} \tag{4}$$

The average CF ($CF_{DTR,av}$, m^2/m^3) is obtained from the division of the impact by the overall human intervention (Curran, 2017).

$$CF_{DTR,av} = \frac{I_w}{C_H} = \frac{a}{C_H}\left(\frac{D_E}{A - C_H} - \frac{D_E}{A}\right) \tag{5}$$

$$CF_{DTR,av} = a \frac{D_E}{A(A - C_H)} \tag{6}$$

For an average CF, the “background” impact has to be removed (corresponding to a state devoid of human intervention $C_H = 0$, see Hauschild and Huijbregts (2015)). This explains the $-\frac{D_E}{A}$ term in equation (5).

2.4. Sensitivity of characterisation factors

The significance of the approach is addressed by the sensitivity of the CFs according to the components of the model. It can be obtained by the partial derivative to highlight the shape of the relationship and the corresponding equations are available in the supplementary materials. As an illustration, the changes (Δ) in CF values can also be plotted with respect to changes in model parameters. To deal with the behaviour of the AWARE and DTR models, an arbitrary reference set of parameters is therefore defined:

$\bar{a} = 1$, $\bar{A} = 1$, $\bar{D}_E = 0.45$, $\bar{C}_H = 0.3$ and $\overline{AMD} = 1$ as well as the corresponding intervals for the first four: $a \in [0.5, 1.5]$ (i.e. $\pm 50\%$), $A \in [0.5, 1.5]$, $D_E \in [0.3, 0.6]$ and $C_H \in [0.1, 0.9]$. The interval of D_E represents 30–60% of $\bar{A}$, which is the limit identified in Boulay et al. (2018). C_H interval boundaries correspond to 10–90% of $\bar{A}$, indicating the large amplitude in human consumption levels. The parameters are varied one by one within the interval using reference values for the others.

3. Results and discussions

3.1. Sensitivity of models for comparison purposes

Although a non-marginal version has been recently proposed (Boulay et al., 2019), the currently used AWARE CFs are defined as marginal and are thus compared to marginal CFs from DTR. Figure 1 illustrates the changes in the CFs (with respect to the reference point) as a function of the changes of the parameter values (with respect to the reference point for a and A, and as a proportion of A for D_E and C_H).

[Insert Figure 1 about here]

As expected, the CFs of the AWARE and DTR models increase linearly with the area, in the same manner. However, this is only true in the range between boundaries for the AWARE model, whereas this proportional relation remains valid for all values for the DTR.

In both situations, an increase in C_H produces the same result as a decrease in A. Although the relationships have an exponential shape, they are actually negative inverse, with order 2 for AWARE and order 4 for DTR (see supplementary materials). The increase grows faster when the AWARE model upper boundary is being reached, and when the complete human appropriation of water ($C_H = A$) is being attained for the DTR model. This implies that the relationships present similar features but at different intervals, without any discontinuities for DTR.

The CFs rise along with D_E, displaying a negative inverse relationship for AWARE and a linear relationship for DTR. The trends therefore differ in their shapes but, within the limits identified by Boulay et al. (2018), not particularly in their results. It is noteworthy that, due to the interval boundaries (30–60% of A), the changes in CFs led by D_E are about 10 times smaller than the changes induced by C_H and A.

3.2. Characterisation factors according to demands

Figure 2 illustrates how the CFs values are determined simultaneously according to demands. This highlights the main contribution of C_H, which drives the value for both models. The ecosystem demand D_E has a lesser effect except for its role in reaching the upper boundary of AWARE CF. The closer $A - C_H$ approaches the threshold D_E, the closer the CF to the cut-off. The DTR model is free from the constraints of this limit, with a continuously increasing CF until complete appropriation of water by human activities. DTR based CFs do not have boundaries, but extreme values are only found with very high C_H (two orders of magnitude between a zero human consumption and 90% of A, three orders with 99% of A).

[Insert Figure 2 about here]

3.3. Discussions

The main properties of CFs based on DTR are listed here, highlighting the similarities and differences with the AWARE. Other alternatives are also briefly mentioned.

3.3.1. Meaning of the indicator

With the AWARE, a CF that is equal to 10 "directly represents a region where 10 times less water is remaining per unit of surface in comparison to the reference flow, i.e. the world average. It can also be interpreted as a region where 10 times more area time is required to generate the same amount of unused water in comparison to the reference flow", excluding cut-offs and standardization to the world average, as the "surface-timed equivalent required to generate one cubic meter of unused water in this region" (Boulay et al., 2018).

