Towards a Region-Specific Impact Assessment of Water Degradation In Water Footprinting

Natalia Finogenova[a*], Markus Berger[a], Lennart Schelter[b], Rike Becker[c], Tim aus der Beek[c], Muhammad Usman[d], Frank-Andreas Weber[e], and Matthias Finkbeiner[a]

[a]Technische Universität Berlin, Chair of Sustainable Engineering, Straße des 17. Juni 135, Berlin, 10623, Germany
[b]Institute of Hydraulic Engineering and Water Resources Management (IWW), RWTH Aachen University, Mies-van-der-Rohe-Straße 17, Aachen, 52074, Germany
[c]IWW Water Centre, Department of Water Resources Management, Moritzstr. 26, Mülheim an der Ruhr, 45476, Germany
[d]Remote Sensing Unit, University of Wuerzburg, Oswald-Külpe-Weg 86, Wuerzburg, 97074, Germany
[e]Forschungsinstitut für Wasser- und Abfallwirtschaft an der RWTH Aachen (FiW) e.V, Kackertstraße 15 – 17, Aachen, 52056, Germany

First submission: 21[th] September 2017, Revised submission: 21[th] November 2017, Acceptance: 10[th] December 2017

Abstract

Water footprint evaluates impacts associated with the water use along a product's life cycle. In order to quantify impacts resulting from the water pollution in a comprehensive manner, impact categories, such as human toxicity, were developed in the context of Life Cycle Assessment (LCA). Nevertheless, methods addressing human health impacts often have a low spatial resolution and, thus, do not enable quantification on a local scale. To address this issue, we develop a region-specific model for the human toxicity impacts for the cotton-textile industry in Punjab, Pakistan. We analyse local cause-effect chains and create an impact assessment model for the region "Punjab" based on the USEtox model using local climate, landscape, and population data. Finally, we calculate human health impacts for the emissions of pesticides from the cotton cultivation and heavy metals from the textile production. The results are compared to that obtained for the region India+ (where Pakistan belongs) provided by the USEtox model. The overall result obtained for Punjab is higher than that for India+. In Punjab, the dominant pathway is ingestion via drinking water, which contributes to two-thirds of the total impacts. Nevertheless, the developed model does not completely reflect the local cause-effect chains due to absence of the groundwater compartment. Since groundwater is the main source for drinking in Punjab, a more detailed analysis of the fate of and exposure to the pollutants is needed. This study demonstrates that a region-specific assessment of the water quality aspects is essential to provide a more robust evaluation of the human health impacts within water footprinting.

Keywords: *water footprint; region-specific impact assessment; water quality; human toxicity; USEtox*

* Natalia Finogenova. Tel.: +493031428455; Fax: +493031421720
natalia.finogenova@tu-berlin.de

1. INTRODUCTION

The United Nations Sustainable Development Goal (UN SDG) #6 “Clean water and sanitation” includes the target #6.3 “By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally”[1]. However, according to the forecast of the Organisation for Economic Co-operation and Development (OECD)[2], global water demand will increase between 2000 and 2050 by 55%, aggravating water scarcity and leading to substantial water quality deterioration. These trends affect in particular developing countries, where contamination of water with pathogens, salts, pesticides, and heavy metals lead to severe impacts on human health and ecosystems[3–5]. For example, in Pakistan, about 20-40% of all registered diseases are caused by the use of unsafe water[6].

Water Footprint (WF) evaluates impacts associated with the water consumption and pollution along a product’s life cycle[7]. The severity of water consumption is quantified using the characterization factors (CFs), which indicate water scarcity in a given region. Many models exist providing water scarcity CFs with a high spatial (more than 11,000 watersheds) and temporal (monthly) resolution[8–11]. Water quality aspects, in contrast, are often disregarded or assessed in a simplified manner, for example, as grey water footprint[12]. The latter demonstrates the amount of freshwater that is needed to dilute the wastewater to a certain quality threshold. To evaluate impacts resulting from the water pollution in a comprehensive manner, the Life Cycle Assessment (LCA)[13,14] impact categories eutrophication, acidification, human and eco-toxicity are used[15].

