HIT.WATER scheme
An integrated LCA-based decision-support platform for evaluation of wastewater discharge limits

Bai, Shunwen; Zhang, Xuedong; Xiang, Yue; Wang, Xiuheng; Zhao, Xinyue; Ren, Nanqi

DOI
10.1016/j.scitotenv.2018.11.209

Publication date
2019

Document Version
Final published version

Published in
Science of the Total Environment

Citation (APA)
Bai, S., Zhang, X., Xiang, Y., Wang, X., Zhao, X., & Ren, N. (2019). HIT.WATER scheme: An integrated LCA-based decision-support platform for evaluation of wastewater discharge limits. *Science of the Total Environment*, *655*, 1427-1438. https://doi.org/10.1016/j.scitotenv.2018.11.209

Science of the Total Environment 655 (2019) 1427–1438

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

HIT.WATER scheme: An integrated LCA-based decision-support platform for evaluation of wastewater discharge limits

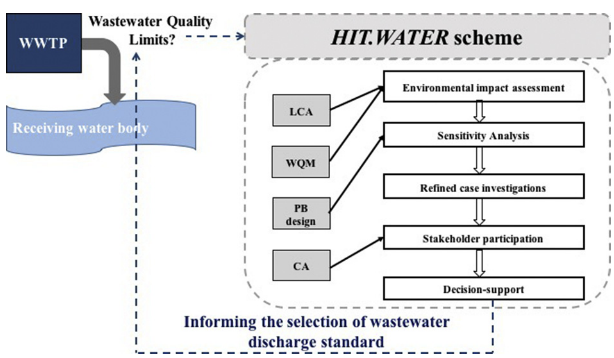
Shunwen Bai [a], Xuedong Zhang [b,c], Yue Xiang [a], Xiuheng Wang [a,*], Xinyue Zhao [d], Nanqi Ren [a,*]

[a] State Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, 150090 Harbin, China
[b] Section of Sanitary Engineering, Department of Water Management, Delft University of Technology, Delft 2628CN, the Netherlands
[c] Veolia Water Technologies Techno Center Netherlands B.V., Tanthofdreef 21, 2623 EW Delft, the Netherlands
[d] College of Resource and Environment, Northeast Agricultural University, 150030 Harbin, China

HIGHLIGHTS

- An integrated LCA-based decision-support system is established by synthesizing four modelling systems.
- Wastewater discharge limits can be screened and evaluated before implemented to constrain WWTP.
- Upgrading WWTP to meet stricter limits can achieve net improvement in not all cases.
- Stakeholders shift their evaluation emphasis with the change of decision scenarios.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 September 2018
Received in revised form 14 November 2018
Accepted 14 November 2018
Available online 16 November 2018

Editor: Deyi Hou

Keywords:
Life cycle assessment
Wastewater discharge
Decision-support system
Stakeholder involvement

ABSTRACT

Determination of appropriate effluent quality limits (EQL) for wastewater treatment plants in China is a complicated process involving multiple factors that need joint consideration. Based on advantages of compiling the energy and material flows as well as the emissions into air, water and soil, life cycle assessment (LCA) presents a standardized approach for evaluation of EQL alternatives. However, challenges arise when incorporating more factors is indispensable, especially for the elements concerning downstream receiving water body, official watershed planning and stakeholder's participation. To this end, an integrated LCA-based decision-support platform named *HIT.WATER* scheme is proposed, linking the currently available LCA system with Water Quality Model (WQM), Plackett–Burman (PB) design and Conjoint Analysis (CA). A demonstrative case study was conducted to illustrate the processing procedures. Results obtained in the current study show that the officially defined river functions and the downstream cross-section distances resulted in more significant effects on the assessment outcome than other factors such as self-purification coefficients and weighting factors. Nevertheless, the comparisons among EQL alternatives were carried out and the differences were observed, which were dynamic, varying with the changed conditions of either natural factors (e.g. downstream distances) or human factors (e.g. officially defined river functions). Quantitatively presenting the dynamic comparisons to indicate the differences among the alternatives was a principal function of the *HIT.WATER* scheme. In particular, the approach allows the environmental impacts of EQL examined from various perspectives, which is conducive to the preclusion of "one-size-fits-all" determination with sustainability consideration. Stakeholder's participation was achieved through a transparent decision-making process, and their selection and judgment criterion could be explicitly presented

* Corresponding authors.
E-mail addresses: xiuheng@hit.edu.cn (X. Wang), rnq@hit.edu.cn (N. Ren).

https://doi.org/10.1016/j.scitotenv.2018.11.209

using quantitative metrics. We conclude that the *HIT.WATER* scheme can be applied to broader scales where the evaluation of paradigm shifts (technological advancement or effluent standard changes) in sewage systems is necessary.