With DTR, a CF equal to 10 m^2/m^3 corresponds to a 10 m^2 "area" that is degraded to a fair condition by human use of one cubic meter in the region. Although this could be equivalent to 10 m^2 in a fair condition or 1 m^2 in conditions 10 times more severe, it represents the impact expressed in surface equivalent in a fair condition in the region. As the environmental and human demands can be defined in various ways, they are applied differently in the model. Even though the meaning differs, the DTR impact satisfies the same expectation as the AWARE impact, addressing the deprivation for another use due to freshwater consumption in the region.

3.3.2. Approach

The design process of CFs is different for the AWARE and DTR models. With the AWARE, the CF is directly built considering the desired properties and constraints. One of the constraints is in the dimensionless nature of the DTA ratio, which consequently cannot be used as a CF. This CF is thus defined as marginal. With the DTR, first a model of the impact is established, and properties and limitations are also considered. However, in this case the lack of unit in the ratio is not an issue anymore, precisely because it represents the impact and not the CF. The CFs are consequently defined from the DTR model by marginal and average approaches, which provide CFs with a consistent unit.

3.3.3. Model Behaviours

The AWARE model addresses in the same way both the human and ecosystem deprivations, by subtracting both C_H and D_E from the availability. The impact covers these two uses of freshwater. The DTR model differs with D_E as numerator and C_H in the denominator. The impact is then mainly focused on the ecosystem issue. However, AWARE and DTR approaches share comparable trends.

CFs that are AWARE based within the cut-offs and DTR based show similar behaviours with respect to the area (linear), water availability in the region and human consumption (exponential-like shape, but at a higher order of magnitude for DTR). The relation with respect to the ecosystem demand differs as it is exponential-like and linear with AWARE- and DTR respectively, however the range of applications reduces the gap between them. When there are no cut-offs, AWARE- and DTR-CFs seem quite identical.

A non-linearity for D_E could be introduced by considering both the DTRs of the ecosystem and of human demands (see alternatives 1 and 2 in supplementary materials). With these configurations, both the human and ecosystem uses are addressed jointly, as it is done with the AWARE model. Nevertheless, it renders the model more complex without actually modifying its meaning. It therefore seems appropriate to keep the DTR defined here which is simpler.

One could also reasonably wish for a linear relationship between CFs and C_H, assuming that a human water appropriation twice larger should induce a two-fold stronger impact. Nonetheless this leads to DTA$_X$ or ADP based CFs (see alternative 3 in supplementary materials). While this kind of relationship is probably better justified by the ADP reasoning (Guinée and Heijungs, 1995), or by considering it as a marginal approach to dynamic stock models (Hélias et al., 2018; Hélias and Heijungs, 2019), than by the argument presented in Boulay et al. (2018), this shape of model was not selected by the WULCA group. By choosing the AWARE, the impact is expected to grow increasingly faster as consumption increases.

Looking at CF_{AW} with respect to A or C_H, the upper cut-off induces a "saturation": above the limit, the CF does not change. This is expected with relationships such as the cumulated normal law or the logistic law (i.e. an exponential limited increase) which has been used in previous models. The WULCA group chose not to introduce this kind of scaling functions due to lack of knowledge on curve tuning parameters. No additional scaling function is thus used in the DTR to overcome the cut-off limitation. It is worthwhile to design the impact (and not the CF) as a logistic function of human consumption, by only using the ecosystem demand for tuning parameters. However, this becomes another topic to discuss.

4. Conclusion

AWARE consensus model brings a major benefit to the community by proposing a shared standard. However, AWARE relationship is only defined when human consumption has spared sufficient water for an ecosystem in fair condition and loses its validity for more severe situations. This leads to the introduction of cut-offs. By defining impact as the fraction of ecosystem demand on what is left by human activity, the DTR model proposed in the present work makes it possible to overcome this limitation.

The DTR model is justified by differences in the definition between the demand for the ecosystem (requested quantity to a fair state) and for human use (effective consumption). The marginal and average approaches used on this model lead to corresponding factors. The formal sensitivity analysis showed that the DTR model provides similar features as the AWARE model but can cover all situations. It can therefore be used instead, while guaranteeing the same outcome behaviour without validity limitations.

The consensus construction that led to the AWARE model was a necessary and useful task. It resulted with the proposition for a unique midpoint water impact indicator, useful for LCA by practitioners which need consensual and validated impacts. Research in LCA has to take into account two aspects: operationalization by standardization and its improvements in modelling for future use. This work addresses the second aspect in particular.

