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Quantification of Stress Arisen from Freshwater Consumption in the Context of Life Cycle Assessment

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1. Introduction

Freshwater is one of the most essential resources for living things on the earth. Increasing water demand due to population and economic growth in the world may threaten the balance of freshwater supply and demand. Consequently, almost 30% of world population is expected to be suffering from water scarcity in 2025 according to the UNESCO's prospects [1]. Physical scarcity of freshwater will cause several kinds of stress on human and ecosystem. In order to avoid or minimize the effects of freshwater scarcity, the balance of freshwater demand and resource amount should be managed appropriately.

Freshwater is consumed not only directly but also indirectly in our activities. For instance, a cup of coffee directly requires freshwater for dripping coffee and washing a cup and drip equipment. In addition, freshwater is indirectly consumed for making a cup of coffee through the life cycle (growing coffee plants, processing coffee beans, producing packaging and so on) [2-3]. Thus, freshwater consumption should be analyzed and managed in the context of life cycle thinking.

As a tool for accounting stress of freshwater consumption based on life cycle concept, water footprinting has attracted high attention in recent years. Water footprinting generally accounts both the volume of consumed freshwater and the impact resulting from freshwater consumption. The stress of freshwater consumption will be different among regions. In this context, to quantify the impact of freshwater consumption with the consideration of regional differences has been seemed to be of significance and several researches on this topic have been performed for modelling the impact of freshwater consumption as life cycle impact assessment model.

The stress arisen from freshwater consumption can be identified in two steps (midpoint and endpoint) in accordance with general life cycle impact assessment methodology. In the midpoint assessment, physical scarcity of freshwater due to consumption is quantified by considering freshwater availability in each region. Endpoint assessment focuses on more concrete damage caused by freshwater consumption. The details of advanced knowledge on quantifying stress of freshwater consumption, from physical scarcity to concrete damage on human and ecosystem, in several researches will be introduced in the following sections as state-of-the-art activities for accounting water stress in the quantitative aspect.

2. Midpoint assessment

The critical problem of water consumption is the availability loss of freshwater for downstream users. If withdrawn freshwater were returned to the original basin without any quality degradation (chemical and thermal), the availability of freshwater for downstream users are not restricted and no stress can be arisen. In such case, the amount of withdrawn water is defined as “water use” and excluded from accounting the stress of freshwater consumption [4-5]. Disappeared and/or degraded amount of freshwater is defined as “water consumption” and accounted for assessing the stress of freshwater consumption in both midpoint and endpoint assessment.

Midpoint assessment in life cycle impact assessment is the step to quantify the scientifically clear and category specific change in the environment. For instance, greenhouse gas emission will cause the change of radiative forcing and result in human health damage like malaria and dengue fever. While human health damage is a common issue among different environmental categories, the change of radiative forcing is a unique natural phenomenon relevant to global warming. Thus, the change of radiative forcing is generally selected as the indicator of global warming at midpoint level. In accordance with this concept of life cycle impact assessment, physical scarcity of freshwater is defined in most researches as the indicator of freshwater consumption stress at midpoint level.

Several methods on midpoint assessment have been proposed [5-10]. The basic and common concept of impact assessment indicator on freshwater consumption at midpoint level is the ratio of consumed amount of freshwater to the amount of available freshwater resources, indicating physical scarcity of freshwater as shown in equation 1.

$$\text{The impact indicator} = \frac{\text{Consumed amount of freshwater}}{\text{The amount of available freshwater}} \quad (1)$$

Methods on midpoint assessment can be characterised by the consideration of influential factors (the threshold of available freshwater resource amount, temporal variation, spatial differences, non-linearity of sensitivity to scarcity and quality of freshwater resources). Characteristics of each method in the above describe five factors are as follows.

1. The threshold of available freshwater resource amount

All the amount of freshwater resources is not necessarily available. Thus, some methods applied threshold amount of freshwater resources [5-8]. Frischknecht et al. [5] adopted 20% of total freshwater resources as a threshold based on expert judgement. Mila i Canals et al. [6] and Hoekstra et al. [7] considered environmental water requirement including ecosystem as an elementary water demand. The difference between total amount of freshwater resource and environmental water requirement is defined as the amount of available freshwater in their methods. Boulay et al. [8] differentiated surface water from groundwater as freshwater resources and defined 90% low flow (the low flow is exceeded in 9 month out of 10) of surface water as the threshold in order to exclude unusual high flow effects. Determination of a threshold of freshwater resource is different among methods and generally performed by expert judgment, and it can be a critical argument point.

2. Temporal variability

The amount of freshwater resource tends to have temporal variation (ex. differences between the dry seasons and the rainy seasons). The monthly variation of available freshwater resource (river runoff) was estimated by Hoekstra et al. [7]. Actually, stored freshwater (like pond, lake, dam and so on) can be available freshwater resource in addition to flowing water. Pfister et al. [9] considered temporal variation of precipitation (monthly and annual) in assessing available freshwater resource including stored water by introducing variation factor of annual and monthly precipitation.