1. Introduction

During extensive economic development, China is facing serious urban water pollution, which mainly results from both point source pollution (domestic sewage and industrial wastewater) and non-point source pollution (stormwater runoff) (Ebenstein et al., 2015; Han et al., 2016; Wang et al., 2018). There are massive amounts of water pollutants being released into urban aquatic environment every year. Specifically, emissions of chemical oxygen demand and total nitrogen in 2015 were 22.23 million tons and 4.61 million tons, respectively (China Environmental Status Bulletin, 2015). Mitigating these impacts remains a persistent challenge for urban wastewater management in China. To address this problem, tightening the effluent quality limits (EQL) of wastewater treatment plants (WWTP) has been the most common approach for both central and local government (MEP, 2014; MEP, 2002a). A leading contributor to the increasingly stringent EQL lies with the fact that, WWTP serve the most principal function of reducing water pollutants in China, where >100,000 km combined sewer networks are in operation, collecting domestic sewage, industrial wastewater and rain runoff in the same pipe, and transporting them to centralized WWTP for biological and chemical treatment (China Urban Water Association, 2016). As a result, strikingly high reduction of discharge of water pollutants has been achieved nationally by a wide-ranging construction and upgradation of WWTP (MEP, 2017; Zhang et al., 2016).

In spite of the desirable improvement, debates have never ceased as EQL becomes more and more demanding (Huang et al., 2018; Lu et al., 2017; Wang et al., 2012). One of the primary issues is the shift of unintended negative impacts to other environmental aspects such as climate change or resource consumption (Floresalsina et al., 2011), which could add more burdens to the overall environment (Wang et al., 2015; Zhao et al., 2017a). On the other hand, ecological measures are not fully considered by current administration management of wastewater (Ren et al., 2017). In general, there would be a distance between the emission point of WWTP and the protected section of receiving river. Natural environment within this distance can provide purification capacity to dilute and degrade water pollutants (Kabisch et al., 2017). Thus, taking advantage of the nature-based solution can partly replace the functions of WWTP and contribute to conserving resources. Moreover, involvement of stakeholder participation has been limitedly incorporated in the stipulation procedure of EQL, which may lead to the “one-size-fits all” decisions made in an arbitrary manner without consideration of inner conflicts and reality (Corominas et al., 2013; Glucker et al., 2013; Guest et al., 2009).

Properly addressing the aforementioned debates needs the development and implementation of scientific tools that can enable the sustained evaluation of EQL alternatives from comprehensive perspectives. There are several methods that have been implemented to investigate the impacts of EQL alternatives. A cost-benefit analysis was conducted to assess a number of wastewater treatment standards in Israel, and results showed that a net benefit was achievable to national economy when more stringent standard was adopted to generate reusable wastewater for agriculture (Lavee, 2011). An operational strategy-based permitting approach was developed to facilitate the identification of appropriate wastewater treatment options, highlighting the importance of involving stakeholders in the decision making process for water quality management (Meng et al., 2016). In an integrated model proposed for reducing overall environment impact of Eindhoven urban wastewater system, purification capacity of receiving water was taken into account, representing the first effort to incorporate hydraulics as well as natural biochemical processes into the decision making for sustained sewage disposal scenarios (Hadjimichael et al., 2016). Compared with the aforementioned methods, life cycle assessment (LCA) presents a more standardized technique that includes multiple indicators and efficient databases for comparisons of different EQL alternatives as well as the identification of environmental hotspots incurred by enhanced wastewater treatment (Bai et al., 2017a; Bai et al., 2017b; Guven et al., 2018; Lu et al., 2017; Rahman et al., 2018; Rahman et al., 2016; Wang et al., 2015).

Admittedly, each method presents its own advantage and proper scope, and there is no general consensus on which method can provide the most reasonable assessment of EQL alternatives. However, to our best knowledge, currently no available method can enable an integrated estimation that allows the environmental impact assessment being supplemented by consideration of nature-based solutions and involvement of stakeholder participation. Accomplishment of the integrated estimation is of great significance, especially for urban wastewater management in China. It is because China is a vast country having substantial discrepancies across different regions in terms of environmental condition, population density and economic development, which naturally results in a significant requirement to formulate EQL depending on specific urban characteristics and environmental features. To tackle the issue aforementioned, it is necessary to jointly take into account of (1) trade-offs between environmental improvement and resource consumptions, (2) natural carrying capacity of aquatic environment, as well as (3) stakeholders from diverse background to balance multiple variables based on their professional knowledge and judgment. Taking together the three elements leads to a demand for a decision-support tool that can integrate the WWTP management, watershed planning and stakeholder participation. With this respect, LCA provides a viable interface by linking with other methodologies. As demonstrated by previous studies, self-purification capacity of receiving river was incorporated by combing water quality model (WQM) with LCA (Bai et al., 2018a), and stakeholder's understanding of LCA results could be identified by using Conjoint Analysis (CA) (Bai et al., 2018b; Bai et al., 2018c).