In contrast to water scarcity assessment, water quality aspects are often evaluated with lower spatial resolution and level of detail. To address this issue, we calculate the region-specific human health impacts on example of the cotton-textile value chain in the province Punjab in Pakistan based on the USEtox model[16], which is introduced in the following.

2. METHODS

2.1 The USEtox model

The USEtox model allows linking the emissions of organic and inorganic contaminants with their human and eco-toxicity impacts. The characterization factors for human toxicity ($\overline{CF_h}$) are calculated by multiplying the fate ($\overline{FF}$), exposure ($\overline{XF}$), and human effect factors ($\overline{EF_h}$) (eq.1). The fate factors calculate the mass increase of a pollutant in different environmental compartments (e.g. air, soil, water) due to its emission based on the inter-media transfer and removal models. The human exposure factors quantify the increase in the amount of a pollutant transferred to the population due to its increase in an environmental compartment and distinguish between direct (drinking water and inhalation of air) and indirect (food) pathways[16–18]. The food consumption includes agricultural products (below-ground and above-ground), meat, dairy, and fish[17]. By multiplying the fate and exposure factors, the intake factor ($\overline{\iota F}$) is calculated, which describes the share of the pollutant taken up by the population [kg intake per kg emitted] (eq.1)[16].

$$\overline{CF_h} = \overline{FF} * \overline{XF} * \overline{EF_{human}} = \overline{\iota F} * \overline{EF_h} \quad (1)$$

The model contains two spatial scales - global and continental. The continental scale includes 24 regions, e.g. Central Asia, Brazil+, Europe, and North America. Each region is characterized by the specific climate (e.g. rainfall, temperature), landscape (e.g. fraction of agricultural and natural soil, freshwater depth), and population data. For the population, the intake of different food types (e.g. fish, dairy, meat) are considered for each region.

2.2 Cotton-textile value chain in Punjab: the region-specific cause-effect chains

In order to calculate the region-specific human health impacts, we analyse the cause-effect chains from the water pollution to the health damage for the cotton-textile value chain in Punjab, Pakistan. Then, a new region “Punjab” is created in the USEtox model by introducing the local climate, landscape, and population data. We quantify impacts on human health caused by the emissions of pesticides from the cotton cultivation and heavy metals from the textile production. The results are compared to that obtained for the region India+ of the USEtox model, where Pakistan belongs. Finally, we discuss the relevance and applicability of and data needs for the region-specific impact assessment for the human health.

Cotton cultivation and textile production belong to the main industrial sectors in Pakistan[19]. At the same time, these processes lead to water pollution and may significantly affect human health. In order to understand better the region-specific fate and exposure pathways, we depict and analyse the cause-effect chains that take place in Punjab.

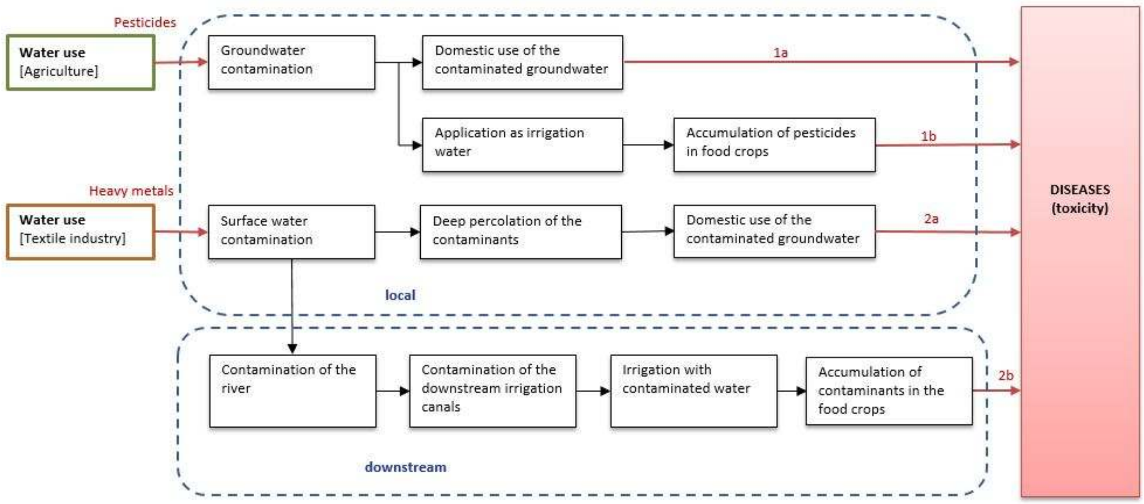

Figure 1. The region-specific cause-effect chains for the toxicity impacts on human health for the cotton cultivation and textile production in Punjab, Pakistan