3. Regionalized differences

Freshwater supply by precipitation and influential factors on that (like climate and landform condition) are not even on the earth. Thus, the availability of freshwater is spatially different. Spatial difference is taken into account in each method on different resolution (on country scale to grid scale). Detailed resolution would be preferable in the context of science. However, very detailed site specification might be not necessarily practical because supply chain of products and companies are too complicated to specify the precise location of consumed freshwater. Both of preciseness and applicability should be harmonised from the view point of practical use.

4. Non-linearity of sensitivity to scarcity

The increase of freshwater consumption results in increasing the impact of physical water scarcity, but obviously the rate of the increase will not be equal between resource abundant and scarce area. In the Swiss Ecological Scarcity Method [5], the ratio of critical water flow and current water flow was squared to reflect the severity in freshwater scarce region and the strength in freshwater abundant region. Pfister et al. [9] described non-linearity between available freshwater resource amount and impact of freshwater consumption by adjusting equation 1 to a logistic function. As a result, resource abundant areas are not sensitive to freshwater availability change, and resource scarce areas are sensitive to that. Potential adaptability to freshwater

consumption in the physical aspect of freshwater resources is reflected in the method. On the other hand, Boulay et al. [8] also considered non-linearity between withdrawal-based and consumptive-based amounts of freshwater by applying the S-curve fitting on the basis of regression analysis. This method seems to focus on the adaptability to freshwater consumption in the social aspect of freshwater use rather than physical aspect of resources.

5. Quality of freshwater resources

Freshwater availability will be also controlled by the quality of resources and of emitted/returned water. From the perspective of input freshwater quality, the freshwater availability of downstream user depends on the quality of resource even if the same amount is consumed. Pure quality freshwater can be used by most users but degraded freshwater in chemical/thermal composition will be available for only limited users. "Gray water" is one of the concepts to reflect the impact of quality degradation of water. The emissions with used water will demand freshwater for the dilution of the emissions to avoid restricting downstream users' availability. The amount of freshwater enough to diminish the emissions to the acceptable level (generally environmental criteria of the basin) is regarded to be consumed virtually. Gray water is the amount of assumed freshwater volume for the dilution. This concept was adopted to take the quality degradation into account in two studies [7, 10]. A point to notice is that gray water is not actually consumed freshwater but virtually assumed consumptive freshwater. Boulay et al. [8] developed the impact indicators correspond to the quality of freshwater resource by considering threshold value of the quality for each user's demand. In addition, their method can assess the impact in quality of not only input water but also output water by calculating the difference between negative effect of withdrawn water and positive effect of returned water.

In the context of midpoint assessment, existing methods have unique characteristics by considering a different combination of above aspects. Thus, the relevance of each aspect is difficult to be clarified through simple comparison of impact factors of each method. On the other hand, the consideration of influential factors on the impact of freshwater scarcity made it possible to reflect the actual situation relevant to freshwater scarcity. For instance, rank of renewable freshwater resource per capita in each country [11] and impact factors on freshwater consumption developed by Pfister et al. [9] are shown in Figure 1, Figure 2, respectively. Higher ranked countries (severe to water scarcity) are deeply colored in Figure 1, Figure 2. Severity in resource amount and impact factor shows similarity in some countries but difference in others. A typical difference can be seen in Australia. While the amount of freshwater resource is abundant, stress to water scarcity is relatively higher. Method of Pfister et al. [9] integrated temporal variation of precipitation, and actually drought has sometimes occurred in Australia. Such a real condition in some aspects could be reproduced in existing methods on midpoint assessment. However, it should be verified through the comparison with endpoint assessment model whether a midpoint assessment model is adequate to represent the final consequences of freshwater consumption.