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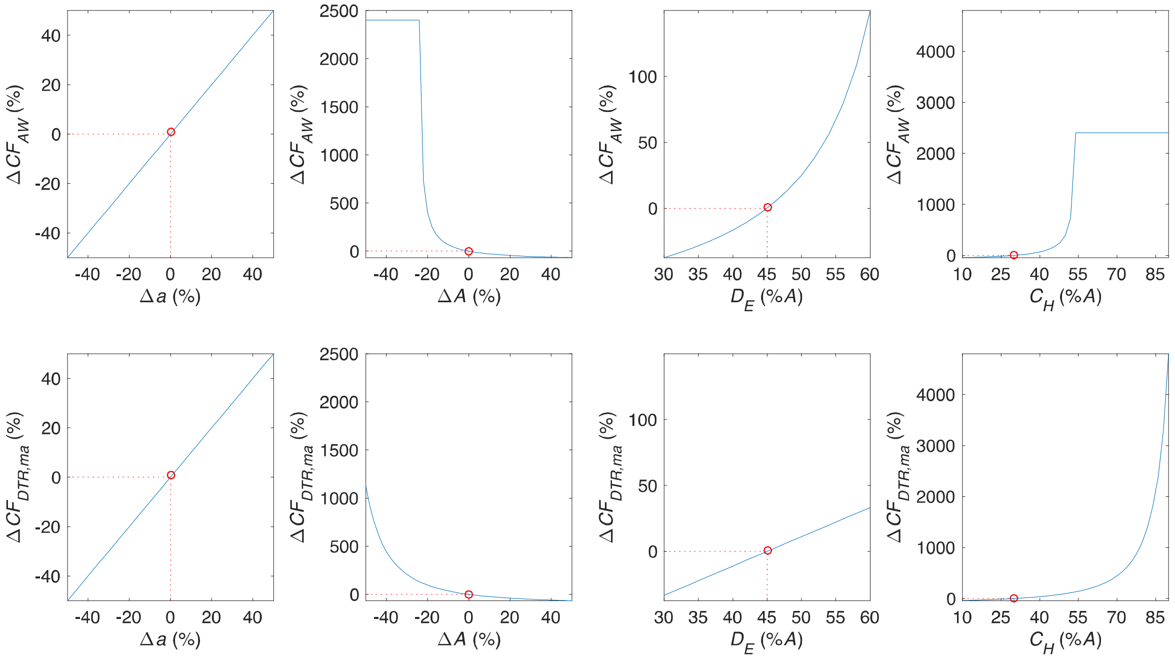
Figure captions

Figure 1. Illustration of the sensitivity of the characterization factors according to the model parameters. The circle is the arbitrary reference point.

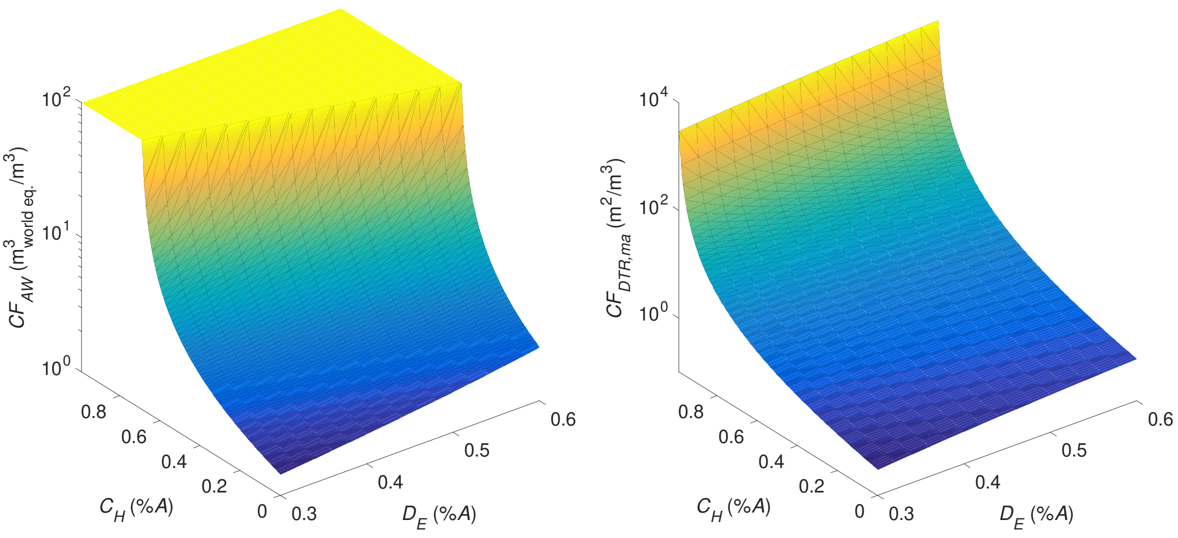
Figure 2. a) AWARE and b) marginal DTR characterization factors as a function of human water consumption ($0 \leq C_H \leq 99\%A$) and ecosystem demand ($60\%A \leq D_E \leq 60\%A$). Z-axis is in log-scale.