Cotton is cultivated in the rural areas of Punjab, while textile is produced in industrial areas, which are mainly big cities like Faisalabad and Lahore. During the cotton cultivation, fertilizers and pesticides are applied to the fields. As a consequence, part of the nitrogen, phosphorus, and active ingredients that are contained in the pesticides leach into the groundwater[†]. After the pesticides leached into the groundwater, they may contaminate the aquifer used by the local population for drinking and, therefore, lead to toxicity impacts on human health (fig.1, cause-effect chain 1a). The contaminated groundwater may also be used for the irrigation, which leads to accumulation of the pesticides in the crops and cause human health impacts through food ingestion (fig.1, cause-effect chain 1b). It should be noted that we consider only the pesticide's propagation via water while other potentially relevant pathways (e.g. accumulation in crops or direct contact of the field workers) are not considered. This modelling choice is induced by the water footprint methodology, according to that only the cause-effect chains directly related to water have to be considered[7].

During the textile production, in particular dying and bleaching processes, significant amount of wastewater is generated. In Punjab, the effluent is discharged into the surface water drain mostly without any treatment. The drain transports the wastewater produced in the industrial areas (big cities, e.g. Faisalabad) towards two big rivers – Ravi and Chenab, which are used downstream as sources for the irrigation water. The fate of this wastewater is twofold. On the one hand, because the drains are not lined, part of it leaches into the groundwater and, thus, may contaminate the groundwater aquifer, which is used as a source for drinking water (fig.1, cause-effect chain 2a). Another part of the wastewater reaches the river, where it is mixed with the freshwater. Since the river water is withdrawn for the irrigation, part of the pollutants may be transported on the agricultural fields and accumulate in the food crops. Thus, this contamination may affect human health through the food ingestion (fig.1, cause-effect chain 2b). While the cause-effect chains 1a, 1b, and 2a are relevant on a local level where the pollution takes place, the cause-effect chain 2b applies mainly to the population downstream.

2.3 Adjusting the landscape and population data

In the first step, we compile the landscape and climate inventory for Punjab. It includes sixteen parameters, which describe the regional geographical characteristics as land and sea area, fractions of different land uses (natural soil, agricultural soil), average annual temperature, rainfall etc. The inventory is developed based on the data provided by Pakistan's and Punjab's Bureau of Statistics[19,20] and the data provided by the project InoCottonGROW[21]. Some parameters for which the region-specific data was not available were taken over from the region India+ of the USEtox model. The full list of the parameters compiled for Punjab is presented in table 1.

In the next step, the data for the population and intake rates was collected. The exposure data (water ingestion and breathing rate) were taken over from the

[†] In this study, we analyse the toxicity impacts of the pesticides, thus, emissions from the fertilisers' application are not considered in the following.

USEtox model. For all other parameters, the region-specific data was used (see table 2). The intake rates are based on the data on per capita monthly consumption of major food items provided by the Pakistan Bureau of Statistics[20].

Table 1. The introduced landscape and climate inventory for Punjab. Parameters in *italic* where taken over from the region India+ of the USEtox model without any modification

Parameter	Parameter specification	Unit	Data
Area	land	km^2	2.05E+05
Area	sea	km^2	0.00E+00
Areafrac	fresh water	[-]	2.00E-02
Areafrac	nat soil	[-]	2.00E-03
Areafrac	agr soil	[-]	8.00E-01
Areafrac	other soil	[-]	1.80E-01
Temp		ºC	2.43E+01
Surface wind speed		$m.s^{-1}$	3.00E+00
Wind speed over mixing height		$m.s^{-1}$	4.98E+00
Rain rate		$mm.yr^{-1}$	6.29E+02
Depth	fresh water	m	3.00E+00
Fraction fresh water discharge	cont-global	[-]	0.00E+00
Fraction run off		[-]	2.72E-01
Fraction infiltration		[-]	2.70E-01
Soil erosion		$mm.yr^{-1}$	3.00E-02
Irrigation		km^3	1.20E+02

Table 2. The introduced human population, exposure, and intake parameters for Punjab. Parameters in *italic* where taken over from the region India+ of the USEtox model without any modification.