In the present work, an LCA-based decision-support scheme was established by linking with WQM and CA, with the statistical Plackett–Burman design implemented for parameter management and sensitivity analysis. On the basis of retaining LCA advantages, the established system is capable of (i) systemically assessing and comparing environmental impacts of EQL alternatives, (ii) comprehensively considering the impact of self-purification capacity of receiving river, as well as (iii) particularly involving stakeholder's participation in water quality management. In the following sections, a detailed description illustrates the assessment framework and processing procedure. In the end, a case study on a demonstrative WWTP was conducted to visualize the comparisons of EQL alternatives, elaborate the interpretations of complicated results, and demonstrate how the application of the LCA-based decision-support scheme could contribute to the urban wastewater management in China.

2. Methods and materials

The integrated modelling system is named *HIT.WATER* scheme, which derived from the initials for the names of a Chinese scientific institution leading this research- the State Key Laboratory of Urban Water Resource and Environment in Harbin Institute of Technology.

2.1. Main elements in HIT.WATER scheme

Specifically, the *HIT.WATER* scheme contains the following elements that will influence the choice and determination of EQL alternatives:

(1). The ability to take advantage of natural self-purification process would be one of the decisive factors, given that the receiving water can degrade and remove pollutants via transportation (e. g. diffusion and advection) and transformation (e. g. chemical and biochemical reactions) (Gonzalez et al., 2014). Several variables, such as water velocity and downstream distance, can affect the self-purification process. Therefore, the variables influence the determination of EQL.

(2). Determination of EQL generally belongs to water quality management of watershed planning. As such, the factors concerning the watershed planning are worth considering, which include multiple river reaches, various emission points (point or non-point), and the background concentration as well as environmental capacity (Qu and Fan, 2010; Shao et al., 2006; Shen et al., 2014; Wu and Chen, 2013).

(3). The officially stipulated function zoning of water body is also great of importance. Surface waters in China have been classified into different grades that serve different river functions (MEP, 2002b). For example, the water bodies classified as Level I should satisfy the functions of national conservation areas. According to the national standard, different maximum acceptable concentrations of pollutants are allowed for different river functions (MEP, 2002b). Thus, evidently the function zoning also affects the choice of EQL for a WWTP that is located near by a watershed with a certain river function.

(4). Trade-offs between improvement of local environments and global sustainability remain an important element as well, because the reduction in discharge of pollutants present in sewage is inevitably associated with the fossil consumption, chemical usage, and greenhouse gas emission, all of which give rise to other adverse environmental impacts (Li et al., 2017; Molinos-Senante et al., 2015; Wang et al., 2016).

(5). Sustained participation of stakeholder can contribute to the wide acceptance of EQL, and it would help avoid the "one-size-fits all" decisions that are made in an arbitrary manner without consideration of inner conflicts and reality (Corominas et al., 2013; Glucker et al., 2013; Guest et al., 2009). To address the issue, it is needed to have a scientific design that encourages the stakeholders from diverse background to balance multiple variables, make selections, and elaborate the criterion on the basis of their professional knowledge and judgment.

2.2. Methodology descriptions

Whilst the basic components of the scheme are four well-developed modelling systems, the novelty of the *HIT.WATER* scheme lies with its unique pathways that integrate the models as well as the procedures of data processing. The overall modelling framework, processing procedures and methodology basis are illustrated in Figs. 1–3, respectively.

Environmental impacts of EQL are first quantified using the *HIT.WATER* scheme. With a similar processing manner in our previous studies (Bai et al., 2017a; Bai et al., 2017b; Wang et al., 2015), environmental impacts are divided into three types: Total, Global, and Regional environmental impacts (hereafter, abbreviated as TEI, GEI and REI). The TEI is calculated by aggregating REI and GEI.

LCA is applied to evaluate the GEI of EQL alternatives. Site-generic impact categories that have large-scales, such as climate change and ozone depletion, are selected. Rationale for the selection is that LCA can afford comprehensive databases for those generic impact (Zhou et al., 2011), and consistent outcome can be obtained from different