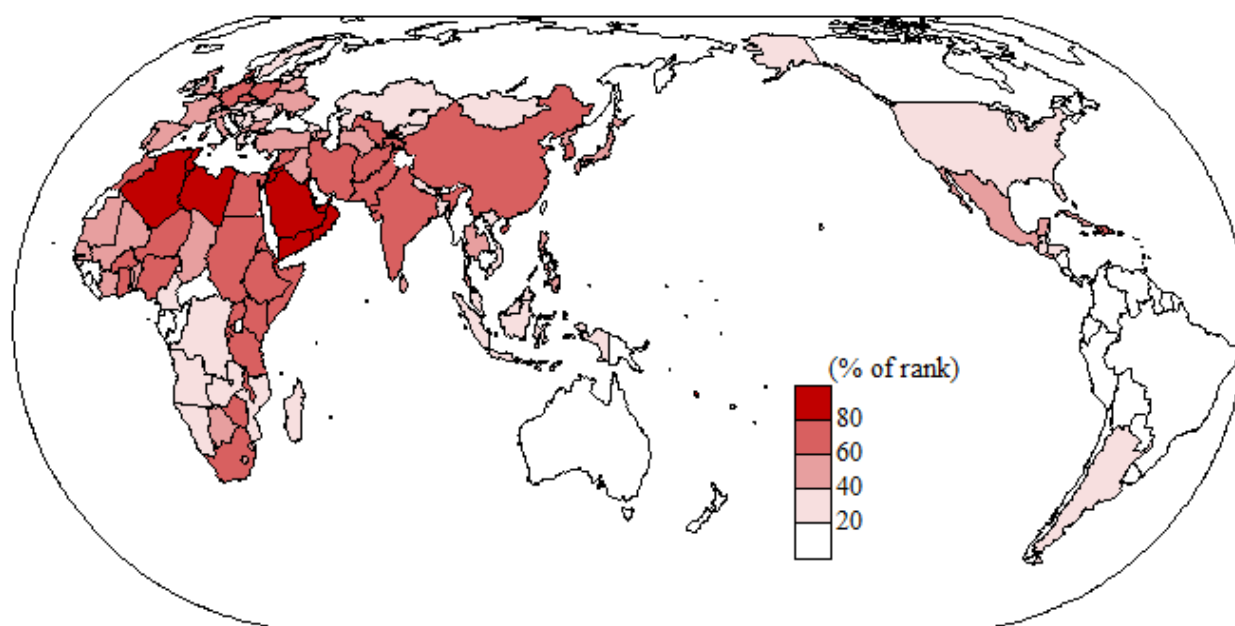


Figure 1. Renewable freshwater resource per capita in each country

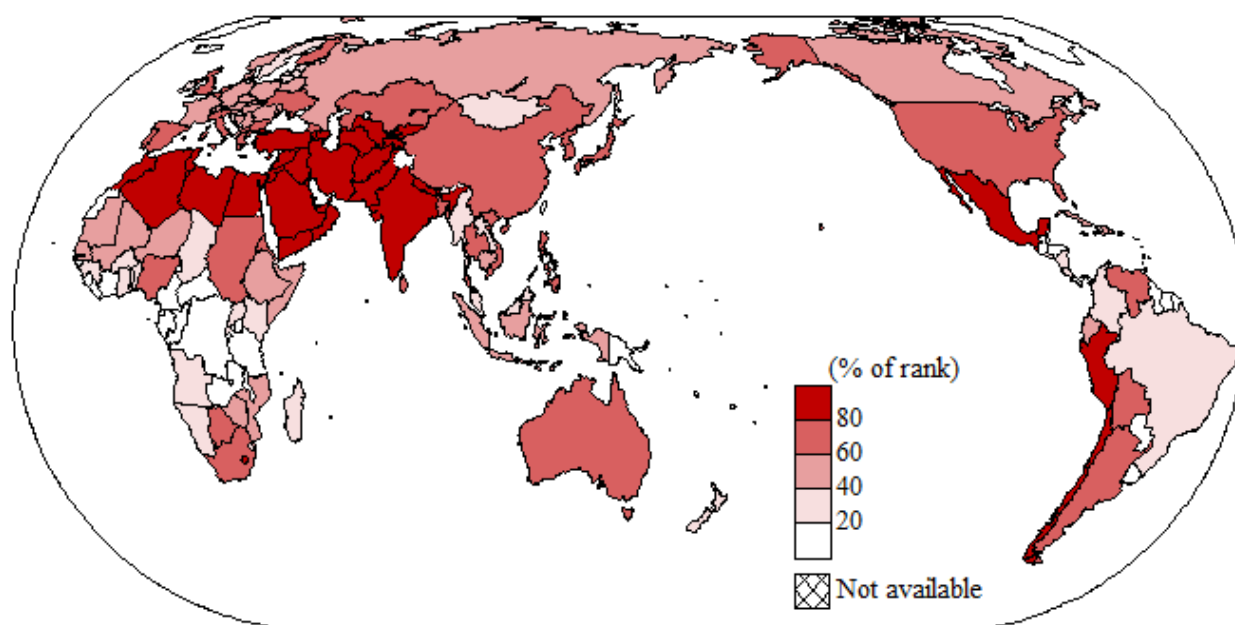


Figure 2. Impact factors (water stress index per unit volume freshwater consumption) of each country [9]

3. Endpoint assessment

Freshwater consumption will cause several kind of damage on human and ecosystem through physical water scarcity. As major endpoints of freshwater consumption, damage on

human health, ecosystem and resources is modelled in several studies. Classification of endpoints and corresponding assessment methods are summarized in Table 1. Details of modelling on each endpoint are explained in the following sections.

