PART B: HUMAN HEALTH EFFECTS

5.13 Scope

Water use may cause a variety of potential human health impacts through different impact pathways as depicted in a previous study (Figure 1: Kounina et al. 2013). There are generally three main types of water use for human needs: domestic, agricultural, and industrial use. The lack of water for human needs may lead to human health damages for those uses that are essential, mainly domestic and agricultural uses (Kounina et al. 2013; Forouzanfar et al. 2015) .

Water deprivation for domestic use may increase the risks of intake of low quality water or lack of water for hygienic purposes, and consequently may result in the increase of damages from infectious diseases, such as diarrhea.

Water demands in agriculture (irrigation) and fisheries or aquaculture are usually essential water needs for human nutrition in many areas of the world. In this context, deficit of water in agriculture and fisheries or aquaculture may decrease food production, and consequently result in the increase of malnutrition damage due to the shortage of food supply.

Previous publications covering these issues were considered as a starting point for this discussion: i) Pfister et al. (2009), Boulay et al. (2011) and Motoshita et al. (2014) regarding agricultural water scarcity, and ii) Boulay et al. (2011) and Motoshita et al. (2011) regarding domestic water scarcity. Moreover, preliminary steps towards harmonization were performed as part of the WULCA (Water Use in LCA) mandate and the different models and modeling choices were analyzed in detail by Boulay et al. (2015a), identifying the significant differences of the methodological concepts of the characterization factors.

A group of experts was consulted in 2015 to answer several questions that appeared during the testing of the existing methods. The debate about these questions resulted in the following conclusions:

- Differentiating between groundwater and surface water, as well as separation between different water quality classes would be nice to have, but likely not feasible with a reasonable amount of effort. Further work on possible double counting of e.g., the effects of health impacts from toxic emissions and inclusion of human health impacts associated with lower water availability due to decrease of water quality should be performed.
- It was deemed important to assess the trade of agricultural products when quantifying food supply shortage due to agricultural water deprivation.
- Regarding human health impacts of domestic water deprivation, no clear preference was provided on any of the existing approaches.
- It was suggested to consider the adaptation capacity and assess it based on an indicator derived from Gross Domestic Product (GDP), Gross National Income (GNI), or Human Health Index (HDI), with no clear preference stated.

5.14 Impact pathway and review of approaches and indicators

5.14.1 Domestic water scarcity

Two models have been developed to assess the potential human health impacts through spread of infectious diseases by water consumption: Motoshita et al. (2011) and Boulay et al. (2011). The cause-effect chain is modeled such that any water consumption in a watershed may cause deprivation based on local scarcity and incapacity to adapt economically, leading to a lack of water for domestic users and consequently impacts of reduced domestic water on human health. The equation of characterization factors in both models can be generalized as follows.

$$CF_{domestic} = SI \times DAU_{domestic} \times SEE_{domestic} \quad \text{(Eq. 1)}$$

where:

- $CF_{domestic}$ is the characterization factor of domestic water use [DALY/m^3];
- SI is a scarcity or stress index [-];
- $DAU_{domestic}$ is the fraction of water consumed by domestic users (Distribution of Affected Users: DAU,) [-];
- $SEE_{domestic}$ is the socio-economic effect factor of domestic water use [DALY/m^3].

A method comparison was performed in a previous study to understand the consistency between the models and uncertainty due to model choices (Boulay et al. 2015). Rank correlation coefficients (RCC) and mean difference coefficients (MDC) were calculated for the set of SEE factors from the previous models.

According to the results of the method comparison, high correlation between overall SEE factors from different methods for domestic water scarcity could be found; however, detailed sensitivity analysis of parameters in SEE factors would be necessary to identify influential factors in the modeling. 5.14.2 Agricultural water deprivation

Previous analysis done by Boulay et al. (2015a) showed that potential health damages due to aquaculture or fisheries water deprivation are insignificant compared with irrigation deprivation. Thus, human health damages related to aquaculture water deprivation was not further evaluated.