Parameter	Parameter specification	Unit	Data
Human Population	Human pop continent	[-]	1.10E+8
	Human pop urban	[-]	4.00E+7
Exposure	*Human breathing rate*	m^3/(person*day)	13
	Water ingestion	l/(person*day)	1.4
Intake rates	Above-ground produce	kg/(day*capita)	4.35E-01
	Below-ground produce	kg/(day*capita)	1.53E-01
	Meat	kg/(day*capita)	1.60E-02
	Dairy products	kg/(day*capita)	4.00E-02
	Fish freshwater	kg/(day*capita)	2.00E-03
	Fish coastal marine water	kg/(day*capita)	0.00E+00

2.4 Inventory for the cotton cultivation and textile production

The inventory for the pesticide emissions from the cotton cultivation is compiled for triazophos, which is widely applied in Punjab. The application rate is 1,4 kg per ton cotton[21]. It is assumed that 1% of the applied pesticide leaches into the groundwater[22].

The inventory for the textile production is based on the literature data by Jaffar et al.[23], who provides average effluent concentrations (mg/l) of heavy metals from the textile production sites in Pakistan. This data was recalculated for one ton of textile with the assumption of wastewater flow of 107 litres per ton textile[21] (table 3).

Table 3. Inventory for the heavy metals emissions from the production of one ton textile

Effluent	Concentration (mg/l)	Inventory (kg/ton textile)
Cd (II)	0.04	0.004
Cr (VI)	0.71	0.076
Cu (II)	0.20	0.021
Ni (II)	0.26	0.028
Zn (II)	0.26	0.028

3. RESULTS

3.1 Cotton cultivation

The human health impacts caused by the cotton cultivation were modelled for the application of the pesticide triazophos. The developed impact assessment model for Punjab was used for the calculation. We used the entry compartment “freshwater” (surface water), because the model does not have a groundwater compartment.

In the following, the results of the toxicity impacts and intake routes are presented. To enable the illustration on a log-scale, which is common for the toxicity impacts, we multiplied the results by factor 10.00E+10. For this reason, the results serve as comparison between two models and cannot be used as absolute values.

Human toxicity impacts of triazophos sums up to 5.61E+5 DALYs in Punjab, which exceeds the impact of triazophos in India+ (8.01E+04 DALYs) by one order of magnitude (fig.2).

In order to analyse these results, we compared the intake pathways in both regions. Figure 3 demonstrates that the intake via fish and drinking water are dominant pathways in both Punjab in India+, but the fractions of the intake are higher in Punjab. Furthermore, while in India+ the intake fractions via drinking water and fish are of the same order (4,17E+05 and 4,49E+05, respectively), in Punjab, the intake pathway via drinking water is slightly higher than via fish ingestion.

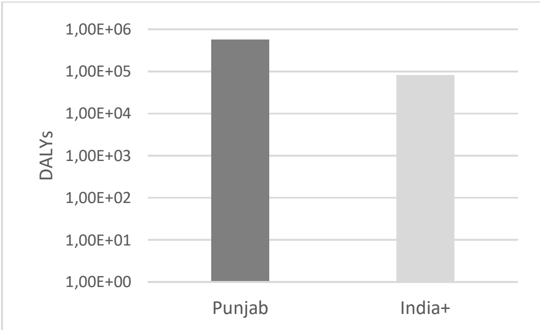

Figure 2. Human health impacts [DALYs] of triazophos application for the cultivation of one ton cotton in the regions Punjab and India+.