Users of freshwater suffering from scarcity		Endpoint and specific consequences		Corresponding assessment methods
Human society	Domestic water	Human health	Increasing damage of infectious diseases	Boulay et al. [8], Motoshita et al. [13]
	Agricultural water		Increasing damage of malnutrition	Boulay et al. [8], Pfister et al. [9], Motoshita et al. [15]
		Resources	Agricultural, animal and aquacultural commodity production loss	Motoshita et al. [15]
	Industrial water		Economic production loss	No method available
	All users		Surplus energy demand for compensation	Pfister et al. [9]
Ecosystem	Terrestrial species	Ecosystem	Plant growth prevention	No method available
			Species extinction due to habitat loss	Pfister et al. [9], van Zelm et al. [18]
	Aquatic species			Maendly and Humbert [19]

Table 1. Classification of endpoint relevant to freshwater consumption

3.1. Human health

Human health damage is one of the most major endpoints as a consequence of freshwater consumption. According to the report of World Health Organization (WHO), almost 9% of total health damage (including both mortality and morbidity) in the world is estimated to be arisen from water, sanitation and hygiene [12]. Particularly, diarrhoeal disease and malnutrition are account for over 70% of water-related health damage, and they seemed to be highly related to the availability of freshwater. Thus, human health damage of infectious diseases and malnutrition due to freshwater consumption has been quantified in previous studies [8, 9, 13, 15].

Infectious diseases will be arisen from the intake of low quality water in the context of freshwater consumption. Damage of four infectious diseases (Ascariasis, Trichuriasis, Diarrhoea, Hookworm disease) related to freshwater consumption was modelled by Motoshita et al.

[13]. The relationship between infectious disease damage and freshwater availability loss on country scale was analyzed based on statistical data by applying multiple-regression model with the consideration of social and economic factors (GDP per capita, capital formation expenditure per capita, temperature, accessibility to safe water/sanitation, nutritional condition and medical treatment opportunity). Boulay et al. [8] evaluated damage of both diarrheal disease and nematode infections caused by freshwater consumption in each country. Health damage due to freshwater consumption on country average was estimated by dividing a deficit volume of freshwater (the difference between actual use and minimum requirement of domestic water) into damage of target diseases per country. Country specific social condition was also considered by introducing the adaptation capacity parameter using gross national income (GNI).

The shortage of freshwater for food production as a consequence of freshwater consumption will cause the nutritional deficit. On the other hand, social and economic conditions in each region will control the effects of nutritional deficit due to freshwater consumption. In the method of Pfister et al. [9], Human Development Index (HDI) was adopted as an explanatory indicator for social and economic condition. HDI is an indicator for representing development degree of each country with the consideration of health (average life expectancy), education (adult literacy and gross enrolment) and economic level (gross domestic production per capita) [14]. The relationship between malnutrition damage and HDI was modelled by regression analysis based on statistical data on country scale and was adjusted from 0 to 1 to reflect the vulnerability to nutritional deficit due to freshwater consumption in each country. More straightforward factors were used to explain the relationship between malnutrition and water scarcity in the modelling by Motoshita et al. [15]. Parameters on nutritional and medical conditions (average food consumption level, gaps in food consumption (Gini coefficient) and medical treatment expenditure per capita) were applied to malnutrition damage modelling by using multiple regression analysis. In addition, food shortage in a country will spread to other countries through international trade. Such a ripple effect was also integrated into the modelling to reflect the interaction among countries. While Boulay et al. [8] simply estimated malnutrition damage due to freshwater shortage by dividing the water requirement per calorie into malnutrition damage per unit total calorie deficit on country scale, differences of social and economic situations among countries were considered by applying adaptation capacity parameter (GNI) as same as the modelling on domestic water scarcity. Aquaculture is one of the nutritional resources in some countries. Boulay et al. [8] considered the effect of freshwater shortage in aquaculture while other two methods [9, 15] on malnutrition damage did not consider.

The significance of infectious disease and malnutrition damage can be compared based on the characterisation factors of Motoshita et al. [13, 15]. Both damage of infectious disease and malnutrition caused by freshwater consumption on country scale was shown in Figure 3. Malnutrition damage due to agricultural water scarcity is dominant in most countries, except for some countries. Most countries close to the equator (many in African regions and few countries in American region and West pacific region) appear to show high vulnerability to infectious disease in the context of freshwater consumption.