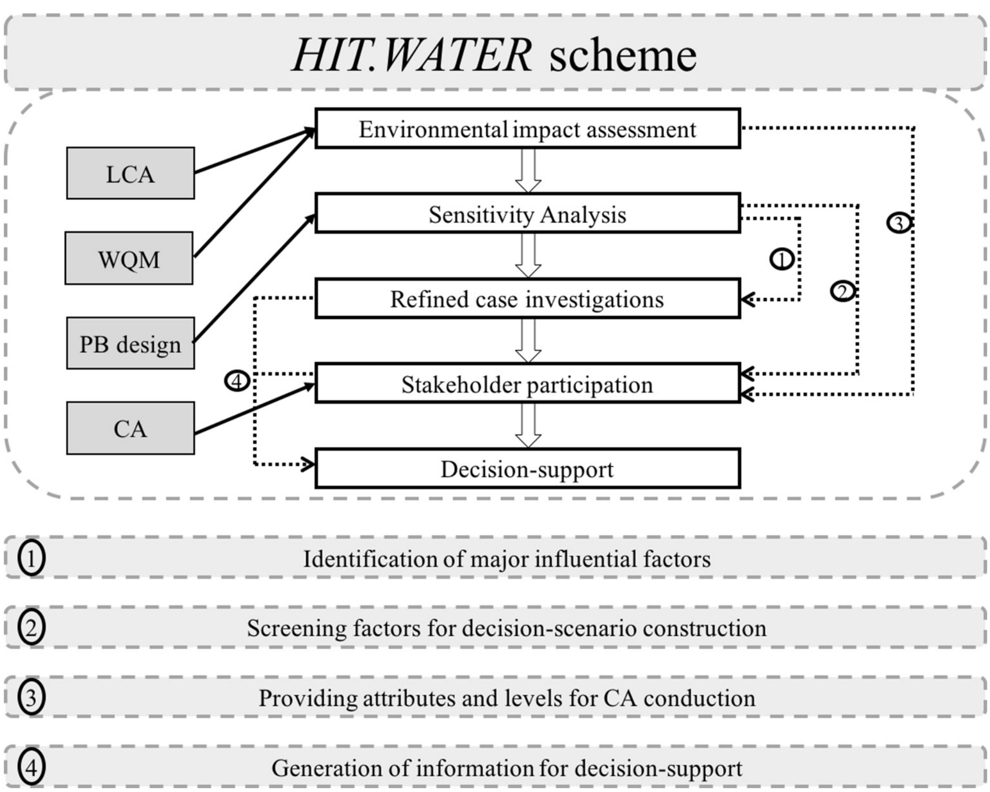


Fig. 1. Overall methodology for *HIT.WATER* scheme.

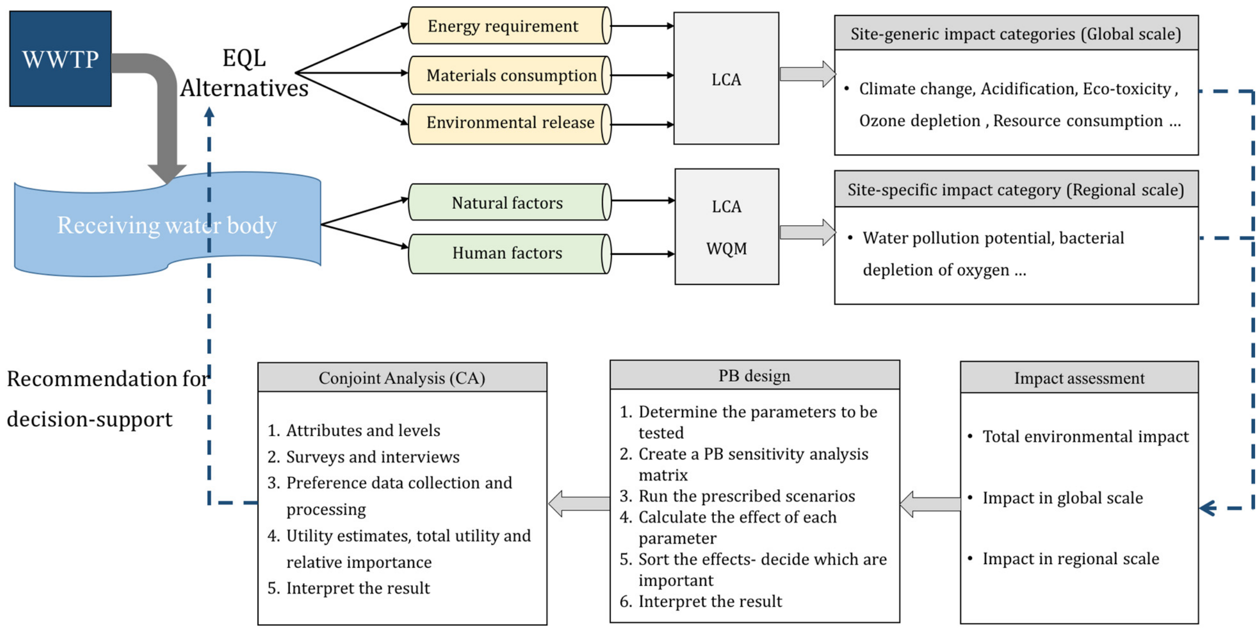


Fig. 2. Diagram of data processing procedures and data flows for *HIT.WATER* scheme.