Regarding the malnutrition impacts due to agricultural irrigation deprivation, three models have been developed: Pfister et al. (2009), Boulay et al. (2011) and Motoshita et al. (2014). The cause-effect chain starts from any water consumption in a watershed, quantifies the lack of water for agricultural users, and consequently quantifies the impacts of reduced food production, considering local scarcity and economic adaptation capacity. Reduced food production might directly influence domestic food availability on the one hand, and have an impact on the world market on the other hand. The impact on the world market may indirectly affect people in other countries through trade effects. Both pathways may lead to malnutrition and consequently human health impacts. The equation of characterization factors (CF) in these three models can be generalized as follows.

$$CF_{agricultural} = SI \times DAU_{agricultural} \times SEE_{malnutrition} \qquad \text{(Eq. 1)}$$

where

- $CF_{agricultural}$ is the characterization factor of water scarcity of agricultural water use [DALY/m^3];
- SI is a scarcity or stress index;
- $DAU_{agricultural}$ is the fraction of water consumed by agricultural water users [-];
- $SEE_{malnutrition}$ is the socio-economic effect factor of agricultural water use [DALY/m^3].

A sensitivity assessment of the difference between $SEE_{malnutrition}$ in the different models has been performed (Boulay et al. 2015). Distinctly different results of Motoshita et al. (2014), which includes the trade effect by allocating food deficit effects to national and international impacts, suggest that the trade effect is an important element to include in the impact assessment model.

The evaluation of the different parameters and options composing the damage indicator CF used the same criteria as those presented in the scarcity chapter. In addition, the consistency between the impact category indicator for water scarcity and the damage indicator on human health was evaluated. The analysis of the proposed methods according to these criteria are presented in Table 5.5 (next page).

5.15 Description of indicator(s) selected

The indicator for the impact pathway for agricultural water deprivation published in Motoshita et al. (2014) is modified as follows:

$$CF_{agri}=\overbrace{\underbrace{(HWC_{agri}/AMC)}_{\text{Fate}}}^{SI\times DAU_{agricultural}}\times\overbrace{\left\{\underbrace{FPL\times DSR}_{\text{Exposure}}\times\underbrace{HEF}_{\text{Effect}}+\underbrace{FPL\times(1-DSR)\times\sum(ISR_i}_{\text{Exposure}}\times\underbrace{HEF_i)}_{\text{Effect}}\right\}}^{SEE_{malnutrition}}$$

Where:

- HWC_{agri} is the Human Water Consumption (HWC) in agricultural use (m^3);
- AMC is availability minus consumption, or more precisely, the water available minus human water consumption by all users (similar to the water scarcity indicator, AWARE, but not considering EWR, m^3);
- FPL is the food production losses as a result of reduced irrigation, measured in energy units (kcal / m^3);
- DSR is the domestic supply ratio of dietary energy from foods (including trade adaptation capacity, dimensionless);
- ISR_i is the import sharing ratio (including trade adaptation capacity, dimensionless) of country i;
- HEF is the health effect factor of a country where water is consumed (DALY/kcal) and
- HEF_i is the health effect factor of country i (DALY/kcal).
- All water consumption and availability data is based on WaterGAP 2.2 (Müller Schmied et al. 2014).

The determination of each indicator is described in further detail in section 5.16 below.

Table 5.5: Analysis of damage indicator parameters against selection criteria

Criteria	Fate	Effect factor			
	Withdrawal based	**Consumption based**	**SEE Local Malnutrition**	**SEE trade effect**	**SEE domestic water**
Stakeholders acceptance	Good: Applied in widely used methods	Good: Applied in widely used methods	Moderate: Applied in used methods	Low-moderate: Applied in some used methods	Low-moderate: Applied in some used methods
Main normative choice	Withdrawal is most relevant for depriving local users (local competition); AMC (availability minus consumption: actual availability) is used	Consumption is most relevant for depriving users in a watershed (watershed competition); AMC (actual availability) is used	Water deprivation on watershed level leads to reduced water availability for irrigation / link of DALYs due to protein-energy malnutrition to calorie deficit	Reduced food production in one country may affect world market and supply in other countries as a function of purchase power parity income	Water deprivation on watershed level may lead to reduced water availability for domestic use
Physical meaning	Share of water that potentially deprives other local uses [0,1]	Share of water that potentially deprives other uses within a watershed [0,1]	DALY from malnutrition / food calorie supply loss (induced by m^3 irrigation water deprivation [DALY/kcal] / [DALY/m^3]	Food calorie supply loss effects on trade per calorie loss in producer country (spatial distribution of consequence on country level) [DALY/kcal]	DALY from waterborne diseases / domestic water deprivation (induced by watershed domestic deprivation) [DALY/m3]
consistency with midpoint indicator	*Lower consistency (demand = withdrawal), ratio instead of A/AMC*	Higher consistency, *ratio instead of A/AMC*	*Not applicable*	*Not applicable*	*Not applicable*
Robustness with reference data	*Not available*	*Not available*	Underestimate impacts (mainly of reduced production in high income countries on other areas)	Improved *match with total malnutrition impacts*	*High uncertainty of cause-effect chain*

