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Sector-wise midpoint characterization factors for impact assessment of regional consumptive and degradative water use

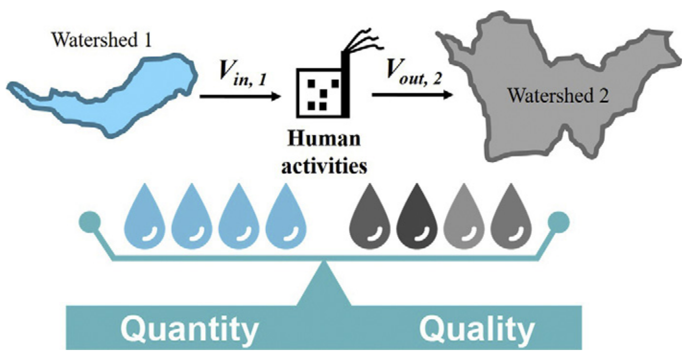
Chia-Chun Lin, Jia-Yu Lin, Mengshan Lee, Pei-Te Chiueh *

Graduate Institute of Environmental Engineering, College of Engineering, National Taiwan University, 71, Chou-Shan Road, Taipei 106, Taiwan

HIGHLIGHTS

- Characterization factors of consumptive and degradative water use are developed.
- Higher withdrawals result in higher water stress even during high-flow periods.
- Water quality is a strong concern for the agricultural sector.
- Reduction in water intensity decreases the impact of industrial activities.
- Sector-wise impacts are used to support decision making.

GRAPHICAL ABSTRACT



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ABSTRACT

Water availability, resulting from either a lack of water or poor water quality is a key factor contributing to regional water stress. This study proposes a set of sector-wise characterization factors (CFs), namely consumptive and degradative water stresses, to assess the impact of water withdrawals with a life cycle assessment approach. These CFs consider water availability, water quality, and competition for water between domestic, agricultural and industrial sectors and ecosystem at the watershed level. CFs were applied to a case study of regional water management of industrial water withdrawals in Taiwan to show that both regional or seasonal decrease in water availability contributes to a high consumptive water stress, whereas water scarcity due to degraded water quality not meeting sector standards has little influence on increased degradative water stress. Degradative water stress was observed more in the agricultural sector than in the industrial sector, which implies that the agriculture sector may have water quality concerns. Reducing water intensity and alleviating regional scale water stresses of watersheds are suggested as approaches to decrease the impact of both consumptive and degradative water use. The results from this study may enable a more detailed sector-wise analysis of water stress and influence water resource management policies.

1. Introduction

Freshwater is an important natural resource and its availability resulting from either a lack of water or poor water quality is a key factor contributing to regional water stress. A broad range of accounting methods have been developed for assessing the impacts of water withdrawals by a life cycle assessment (LCA) approach, including the quantification of water footprints, analyzing virtual water requirements using a water inventory, and the establishment of impact categories to support a life-cycle impact assessment (LCIA) (Berger and Finkbeiner, 2010). While water withdrawals, also known as off-stream water use,

* Corresponding author.
E-mail address: ptchueh@ntu.edu.tw (P.-T. Chiueh).

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are often recorded in these processes, their associated impacts such as water scarcity (when demand is greater than availability) or reduced water functionality are often overlooked within LCIA frameworks (Koehler, 2008; Pfister et al., 2009). Therefore, recent research efforts have developed specific characterization factors (CFs) to address these potential consequences within a defined spatial scale.

A number of studies have adopted CFs for use within LCIAs as indicators to evaluate the consequences of water withdrawals on human health (Pfister et al., 2009; Motoshita et al., 2010; Boulay et al., 2011; Motoshita et al., 2014), ecological quality (Milà i Canals et al., 2008; Pfister et al., 2009; Hanafiah et al., 2011), and resource depletion (Milà i Canals et al., 2008; Pfister et al., 2009). For example: Motoshita et al. (2014) developed CFs incorporating physical (e.g. water source) and social (e.g. food stocks supply) compensation capacities to estimate the impacts of agricultural water scarcity on a national scale; Boulay et al. (2011) proposed the use of consumptive and quality-based water scarcity indicators to define regional human health impacts; Hanafiah et al. (2011) characterized the relationship between water consumption and the decline of freshwater fish species to represent impacts on freshwater diversity; and Pfister et al. (2009) applied the concept of backup technology to quantify the impacts of water resource depletion. All of these studies followed a cause and effect chain concept (Kounina et al., 2013) to develop impact-oriented indicators, which can potentially be incorporated into existing LCIA approaches (Jolliet et al., 2014; Boulay et al., 2015).

One major concern about existing LCIAs is their validity at different scales. These approaches have mainly been used to assess impacts of global supply chains (Hellweg and Milà i Canals, 2014). However, the applications of these approaches at smaller scales are likely to contribute to different results. For example, a global assessment might consider economic adaptability and international trade activities (Motoshita et al., 2014); whereas, a regional one might consider water quality, water allocation, and competition among water users (Sullivan, 2002).