impact-assessment methodologies (Renou et al., 2008). Aggregation across all site-generic categories using weighting approach produces a single score, representing the GEI for each EQL alternative.

$$\text{TEI} = \text{REI} + \text{GEI} \tag{1}$$

$$\text{GEI} = \sum_r \left[w_r * NOR_r(EI_r)\right] \tag{2}$$

$$\text{REI} = \sum_p \left[w_p * NOR_p(EI_p)\right] \tag{3}$$

$$1 = \sum_{r+p} w \tag{4}$$

where: NOR represents the normalized process for evaluation results of environmental impact (EI). Weighting factors (w) are introduced as

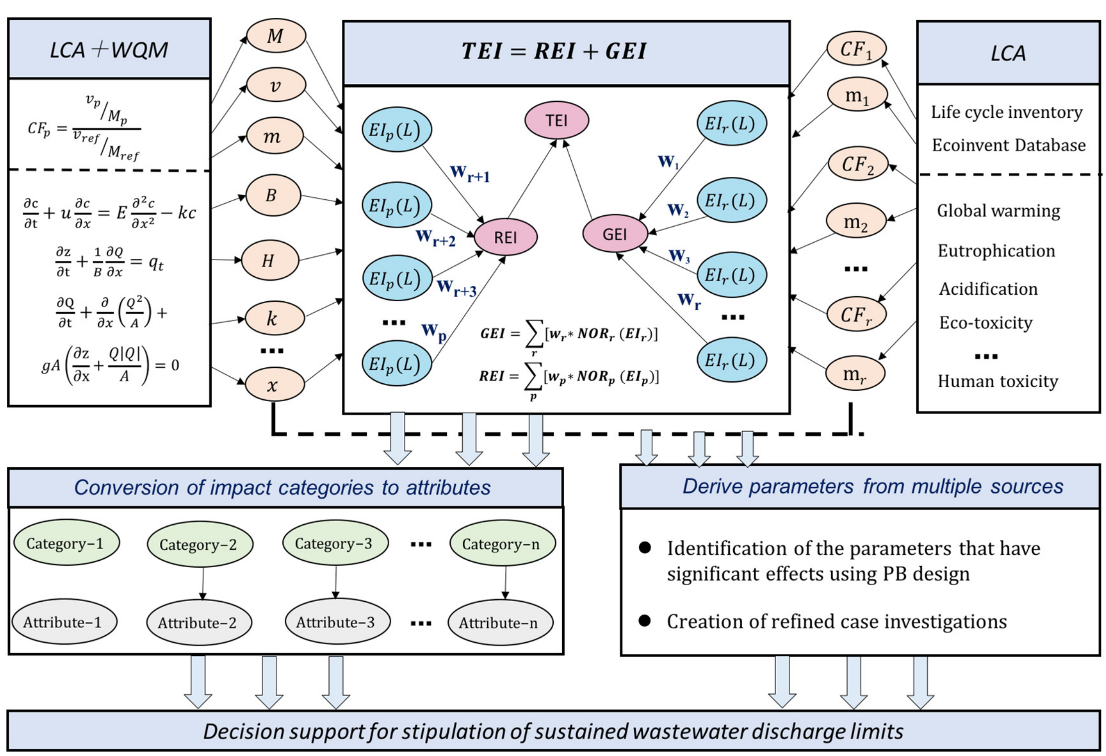


Fig. 3. Methodology basis for *HIT.WATER* scheme.

measures of the relative importance for each impact category. The r refers to the site-generic impact category and the p represents the site-specific impact category.

To characterize REI, water quality model (WQM) is engaged to couple with LCA framework. In this study, a site-specific impact category named Bacterial Depletion of Oxygen (BDO) is introduced and defined with the aim of quantifying direct impact of discharge of wastewater on receiving water. Characterization factors and models for BDO category are developed, measuring the potential growth of bacteria, which can be encouraged by organic matter and nitrogen contained in wastewater. In consideration of the dynamic changes in natural conditions of receiving water (e.g. water velocity or water temperature), one-dimensional WQM is applied to incorporate the dynamic site-specific conditions associated with generation of the spatially differentiated estimation results for BDO category.