Three main aspects are adapted from Motoshita et al. (2014):

- The scarcity and DAU factors are combined in [HWC_{agri} / AMC] with monthly resolution, using CTA (Consumption to Availability) as a basis for scarcity, with availability reflecting actual availability (defined as AMC, availability minus consumption, consistently with scarcity indicator recommended), and DAU being based on the fraction of water consumed by agriculture.
- The income component of the inequality adjusted Human Development Index ($I\text{-}HDI_{income}$) is applied in DSR and ISR to reflect the trade adaptation capacity (whether the population will be able to purchase food at higher prices if food production decreases due to lack of irrigation), for the middle income countries. For high and low income countries, the trade adaptation capacity is set to 1 and 0 as thresholds of maximum and minimum capacity, respectively.
- HEF is taken as the average value of malnutrition damage per calorie deficiency of the undernourished population, similarly to what was done in Boulay et al. 2011, using updated data from 2013 World Health Organization (WHO) and Food and Agriculture Organization (FAO) reports.

No indicator for the impact pathway of domestic water deprivation is recommended. At this point, there are no data supporting the impact pathway that an additional water consumption and water scarcity in an area affect human health by reducing the amount of water available for domestic use, as other factors such as infrastructure, legislation, and local practices also influence the amount and quality of water consumed by domestic users. It is suggested to use one of the two previous models as analyzed in Boulay et al. (2015) for sensitivity assessments of the impacts by domestic water deprivation until further recommendations are provided.

5.16 Recommended model and specific issues addressed

The recommended fate factor HWC_{agri} / AMC (in previous publications expressed as SI x DAU) describes the effect of the consumption of $1m^3$ of water in a watershed on the change of water availability for agricultural use. This factor could vary from 0 (assuming no agricultural water users in a region) to 1 (the entire volume of water consumed is depriving agricultural users). HWC_{agri} / AMC might be >1 in case agricultural water consumption exceeds the remaining water (AMC), but is limited to 1. The factor retained assumes that agriculture suffers proportional to the share of current agricultural water consumption. This could over- or underestimate the real amount of water by which agriculture will be deprived by the consumption of water in a watershed, as water rights, regulations, water markets, and specific willingness-to-pay of some users are not considered in this assumption.

FPL needs to be defined in alignment with HWC_{agri}/ AMC as defined above, based on the amount of water consumed. According to Motoshita et al. (2014), this is defined by the ratio of production amount attributable to irrigation (kcal: total crop production multiplied with the ratio of irrigation water volume to total water volume consumed for crop growth) divided by irrigation input (m^3). This was expressed as a function of water withdrawal and has now been adjusted to consumption to improve consistency with the midpoint indicator.

DSR and ISR model the effects of trade and take into account the fraction of food exports and imports, as well as the trade adaptation capacity. Countries with a high trade adaptation capacity can increase food imports (or reduce food exports) when their domestic food production decreases due to reduced water availability. This domestically reduces the lack of calories from food production loss by agricultural water deprivation, but may result in health impacts internationally by reducing food availability in other countries, leading to an increase in food prices and hence reduced ability to import by some countries (as described in more details in Motoshita 2014). The income-component of the inequality-adjusted Human Development Index ($I\text{-}HDI_{Income}$: United Nations Development Programme 2014) is used to represent the trade adaptation capacity for middle income, whereas low income and high income countries defined by the World Bank have the same adaptation capacity as defined in Boulay et al. (2011) and Motoshita et al. (2014), i.e., 0 and 1 respectively.