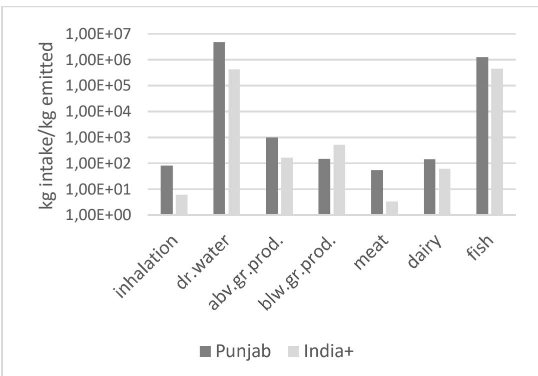

Figure 3. The intake factors [kg intake/kg emitted] for triazophos in the regions Punjab and India+.

3.2 Textile production

The results for the human health impacts caused by the textile wastewater are presented in fig.4. The impacts in Punjab and India+ are of the same order of magnitude (2.40E+08 and 1.36E+08, respectively). Chromium (Cr VI) emissions dominate the impacts, which is due to the high health effect factors of hexavalent chromium. Therefore, the intake factors of chromium in Punjab and India+ are analysed in the following.

The total intake factor for chromium emissions is 1,20E+07 in Punjab and 6,73E+06 kg per kg emitted in India+. The contributions of different intake pathways are presented in fig.5. Drinking water is the main intake pathway of chromium in Punjab (77% of the total intake), while in India+ it contributes to only 44% of the total intake. The indirect pathway (food) is relevant only with regard to the fish consumption in both Punjab and India+, while the contribution of other food items (above-ground produce, below-ground produce, meat, and dairy) is marginal. The intake pathways through inhalation is irrelevant in both regions.

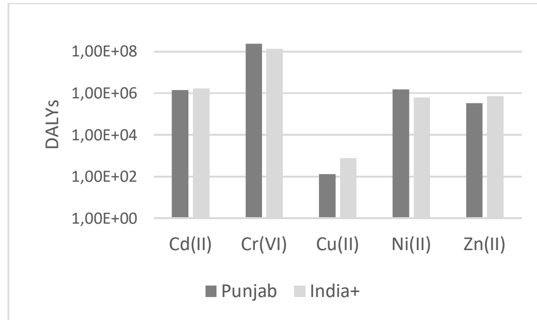

Figure 4. Human health impacts [DALYs] of the textile wastewater (emissions of Cd(II), Cr(VI), Cu(II), Ni(II), Zn(II)) for production of one ton textile in the regions Punjab and India+.

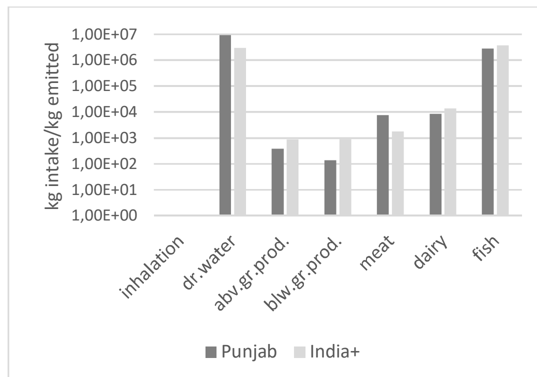

Figure 5. The intake factors [kg intake/kg emitted] for chromium (Cr VI) in the regions Punjab and India+

4. DISCUSSION

Within this study, four region-specific cause-effect chains for the human health impacts caused by the cotton-textile value chain in Punjab were introduced. The study demonstrates that impacts calculated with the region-specific landscape and population data (Punjab) are higher than that of the model with the lower spatial resolution (India+). The intake via drinking water is significantly higher than via the food for both cotton cultivation and textile production emissions. In the following, a sensitivity analysis is conducted for the parameters that were adjusted in the model with the region-specific data. Furthermore, the robustness of the developed model is discussed.