Figure 1

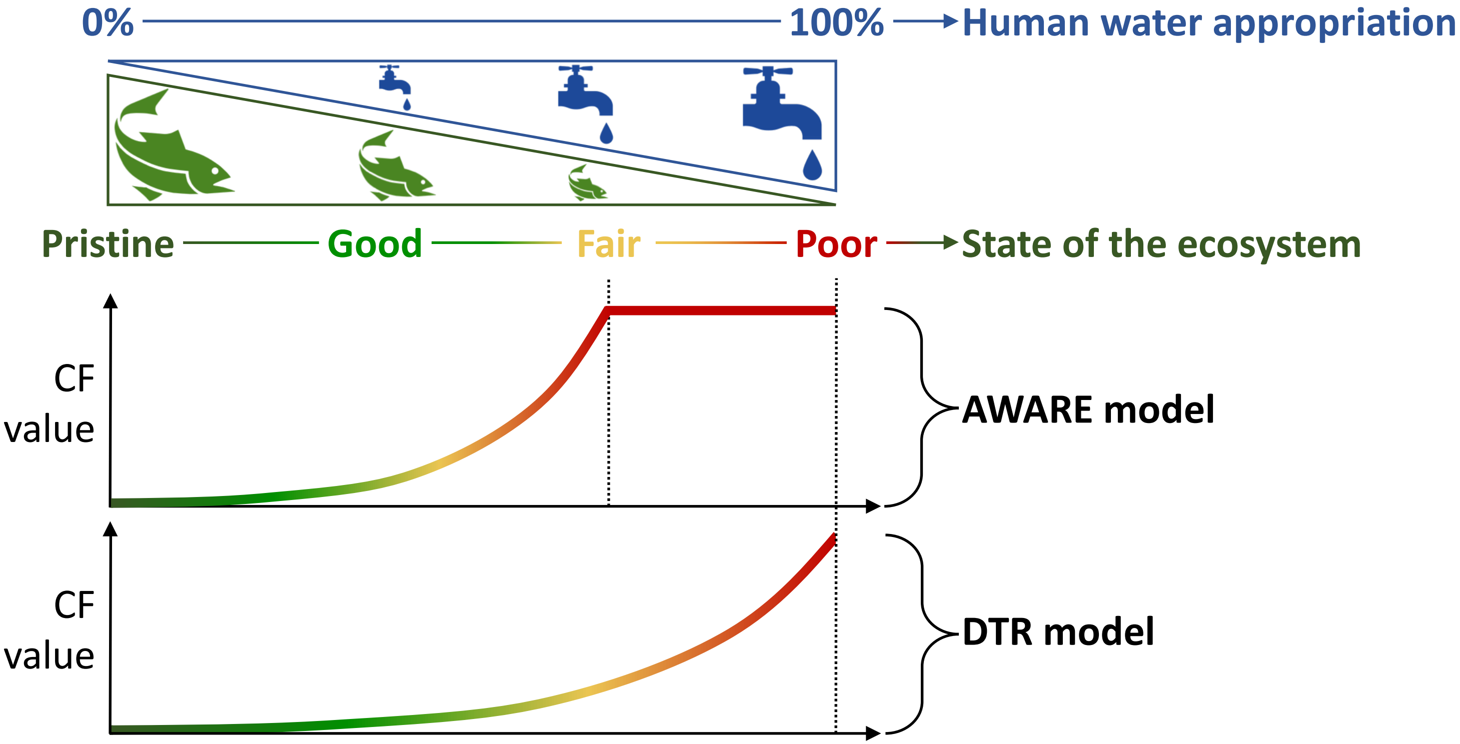


ΔCF_AW (%)
40
20
0
-20
-40
Δa (%)
2500
2000
1500
1000
500
ΔA (%)
100
50
30
35
45
50
55
60
D_E (%A)
4000
3000
10
25
70
85
C_H (%A)
ΔCF_DTR,ma (%)

Figure 2


10^2
10^1
10^0
CF_{AW} ($m^3_{world\ eq.}/m^3$)
0.8
0.6
0.4
0.2
0
C_H (%A)
0.3
0.4
0.5
0.6
D_E (%A)
10^4
10^2
10^0
$CF_{DTR,ma}$ (m^2/m^3)
0.8
0.6
0.4
0.2
0
C_H (%A)
0.3
0.4
0.5
0.6
D_E (%A)

a) *b)*


0%
100%
Human water appropriation
Pristine
Good
Fair
Poor
State of the ecosystem
CF value
AWARE model
CF value
DTR model