The health effect factor (HEF) is calculated based on the average DALY of protein-energy malnutrition damage (taken from GBD 2013) per food deficiency in kcal, as calculated in Boulay et al. (2011).

5.17 Characterization factors (excerpt, including qualitative and quantitative discussion of variability and uncertainty)

Characterization factors calculated at the monthly level and watershed scale were aggregated by weighting based on monthly consumption of water on annual level, and by weighting based on watershed consumption on the national level. Two types of characterization factors for agricultural water consumption and of non-agricultural water consumption are provided (Figures 5.9 and 5.10, next page), since they follow different consumption patterns over time and space (similar to the water scarcity indicator AWARE). Areas where no data are provided (NA) refer to areas where no significant irrigation takes place in the hydrological model that is used as the basis of water availability and demand calculation in this model. Hence, the model does not predict deprivation of agricultural users in this region. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf.

CFs for the elementary flows of agricultural water consumption are generally larger than those for non-agricultural water consumption because scarcity

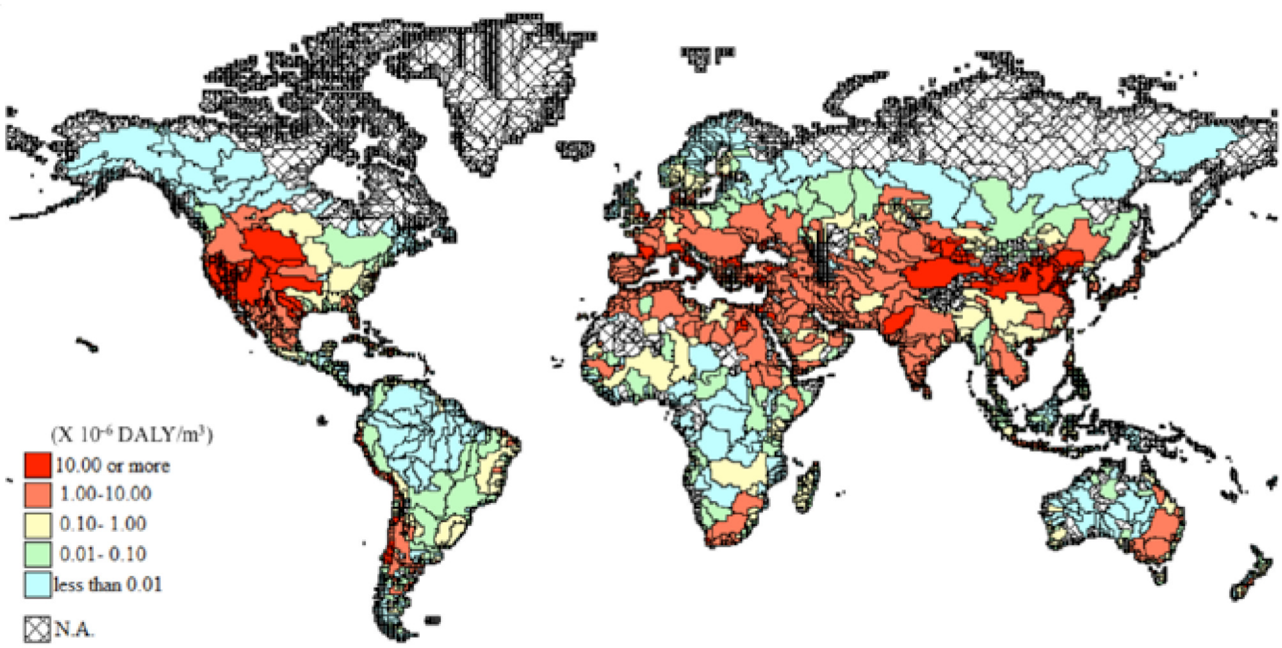

Figure 5.9: CFs for elementary flows of agricultural water consumption

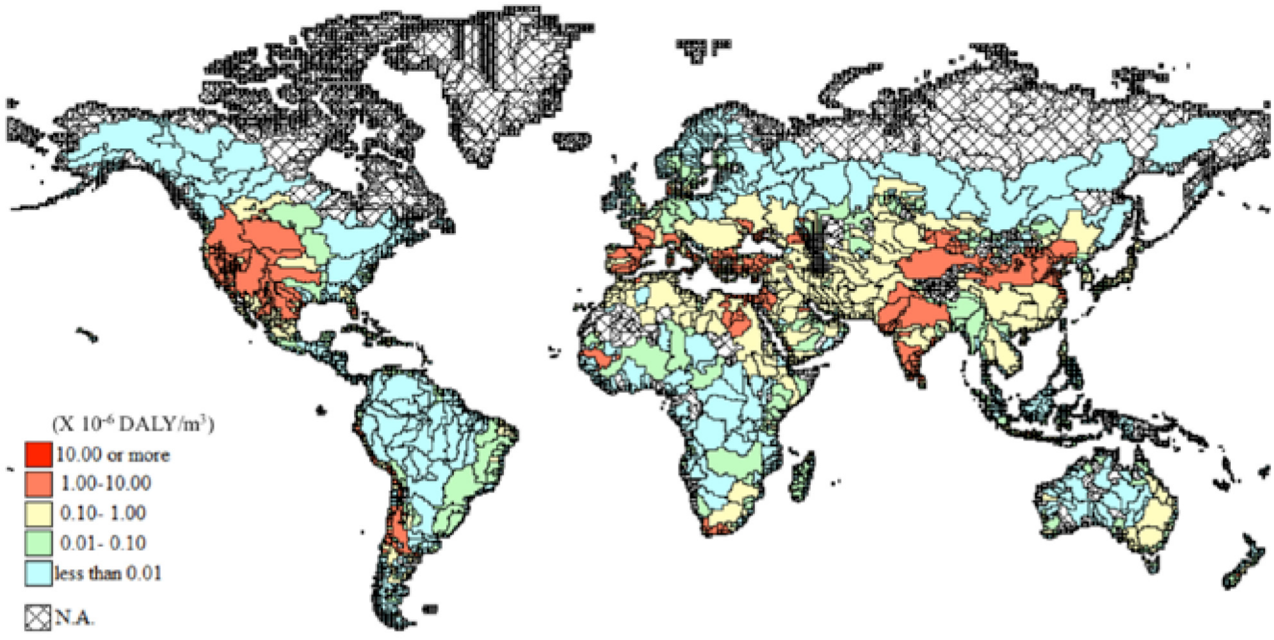

Figure 5.10: CFs for elementary flows of non-agricultural water consumption

is usually higher in regions where irrigation is required.