4.1 Sensitivity analysis

A sensitivity analysis was performed to identify the relevance of the landscape and intake parameters changed in the initial model. For this, the parameters of the model India+ were changed to the values used for the region-specific model for Punjab. Each parameter was changed separately with all other parameters remaining same. Following values were modified: area of freshwater, area of different soil use types (natural, agricultural, other), temperature, rain rate, freshwater depth, irrigation, and intake rates. The toxicity and intake rates were calculated for the emission into freshwater of one kilogram of hexavalent chromium, which was identified as the major pollutant in the current study (fig.6[‡]). Two parameters lead to the reduction of the toxicity impacts by one order of magnitude: increased irrigation and a lower freshwater area compared to the India+. While the introduced intake rates are similar to India+ and do not significantly influence toxicity impacts, other parameters (soil fractions, lower rain rate, higher average temperature and higher freshwater depth) slightly increase toxicity impacts. Changing these parameters also leads to the fact that drinking water becomes the most relevant intake pathway in contrast to India+. Nevertheless, it cannot be stated that increased intake via drinking water implicitly leads to increased toxicity as it is demonstrated in case of lower toxicity by the parameter "irrigation", where drinking is the dominant intake pathway.

4.2 Model robustness

The developed model is only partly able to reflect the region-specific cause-effect chains in Punjab, because it does not have a groundwater compartment. Thus, for the cotton cultivation, the pesticides' emissions were modelled as "into freshwater" (surface water), although these are emissions into the groundwater. For that reason, both fate and exposure pathways may significantly differ from that actually taking place in Punjab. For the same reason, the cause-effect chains for the percolation of the contaminants into the groundwater (fig.1, cause-effect chain 2a) also could not be reflected (the model calculates the removal of the pollutants by sedimentation, but do not accounts for the leaching of the pollutants from the sediment into the groundwater). Therefore, part of the pollution is not considered when calculating the fate factors. The absence of the groundwater compartment also has influence on the exposure modelling. The model assumes that the whole drinking water originates from the surface water. However, in Punjab about 90% of drinking water is pumped from the groundwater aquifers[24]. Since the most part of the pollutants (heavy metals from the textile production) stay in the surface water or are removed by sedimentation, their concentration in groundwater is significantly lower than in the surface water. Thus, although surface water is heavily contaminated, the population is not exposed to this pollution via the drinking pathway.

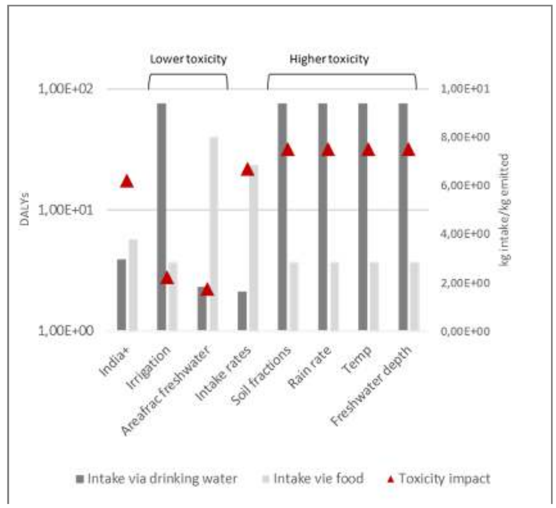

Figure 6. The results of the sensitivity analysis for the emissions of 1 kg chromium (Cr VI) in the region India+

For the textile production, the emissions of the hexavalent chromium were modelled. The emission data for the textile wastewater used as the inventory in the current study is provided only for the total chromium. Thus, the shares of the Cr (VI) and Cr (III) could not be determined. For this reason, only the hexavalent chromium was modelled, which represents the worst case scenario, since the Cr (VI) has a significantly higher toxicity (ten orders of magnitude) compared with the Cr (III).

This study investigates the human health impacts of heavy metals and pesticides. In particular for the textile production, further pollutants, e.g. organic compounds (e.g. dyestuff residues), may be of high relevance due to their high toxicity. Nevertheless, considering these pollutants is currently not possible due to the missing emission data.

‡ The results are presented on a logarithmic scale

5. CONCLUSION

This study calculates the region-specific human health impacts in Punjab, Pakistan based on the USEtox model. It is demonstrated that considering local climate, landscape, and population data changes the results obtained from the global models. The conducted sensitivity analysis demonstrates that introduced parameters for irrigation and freshwater area fraction reduce the toxicity impacts by one order of magnitude, while four region-specific parameters (soil use types, rain rate, temperature, and freshwater depth) lead to increased toxicity impacts.