$$EI_p(L) = \sum_s (CF_s * m_s) \tag{5}$$

$$EI_{BDO}(RW) = \sum (CF_{COD} * m_{COD} + CF_{TN} * m_{TN}) \tag{6}$$

$$m_s(L_n) = m_s(A)\ \exp\left(-k_s \sum_{i=1}^{n} L_i\right) + \sum_{j=1}^{n}\left[m_s(L_j)\ \exp\left(-k_s \sum_{i=j}^{n} L_i\right)\right] + \frac{q}{k_s}\left[1 - \exp\left(-k_s \sum_{i=1}^{n} L_i\right)\right] \tag{7}$$

where: the regional effect of wastewater on the specific location (L) is quantified within the p category, represented by $EI_p(L)$, by means of multiplying the characterization factors (CF_s) and the emitted mass (m_s) of substance s. Building on the general Eq. (5), we employed the BDO category to investigate the regional impact of chemical oxygen demand (COD) and total nitrogen (TN) on the receiving water (RW), using Eq. (6). Moreover, Eq. (7) describes the changing mass of pollutants (COD and TN) along the longitudinal orientation (x). Specifically, m_s (Ln) represents the mass of pollutant s at the end of the n_{th} river reach, with n denoting the number of river reach in an evaluated watershed and L denoting the total distance of the watershed. $m_s(A)$ is the background input of the pollutant, q represents the input of non-point source pollution per unit distance, and k_s is the self-purification coefficient of pollutant.

Given that there are numerous parameters that exert influence on the assessment above, it is necessary to illuminate the relative importance of the parameters in bringing about outcomes (Beres et al., 2001). The clear illumination is conducive to supporting the process of decision-making based upon the outcomes of the modelling. Hence, sensitivity analysis is conducted to systematically and comprehensively test how changes in the parameters affect the outputs of the model. A Plackett–Burman (PB) design is conducted herein. The method provides a convenient and informative tool that allows to simultaneously examine the influence of the entire suite of parameters (George, 1978; Montgomery, 2017; Plackett and Burman, 1946; Zhao et al., 2017b).

Building upon the identified significant parameters, a refined case investigation is employed to examine the links between the environmental impacts of EQL and the influential parameters.

To encourage the involvement of stakeholders from different sectors and exhibit their preferences based on the outcomes of environmental impact assessments, Conjoint Analysis (CA) was employed in this study to construct and simulate the various scenarios of decision-making. Conducting CA needs the determination of attributes, levels and product profiles (Churchill and Iacobucci, 2006). The attributes can be defined from the impact categories of LCA, and the attribute levels can be determined using the characterization results (Bai et al., 2018c). Based on the combinations of attributes and levels, CA used an orthogonal test design to construct a product profile that consists of a bundle of hypothesized alternatives, which is conducive to generate a bundle of hypothesized decision alternatives. Respondents are invited to score those alternatives with preference values such as ranking data. After statistical analyses, the estimation results of CA include the utility estimates of the level of each attribute, the total utility of each alternative, and the relative importance of each attribute. Based on the estimation outcomes, the decision-making processes can be derived to illustrate how stakeholders make decisions with the estimation outcomes of EQL alternatives.

Finally, by means of compiling and synthesizing all the results generated from the entire evaluation process, recommendations are generated to illuminate the final determination of EQL.

2.3. Application of the HIT.WATER scheme to a WWTP case

To visualize the procedures of data processing and the explanations of complicated results, a demonstrative case was presented.

2.3.1. Background of the case

The case was derived from a domestic WWTP operating in the Northern China. The WWTP employs cyclic activated sludge technique as its main treatment technology with the capacity of 10,000 m^3/d, and is located by the bank of the Ashihe River with a total length of 257 km, a drainage density of 0.36 km/km^2, and a bending coefficient of 1.93. A specific river reach (from Xiquanyan to the Maan Mountain) was identified in this study. As defined by Chinese government, there are five possible classifications of river functions concerning the river reach, ranging from Grade I to Grade V, each of which is closely related to a specific acceptable pollutant concentration (MEP, 2002b). With these environmental characteristics and official regulations, this case study aimed to determine the appropriate EQL by means of utilizing the *HIT.WATER* scheme that was associated with the quantitative output, scenario analysis, and involvement of stakeholders.

2.3.2. Environmental impact assessment

Three EQL were identified: basic treatment level (Alternative 1), intermediate treatment level (Alternative 2), and advanced treatment level (Alternative 3).

As for LCA, functional unit was 10,000 m^3 of wastewater, and the operational stage of WWTP was determined for evaluation. The system boundary included the treatment of sewage, electricity production, chemical manufacture, and transportation, as well as treatment of waste activated sludge. Within the boundary, the input and output flows were compiled for Inventory Analysis. Elements including electricity, inorganic chemicals, and PAM-acrylonitrile were employed as the input flows. The main contributors of outflows comprised chemical oxygen demand, total nitrogen, total phosphorus, bio-sludge, tertiary precipitation, phosphorus precipitation, pre-treatment of solid waste, carbon dioxide, and nitrous oxide.