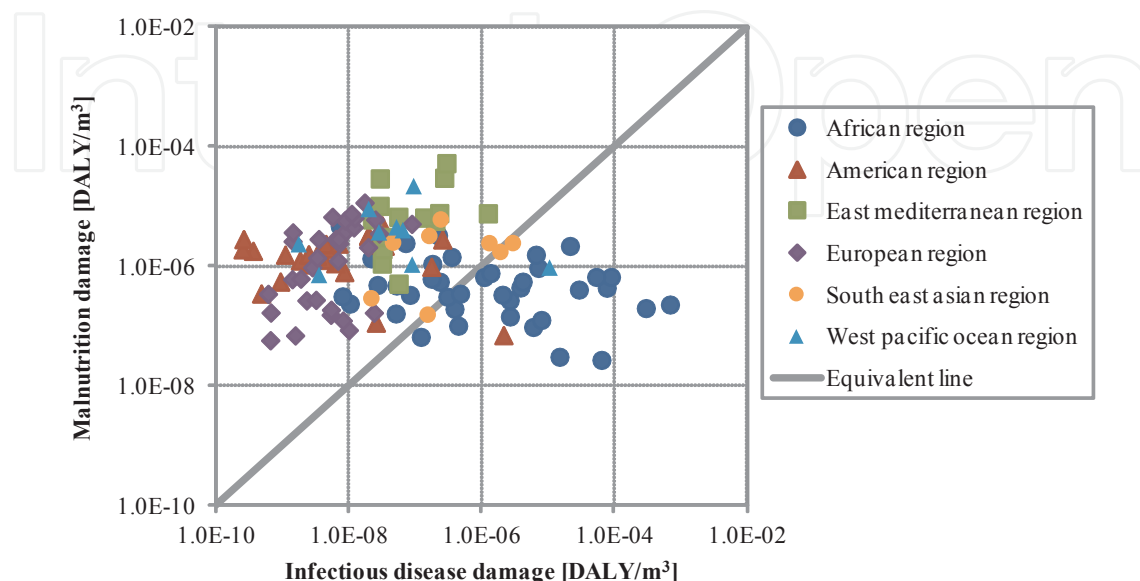


Figure 3. Comparison of infectious disease and malnutrition damage per unit volume freshwater consumption [13, 15]

All methods related to health damage assessment are not comparable because approaches and targets of the assessment are not perfectly corresponding with each other. However, methods of Pfister et al. [9] and Motoshita et al. [15] can be comparable in the aspect of malnutrition damage due to freshwater consumption. Malnutrition damage per freshwater consumption in both methods is plotted in Figure 4. Damage in the method of Motoshita et al. [15] seems to be larger than that of Pfister et al. [9] in most countries. The differences between both methods in the aspect of modelling procedures are selected parameters for reflecting social and economic condition and the consideration of ripple effects by international food trade. Same comparison is shown in Figure 5 after preliminarily excluding international food trade model in the method of Motoshita et al. [15]. Damage of both methods becomes much closer and the opposite tendency to Figure 4 can be seen in Figure 5. Thus, the effect of international food trade might be significant for the differences between both methods. The other method of Boulay et al. [8] cannot be simply compared with others because both of infectious and malnutrition damage are included and not separated as characterization factors. However, the scale of damage is not so different from that in other two methods.

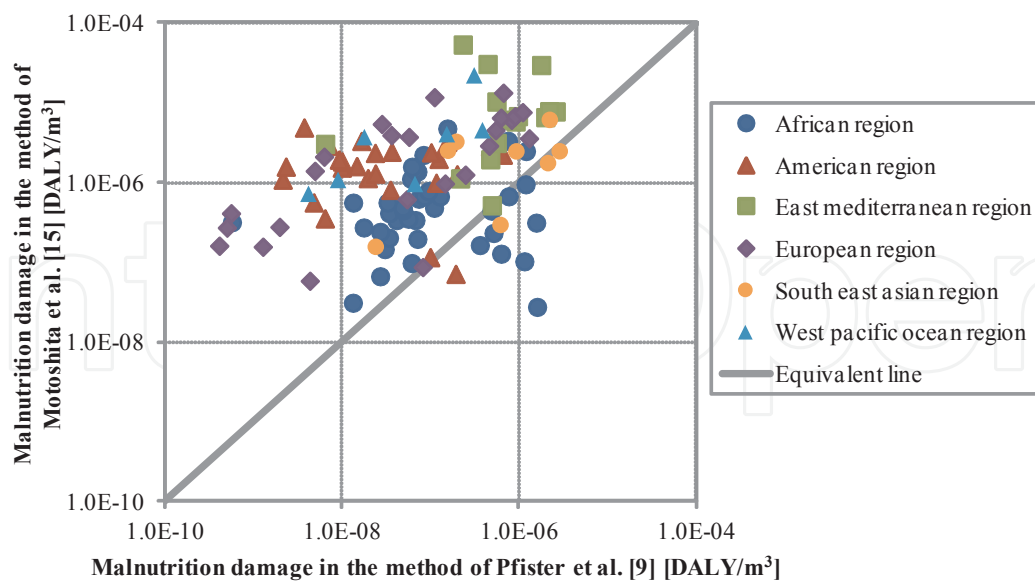


Figure 4. Comparison of malnutrition damage caused by freshwater consumption between in the methods of Pfister et al. [9] and Motoshita et al. [15]