The aggregation from monthly values to annual average values removes a temporal variance. The ratio of the weighted annual average to monthly values of the scarcity index ranges from 0.15 to 3.46. This means CFs implicitly contain a temporal variance from 0.15 to 3.46. Socio-economic effect (SEE) factors are calculated based on annual data, and consequently temporal variances attributed to SEE factors are not quantitatively determined.

Regarding spatial variance, CFs range from 0 - $4.4{\cdot}10^{-5}$ [DALY/m^3] (the lower quartile: $4.3{\cdot}10^{-8}$, median: $8.6{\cdot}10^{-7}$, the upper quartile: $3.5{\cdot}10^{-6}$) for elementary flows of agricultural water consumption and from 0 - $2.20{\cdot}10^{-5}$ [DALY/m^3] (the lower quartile: $1.1{\cdot}10^{-8}$, median: $2.4{\cdot}10^{-7}$, the upper quartile: $1.3{\cdot}10^{-6}$) for elementary flows of non-agricultural water consumption. The health effect factor is determined as the geometric mean value of protein-energy malnutrition damage per calorie deficit for all available countries. While protein-energy malnutrition damage per calorie deficit may differ among countries, no reasonable justification could be found to explain the large variance and outlier countries except the generally low quality of estimating malnutrition and DALY from malnutrition. Additionally, there is discrepancy of data sources for protein-energy malnutrition damage and calorie in deficit (depth of hunger), since they are assessed by different sources. Previous analyses revealed that regional malnutrition damage per case varied by a factor of 2.0 (95% confidence interval), when comparing WHO world regions (Pfister and Hellweg 2011). Additionally, Boulay et al. (2011) analyzed the variance of malnutrition damage per calorie in deficit across countries (geometric standard deviation: 2.43). Therefore, we suggest adopting a geometric standard deviation of 2.0 for sensitivity analysis of CFs in terms of variance of health effect factor.