The dominant impact pathway is via drinking water ingestion, nevertheless it can only partly reflect the local situation due to absence of the groundwater compartment in the model. Thus, a detailed analysis of the pollutant alteration in the groundwater compartment and human exposure via the drinking water is essential to provide more robust results for the evaluation of the toxicity impacts within water footprinting.

ACKNOWLEDGEMENT

This study was developed within the research project InoCottonGRoW founded by the German Federal Ministry of Education and Research (BMBF), funding measure "Water as a global resource (GRoW). The authors would like to thank the Federal Ministry of Education and Research for the financial support and the project partners for their valuable feedback.

REFERENCES

[1] United Nations. Sustainable Development Goals. (2018). Available at: https://sustainabledevelopment.un.org/sdgs.

[2] OECD. *Water. OECD Environmental outlook to 2050: The Consequences of inaction* (2012). doi:10.1787/9789264122246

[3] UNEP. *A Snapshot of the World ' s Water Quality : Towards a global assessment*. (2016).

[4] Waseem, A. *et al.* Pollution Status of Pakistan: A RetrospectiveReview on Heavy Metal Contamination of Water, Soil, and Vegetables. *Biomed Res. Int.* **2014,** (2014).

[5] Afzal, M. *et al.* Assessment of Heavy Metal Contamination in Soil and Groundwater at Leather Industrial Area of Kasur, Pakistan. *Clean - Soil, Air, Water* **42,** 1133–1139 (2014).

[6] Azizullah, A., Khattak, M. N. K., Richter, P. & Häder, D.-P. Water pollution in Pakistan and its impact on public health — A review. *Environ. Int.* **37,** 479–497 (2011).

[7] ISO. *Water footprint — Principles, requirements and guidance. International Organization for Standardization, Ed.* (2014).

[8] Berger, M. *et al.* Enhancing the water accounting and vulnerability evaluation model: WAVE+. *Environ. Sci. Technol.* (2018). doi:10.1021/acs.est.7b05164

[9] Berger, M., Van Der Ent, R., Eisner, S., Bach, V. & Finkbeiner, M. Water accounting and vulnerability evaluation (WAVE): Considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting. *Environ. Sci. Technol.* **48,** 4521–4528 (2014).

[10] Boulay, A. M. *et al.* The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* 1–11 (2017). doi:10.1007/s11367-017-1333-8

[11] Pfister, S., Koehler, A. & Hellweg, S. Assessing the Environmental Impact of Freshwater Consumption in Life Cycle Assessment. *Environ. Sci. Technol.* **43,** 4098–4104 (2009).

[12] Mekonnen, M. M. & Hoekstra, A. Y. Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water. *Environ. Sci. Technol.* **49,** 12860–12868 (2015).

[13] ISO. *Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization, Ed.* (2006).

[14] ISO. *Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization, Ed.* (2006).

[15] Boulay, A.-M. *et al.* Analysis of water use impact assessment methods (part B): applicability for water footprinting and decision making with a laundry case study. *Int. J. Life Cycle Assess.* **20,** 865–879 (2015).

[16] Rosenbaum, R. K. *et al.* USEtox - The UNEP-SETAC toxicity model: Recommended

characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **13,** 532–546 (2008).

[17] Rosenbaum, R. K. *et al.* USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: Sensitivity to key chemical properties. *Int. J. Life Cycle Assess.* **16,** 710–727 (2011).

[18] Henderson, A. D. *et al.* USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: Sensitivity to key chemical properties. *Int. J. Life Cycle Assess.* **16,** 701–709 (2011).

[19] Bureau of Statistics. *Punjab Development Statistics 2015*. (2015).

[20] Pakistan Bureau of Statistics. *AGRICULTURAL STATISTICS OF PAKISTAN 2011-2012*. (2011).

[21] InoCottonGRoW. (2018). Available at: https://www.inocottongrow.net/. (Accessed: 1st September 2018)

[22] European Commission. *PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3*. (2017).

[23] Manzoor, S., Shah, M. H., Shaheen, N., Khalique, A. & Jaffar, M. Multivariate analysis of trace metals in textile effluents in relation to soil and groundwater. *J. Hazard. Mater.* **137,** 31–37 (2006).

[24] Pakistan Bureau of Statistics. *Pakistan Social and living standards measurement survey (2015-15)*. (2016).