Further in Life Cycle Impact Assessment, environmental implications of the three EQL alternatives were quantified in a series of impact categories. The BDO category was employed as the only site-specific category, whereas the site-generic categories included acidification (A), human toxicity (HT), photochemical oxidation (PO), global warming (GW), abiotic depletion of fossil fuels (ADF), freshwater aquatic ecotoxicity (FAET), photochemical oxidation (PO), ozone depletion (OD), and abiotic depletion of elements (ADE).

Characterization results of all the site-generic categories were calculated via CML approach coupled with the Ecoinvent Database. As for the site-specific BDO category, WQM coupling LCA framework was used to generate characterization results. To have comprehensive comparisons between alternatives, five weighting methods were adopted for aggregation across different impact categories. One method was to assign the same relative importance to all categories, and the other four used the pre-defined methods including BEES (Building for Environmental and Economic Sustainability), EDIP (providing ready-to-use factors for LCA practitioners), EPA (a frequently employed weighting method), and ECER-125 (developed in the National 12th Five-Year Plan in China).

2.3.3. Sensitivity analysis

Six independent variables were defined to examine the order of importance upon the modelling output. They were: EQL alternatives, officially defined river functions, downstream distance river velocity, self-purification coefficient, and weighting methods. Specific descriptions concerning the variables were presented in Supplementary Materials. For computational convenience, the independent variables were converted to coded values, with the upper limit, lower limit, and center level coded as +1, −1 and 0. A number of experimental runs were performed, and all the runs were conducted in triplicate. For each run, the TEI (total environmental impact) was used as the response. This study employed Minitab 17.1 (Minitab Inc., State College, PA, USA) to perform statistical analysis, and the factors that presented significant effects on TEI were determined ($p < 0.01$) by means of regression analysis.

2.3.4. Stakeholder participation

In the third phase employing CA to achieve stakeholder participation, the attributes were determined from the LCA impact categories, including COD, ADF, GW, HT, A and PO. Based on the characterization results of three EQL alternatives, three levels were assigned to each attribute. Based upon the orthogonal test design, a bundle of 18 decision alternatives was constructed by combining the attributes and levels. A group of individuals were invited to act as stakeholders in wastewater treatment, and asked to rank the alternatives using the values ranging from 1 to 18, with the value of 1 and 18 representing the most preferred set and the least preferred set, respectively. In this case, preference data were harvested separately at different scenarios, and the scenarios were constructed on the basis of the significant factors that were determined from PB design. By comparing and examining the difference in results between scenarios, the results indicated how those factors would impact the selections and preferences of stakeholders of WWTP.

3. Results

The modelling scheme in this study was a data-driven system that needed data input and generated data output (results). By examining the results, recommendations could be derived to provide scientific decision support for the determination of proper EQL.

3.1. Data input and output

The data input to the *HIT.WATER* scheme included the life cycle inventory data of the three EQL alternatives (Table S1), a list of parameters of the selected river reach in a given time period (Table S2), five types of weighting factors, and five river functions defined by Chinese government (Table S3).

Data output mainly referred to TEI, GEI and REI (Fig. 4). The results from the aggregation of normalized LCA results of all site-generic impact categories show that the GEI was static for each EQL alternative, with values of 1912, 1403 and 1208 for Alternative-1, Alternative-2, and