The CFs for representative countries are shown in Table 5.6. Germany, as an example of developed countries, has no impact of national damage, but high trade-induced damage. Columbia, as an example of average countries, has higher impacts of both national and trade-induced damage than those of Germany. Mozambique, as an example of developing countries, has the highest impacts of both national and trade-induced damage among representative countries in the table. These examples typically express that countries with high economic adaptation capacity can avoid health damages through global trade while trade-induced damage occurs in other food importer countries.

This method assesses potential malnutrition impacts from a reduction in food availability due to a decrease in food production of current agricultural water users, which was caused by a shortage of water for irrigation induced by the increase of water consumption in the system under study. However, when that system is actually a food-producing system, such a reduction in food availability does not occur to the same extent as the assessed decrease in food production, or at all. The net reduction of food availability in the system depends on: 1) the difference in water use efficiency of the two different food-production systems, the previous one and the new one, in kcal/m^3, and 2) the intended use of the crop (animal feed for meat production or direct consumption, for example). If this method is used for the assessment of food producing systems, the functional unit might compensate the calculated potential impact on human health, and therefore results should be interpreted carefully.

5.18 Rice case study application

The rice case study is presented in detail in Chapter 3. Water consumption in all three situations is highly dominated by the rice cultivation phase (more than 99.4%), and therefore the other production stages have been neglected in this analysis. The case study for rice production in the USA is having the lowest water consumption, followed by the one in China (Table 5.7, next page).

The national average characterization factors of water consumption (agri) are similar for USA and China, while the CF (agri) of water consumption in India is 50% lower. As a result, the LCIA results reflect the inventory results for the comparison of the USA-Switzerland and urban China case, while the rural

Table 5.6: Examples of the CFs for representative countries

		CFs for agricultural water consumption [DALY/m^3]	CFs for non-agricultural water consumption [DALY/m^3]		
		National damage	Trade-induced damage	National damage	Trade-induced damage
Developed country	Germany	0	$7.20 \cdot 10^{-7}$	0	$7.90 \cdot 10^{-8}$
Middle income country	Columbia	$4.49 \cdot 10^{-8}$	$1.00 \cdot 10^{-7}$	$7.31 \cdot 10^{-9}$	$1.85 \cdot 10^{-8}$
Developing country	Mozambique	$4.08 \cdot 10^{-7}$	$5.34 \cdot 10^{-7}$	$1.65 \cdot 10^{-7}$	$2.49 \cdot 10^{-7}$

Table 5.7: Results of the rice case studies for 1 kg of white rice cooked

	Inventory		CF_{agri} (DALY/m³)			Impact (DALY)		
Case	Water consumption (m³) in rice production (share of total in %)	Watershed	CF (National)	CF (Trade-Induced)	CF (Total)	National damage	Trade-induced damage	Total damage
			[DALY/m³]	[DALY/m³]	[DALY/m³]	[DALY]	[DALY]	[DALY]
Rural India	0.78 (99.9%)	Average	1.8E-06	1.8E-06	3.6E-06	1.4E-06	1.4E-06	2.8E-06
		Ganges	2.1E-07	2.1E-07	4.1E-07	1.6E-07	1.6E-07	3.2E-07
		Godavari	9.7E-07	9.6E-07	1.9E-06	7.6E-07	7.5E-07	1.5E-06
Urban China	0.46 (99.5%)	Average	3.5E-06	3.2E-06	6.7E-06	1.6E-06	1.5E-06	3.1E-06
		Yellow River	9.2E-06	8.3E-06	1.8E-05	4.3E-06	3.8E-06	8.1E-06
		Pearl River	1.7E-07	1.6E-07	3.3E-07	8.0E-08	7.2E-08	1.5E-07
USA-Switzerland	0.08 (99.4%)	Average	0.0E+00	7.0E-06	7.0E-06	0.0E+00	5.6E-07	5.6E-07
		Red River	0.0E+00	4.6E-07	4.6E-07	0.0E+00	3.7E-08	3.7E-08
		Arkansas River	0.0E+00	4.6E-07	4.6E-07	0.0E+00	3.7E-08	3.7E-08

India case results in lower impacts than urban China. While for China and India the human health impacts are almost equally shared between local population and through trade, the water consumption of US rice production exclusively causes human health impacts on global population through trade.