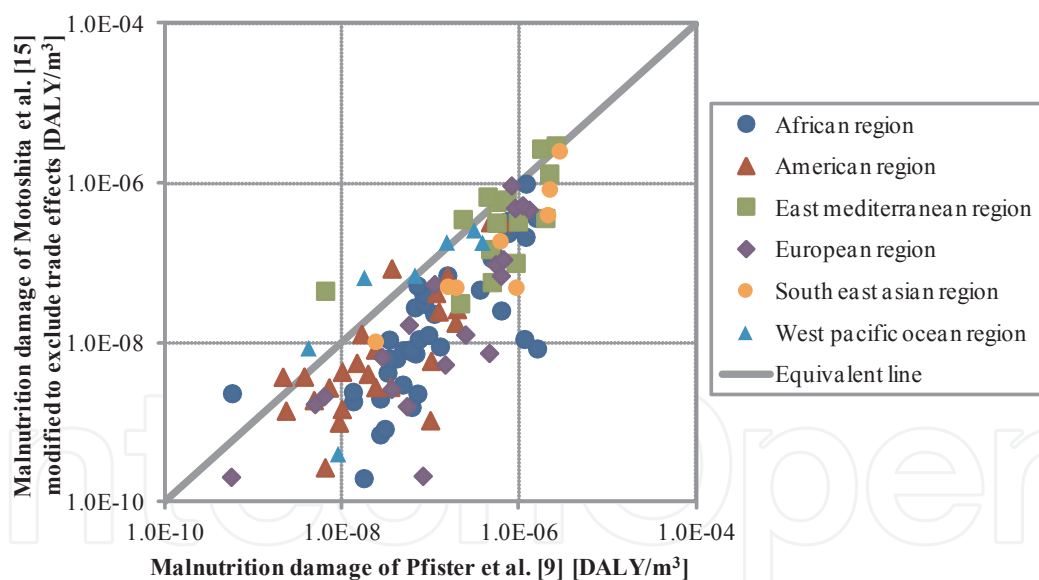


Figure 5. Comparison of malnutrition damage caused by freshwater consumption between in the methods of Pfister et al. [9] and modified Motoshita et al. [15] for excluding the effect of international food trade

3.2. Ecosystem

Freshwater resource is the essential not only for human but also ecosystem. Freshwater resource is utilized for sustaining life of living things and supplying habitats. Anthropogenic freshwater consumption may cause several types of effects on ecosystem. However, any

consensus on cause-effect chain of freshwater consumption related to ecosystem has not been reached yet because of its complexity. On the other hand, several challenges on quantifying the part of impacts on ecosystem due to freshwater consumption have been made. Overview of them is introduced in the following sections.

Anthropogenic freshwater consumption will reduce the availability of freshwater for sustaining plant growth. Prevention of plant growth as a consequence of freshwater consumption was modelled by Pfister et al. [9]. In their modelling, the amount of net primary production (NPP) loss was calculated on grid scale for whole world by using the model calculating NPP limited by water availability [16]. Obtained NPP loss due to freshwater consumption was converted to vascular plant species biodiversity (VPBD) on the basis of the correlation analysis results between VPBD and NPP. Vascular plant species biodiversity was expressed by adopting the index of potentially disappeared fraction (PDF) used in Eco-indicator'99 [17]. While compensation by precipitation was considered in the model, the fate of freshwater from consumption to the availability loss for plants was very simplified by regarding that all the amount of consumed freshwater would restrict plant growth except for barren lands. Site specific water flow relevant to groundwater extraction was considered in the context of Netherland by van Zelm et al. [18]. The probability of occurrence of individual plant species was estimated by using the soil moisture indicator and the soil moisture could be described as a function of average groundwater level. The change of average groundwater level was modelled by hydrological zone model on grid scale. As a result, biodiversity loss of terrestrial plant species caused by groundwater extraction was quantified for the Netherland by using the indicator of potentially not occurring fraction of plant species (PNOF), which is almost same concept as PDF.

Consumption of freshwater may decrease habitats for aquatic species. Maendly et al. [19] modelled the effect of hydropower water dam on the number of aquatic species in downstream based on actual observed change of individuals of aquatic species due to dam construction. The effect of water demand for hydropower was express by adopting PDF. Generalized impact factor is proposed in the model, however it should be noted that the extrapolation was performed based on limited observation data (mainly in the context of Europe and United States of America).

3.3. Resources

Resources are determined as an endpoint of environmental load in life cycle impact assessment. However, "Resources" indicates very wide and fuzzy meanings. The safeguard subject relevant to "Resources" is dependent on methods due to their philosophy [17, 20, 21, 22]. In this context, damage on resources due to freshwater consumption has been quantified in different aspects.

For instance, depletion of fossil fuel or minerals will result in surplus energy demand for future generation to extract from lower grade resources [17, 20]. The same concept was adopted by Pfister et al. [9] for freshwater consumption. In the method, surplus energy demand for compensating the amount of consumed freshwater by desalination was evaluated as

damage on resource only for the countries in that freshwater was overused compared with the available amount of freshwater. Surplus energy for compensation was calculated based on the state-of-the-art technology of desalination in the unit of MJ/m³. Advantageous point of this method is high consistency with damage caused by consumption of other resources and fossil fuels [17, 20]. The significance of damage caused by resource consumption including freshwater consumption is comparable in the same unit (MJ).