The selection of a suitable temporal scale that balances accuracy with data availability is another challenge for developing LCIA methods (Reap et al., 2008a, 2008b; Jeswani and Azapagic, 2011). For example, previous studies have incorporated monthly rainfall variations instead of a single annual value, to represent water availability (Pfister et al., 2009; Boulay et al., 2011). More recently studies have incorporated a global monthly water stress index to assess crop production to account for variation of irrigation water from crop to crop (Pfister and Bayer, 2014). This demonstrates how the use of an appropriate temporal scale for impact assessment is helpful to represent seasonal variations in water availability and water withdrawals.

Many LCIAs assessing the impacts of water withdrawals focus primarily on water quantity and pay little attention to water quality (Zeng et al., 2013). To address this, the grey water footprint was developed to assess the magnitude of water quality degradation by quantifying the amount of water required to dilute water contaminants sufficiently to meet water quality standards (Hoekstra et al., 2011; Motoshita, 2013). However, this approach fails to assess reductions in the functionality and availability of water due to degradation in quality. Poor quality water has lower functionality, which impacts availability for specific uses (Boulay et al., 2011), thus, the quantity of available water may be overestimated if water quality is not considered (Zeng et al., 2013). Therefore, introducing water quality factors to evaluate water stress is useful in reflecting the actual impacts of water withdrawals (Motoshita, 2013).

The goal of this study is to develop a set of sector-wise CFs, expressed as consumptive and degradative water stress, to assess the impact of water withdrawals at the regional scale. The CFs will incorporate influential factors including regional water availability, water quality, competition for water from different sectors and spatial and temporal distribution of water. CFs specific to the domestic, agricultural, and industrial sectors as well as ecosystem were established in this study. These CFs were applied in various watersheds in Taiwan, in order to validate their applicability and feasibility. An assessment of the potential consumptive and degradative impacts from industrial water withdrawals in Taiwan was also conducted. This approach assesses the impact of water withdrawals on different sectors, which provides information that is useful for environmental decision-support in allocating water resources and identifying hotspots for water stress and their impacts.

2. Water withdrawals in Taiwan

Taiwan has high rainfall, however, still suffers from water scarcity. Rainfall is unevenly distributed and geographical conditions make the collection and storage of water challenging (Cheng and Liao, 2011). Economic development and population growth also contribute to increased water stress in urban areas. Currently, agriculture accounts for approximately 70% of water consumption, while 20% and 10% is used for the domestic and industrial sectors, respectively (WRA, 2009). Given these water management challenges, Taiwan presents an interesting case study for the validation of the developed CFs to assess the impact of water withdrawals.

Industrial water withdrawals has high impacts in Taiwan, which can be illustrated by a case study of three major industrial science parks, Hsinchu, Central Taiwan, and Southern Taiwan. Fig. 1 shows there location in Taiwan. Information regarding the annual revenue, water withdrawals and discharges of these parks is provided in Table 1 and Table A.5.

These science parks contain water-intensive, high-tech industries such as integrated computer circuits, optoelectronics, and telecommunications; which consume as much as 325,000 m^3 of fresh water, daily (MOST, 2012). During the dry season, competition for water intensifies between these industries and other sectors. Many opportunities for water conservation and improving water-use efficiency are technically feasible for the majority of the water-intensive industries at these parks and efforts have been made to improve the management of these water resources (Lin et al., 2015). Effluent from these parks can lead to degradation of water quality, decreasing the availability of water for other users.

3. Methods

3.1. Assessment framework

Consumptive and degradative water use impacts were determined by using water inventory flows and sector-wise CFs, as illustrated in Fig. 2, based on Life Cycle Assessment (LCA) standards (ISO14040, 2006; ISO14044, 2006). Multiplying water use inventory (consumptive water use or degradative water use, in m^3) by sector-wise CFs ($CF_{con,i,j}$ and $CF_{de,i,j}$, dimensionless) equals the impacts ($IMPACT_{consumptive}$ and $IMPACT_{degradative}$, in m^3 water eq.). It is worth noting that the unit of m^3 eq is a characterized unit for impact assessment, which is different from the unit for water inventory (in m^3).

The total water withdrawal accounts for all water withdrawn from the watershed, which is then categorized into consumptive and degradative water uses (Owens, 2001). Consumptive water use includes water withdrawals that do not return to its original watershed. For example, water lost to evaporation, consumed in production, or discharged into other watersheds or the sea. This water use results in a reduction of water flow to downstream users in the watershed (Owens, 2001). Degradative water use includes water that is used and then discharged back into the watershed with degraded quality, which reduces the functionality and safety of water access for downstream users (Pfister et al., 2009).

Both of these CFs were developed based on a withdrawal-to-availability (WTA) ratio, which can be used as an indicator of water