As mentioned in Part A of this chapter, national average CFs are not satisfactory for foreground systems, and watershed-specific and time-specific CFs should be applied. As the rice production time schedule is not necessarily fixed to one period, we only focused on spatial specification and further differentiated the rice production locations in each country. For this purpose, we selected two major watersheds where rice is produced within each country: Ganges (case study location) and Godavari in India; Yellow River and Pearl river (case study location) in China; and Red river and Arkansas river in the US (both within case study area) (see Table 5.4).

In the case of India and the US, both major watersheds have lower characterization factors than the national average. In the case of the US, where rice production is restricted to a small area around the state of Arkansas, the CF is 15 times lower than the US average. In the Ganges, CF is almost 10 times lower than the average, and the CF of the Godavari River is still 50% lower than average. In China, the selected case of the Yellow River has much higher CF than in the other cases and therefore results the highest impacts per kg of rice consumed. As a limitation of this analysis, it needs to be noted that changes in the life cycle inventory of rice cultivation as a function of the production site have not been considered.

5.19 Recommendations and outlook

5.19.1 Main recommendation

The group agreed on recommending the CF for the impact pathway describing agricultural water deprivation and consequences on human health. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf. Caution is required for interpreting results for food-producing systems. A minority was reluctant to recommend this method for food-producing systems.

The group suggests not excluding the possibility of modeling the impacts associated with domestic water scarcity. However, given the level of current understanding, there is not sufficient evidence to recommend a specific methodology, where evidence refers to causality between water consumption, scarcity, and domestic water deprivation causing water-related diseases. Further research is needed and envisaged steps are indicated in the roadmap described below.

5.19.2 Judgment on quality, interim versus recommended status of the factors and recommendation

The characterization factors for the impact pathway describing agricultural water deprivation and consequences on human health are recommended for application with special attention to the interpretation of food-producing systems.

5.19.3 Applicability, maturity and good practice for factors application

The recommended model and characterization factors are applicable to life cycle inventory datasets quantifying water consumption. The method is applicable at the scale and time resolution, which can be typically found in background inventory (country, global, year) as well as at highly resolved geographic scales and time resolution (watershed and month). Use of global CF is not recommended. The characterization factors provided together with this publication are recommended for applications to the assessment of marginal changes in water consumption only. If this method is used for the assessment of food-producing systems, only the decrease in food availability due to water consumption of the system is considered in the impact assessment, and not the change in food availability resulting from the food it produces. If this method is used for the assessment of food-producing systems, the functional unit might compensate the calculated potential impact on human health, and therefore results should be interpreted carefully. The endpoint assessed in DALY indicates potential human health impacts and is not meant to represent real measured impacts.

5.19.4 Roadmap for additional tests

Additional refinement of the geographic scale of the adaptation capacity is recommended (e.g., sub-regional maps of GDP [PPP] per capita) to increase the robustness of the malnutrition approach. Investigations about the robustness of the use of calorie-deficit as proxy for protein-deficit malnutrition are recommended, and more specific data on regional health responses to malnutrition should be investigated in the future.

Additional tests should aim at the assessment of the relationship between domestic water scarcity and damage associated to lack of water for domestic use. In particular, linkages between population density, income, accessibility to safe water, water scarcity, and effect factors at the watershed or country level should be investigated.

5.19.5 Next foreseen steps

Additional tests on the impact pathway associated with domestic water scarcity need to be finalized and specified.

We suggest that further work on possible double counting and the inclusion of human health impacts associated with lower water availability due to decrease of water quality be performed.

5.20 Acknowledgements

The task force acknowledges the contribution and work from the WULCA members of the human health sub-group that were not present in this task-force at the Pellston Workshop®: Jane Bare, Cecile Bulle and Bradley Ridoutt, as well as the experts who contributed to the workshop in Barcelona: Tereza Levova, Andrew Maddocks, Bo Weidema, Julie Clavreul, Camillo de Camilis, Tommie Ponsioen, and Sebastien Humbert.

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