Economic value of resources is also regarded as an endpoint of environmental impact and will be lost by resource consumption [21, 22]. In the same meaning, the economic loss of agricultural commodity due to agricultural water scarcity was quantified by Motoshita et al. [15]. The loss of agricultural commodity due to freshwater consumption was calculated based on crop productivity per unit volume of water on country scale and commodity price. In this context, animal commodity and aquacultural commodity should be also affected by freshwater consumption but did not considered in the method at present.

4. The specific example of the application to water footprinting

There are many kinds of methods from the perspectives of midpoint and endpoint as introduced in the above section. The specific example of the application will be helpful for understanding the significance of impact assessment in the context of water footprint. As an example, Pfister et al. [9] reported the results of impact assessment due to freshwater consumption in cotton textile production based on their method at midpoint and endpoint on country scale. The amount of freshwater consumption in 1kg cotton textile production and its impact at midpoint (shown as water deprivation) is shown in Figure 6. Generally, the impacts at midpoint level (physical scarcity) increase with the amount of consumed freshwater in Figure 6. However, some countries show relatively low impacts due to the physical abundance of available freshwater resources.

On the other hand, the impacts for each country at endpoint level are plotted against to those at midpoint level in Figure 7. The difference between physical stress of freshwater resources and specific results of water scarcity can be found out. For instance, Mali showed relatively lower impact than Australia in Figure 6, but human health damage as an impact at endpoint level is larger than Australia. While almost same amount of freshwater consumed for 1kg cotton textile production in both countries, the impacts at midpoint and endpoint shows opposite tendency. Thus, physical scarcity is not necessarily available for perfectly substituting for specific results of freshwater consumption.

The results of endpoint assessment on human health and ecosystem due to freshwater consumption for 1kg cotton textile production are shown in Figure 8. While human health damage due to freshwater consumption is relatively serious rather than damage on ecosystem in India and Mali, damage on ecosystem is more significant in Argentina, Australia and Mexico. The consequences of freshwater consumption are different among countries even though in the perspective of endpoint assessment.

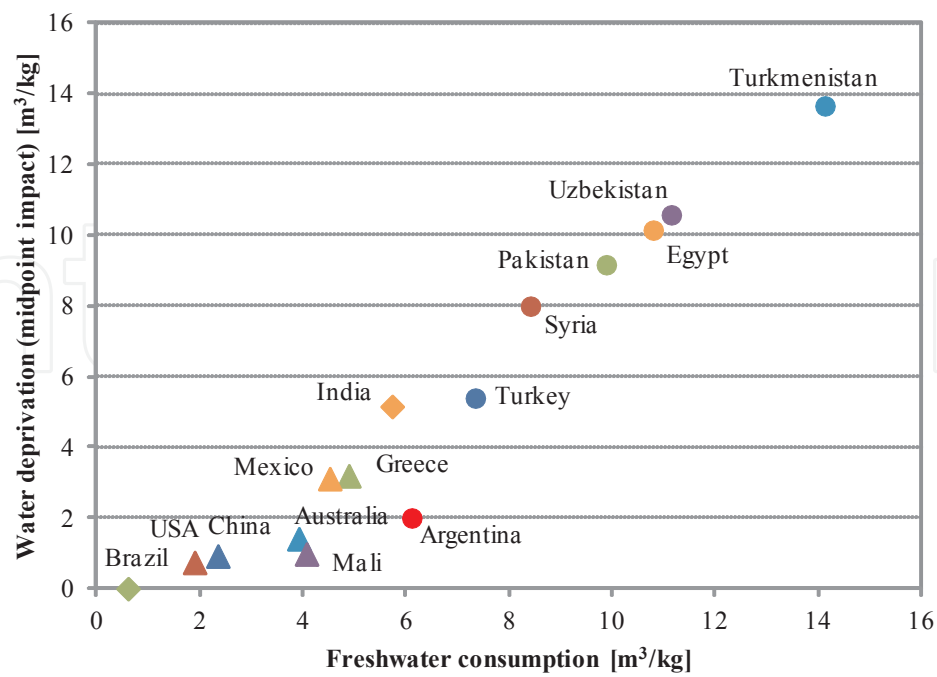


Figure 6. The comparison between the amount of freshwater consumption for cotton textile and its impact (water deprivation) at midpoint level

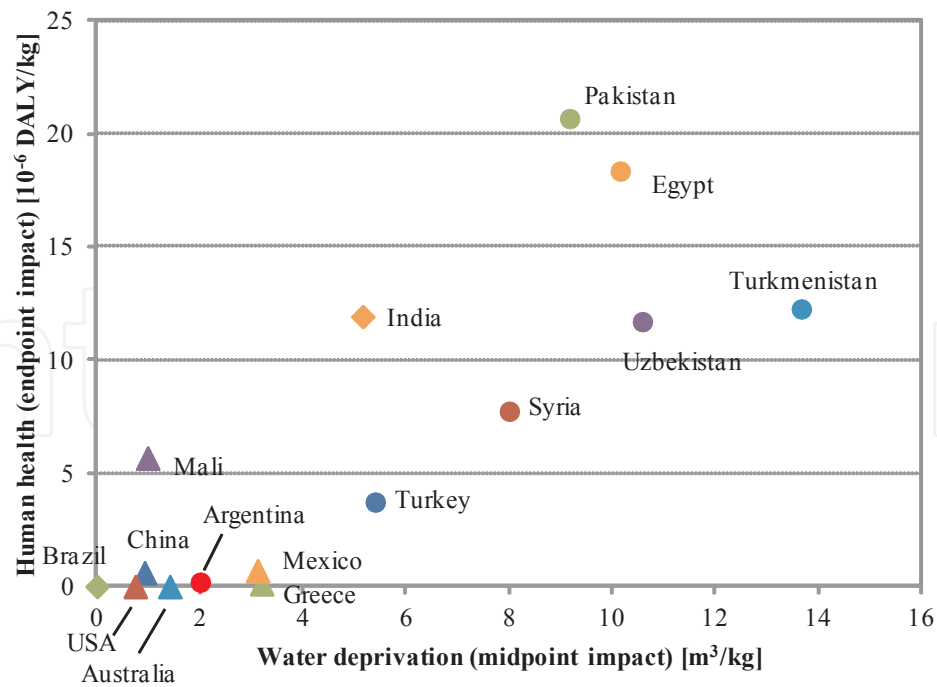


Figure 7. The comparison between water deprivation (midpoint impact) and human health damage (endpoint impact) due to freshwater consumption for cotton textile production

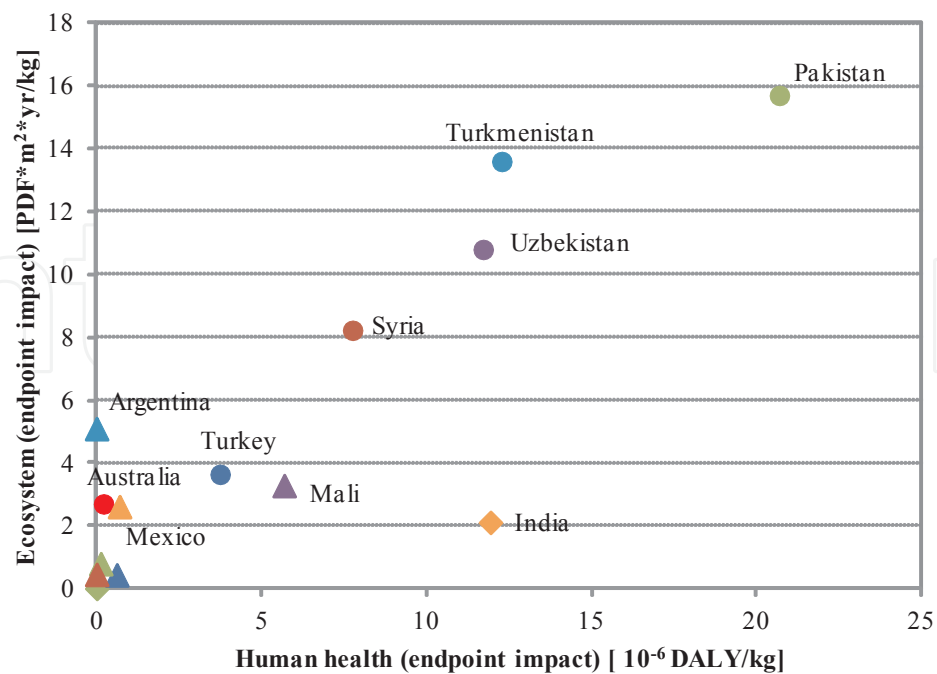


Figure 8. The comparison between damage on human health and ecosystem due to freshwater consumption for cotton textile production

5. Summary

As shown in the example of water footprinting, the amount of consumed freshwater is not an enough indicator to consider water stress in the quantitative aspect. There are many methods relevant to from midpoint to endpoint. Midpoint assessment is based on the physical scarcity and close to the cause side of freshwater consumption. The results of midpoint assessment have more robust relationship with freshwater consumption. On the other hand, endpoint models focus on the specific results of freshwater consumption and close to the effect side of freshwater consumption. Generally, uncertainty of the assessment results may increase in endpoint assessment due to considering the cause-effect chain of freshwater consumption. However, the assessment at endpoint level will make it possible to compare the effects of other environmental categories related to same endpoint. Therefore, water stress due to freshwater consumption should be assessed in both aspects of midpoint and endpoint. In addition, each assessment method has different characteristics on the basis of their philosophy. Sensitivity analysis by using multiple methods will be useful to verify the robustness of the assessment results. In recent years, many methods for quantifying water stress in the quantitative aspect have been developed. However, there is still more space to sophisticate the methods for more precise assessment and expand the targets of the modeling (ecosystem and resources in endpoint assessment).

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