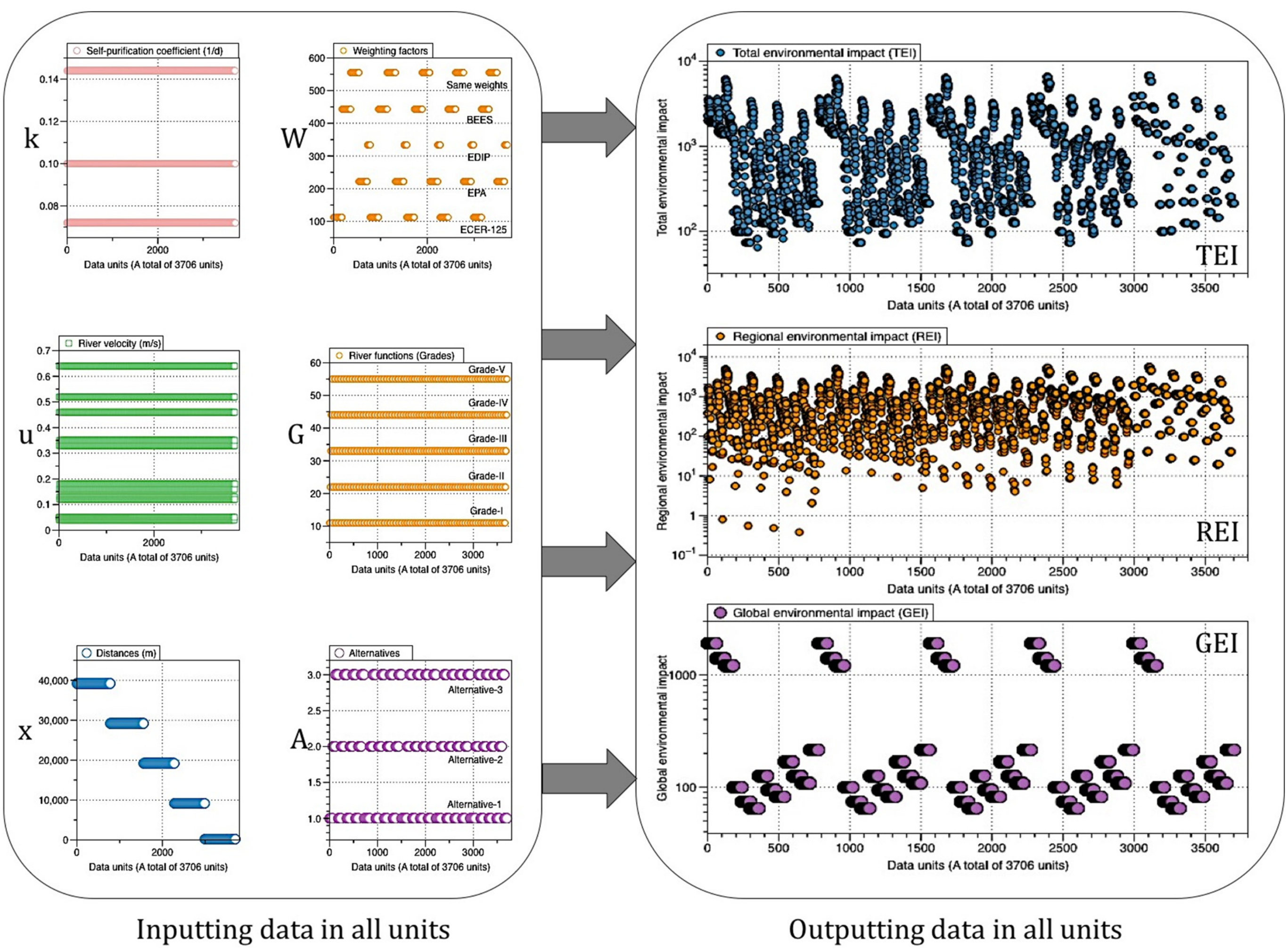


Fig. 4. Data input (*k*, *w*, *u*, *x*, *A* and *G*) and output (TEI, REI and GEI) in the case study using the *HIT.WATER* scheme. Specifically, *k*, *w*, *u*, *x*, *A* and *G* represent self-purification coefficient, weighting factors, river velocity, downstream distances, EQL alternatives and river functions, respectively.

Parameters	Initial ranges
River function	(Grade I to V)
Alternative	(Alternative 1 to 3)
Distance (x)	(200m, 39200m)
River velocity (u)	(0.4m/s, 0.64m/s)
Weighting	(Five types)
Coefficient (k)	(0.04 1/d, 0.144 1/d)

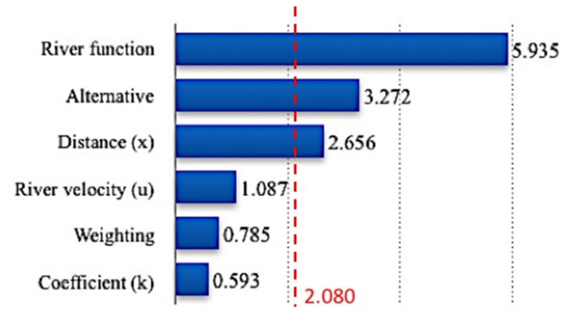


Fig. 5. Identification of the orders of significance for six variables. Initial ranges of variables are shown in the table (see Left), and the significance values are demonstrated in the figure (see Right). The variable with the value higher than 2.080 can be identified as an influential factor.

Alternative-3, respectively. Unlike the static GEI, dynamic REI and TEI were generated by the *HIT.WATER* scheme. Both of them (REI and TEI) were affected by a list of parameters embedded in the modelling scheme.

3.2. Sensitivity analysis performed by PB design

This current case study examined six parameters that could lead to influences on the output variables. These parameters included the EQL alternatives, river velocity (u), self-purification coefficient of water pollutant (k), downstream cross-section distance (x), officially defined river functions, and weighting factors.

Base on the background information incurred in the case study, the initial ranges of the six variables for PB design were determined, as shown in Fig. 5. Under those ranges, the order of significance was identified. Results of TEI were selected as the response for each experimental run. A ranking for the main effects was generated by sorting the scores of each parameter.

Examination of the Fig. 5 indicated that all of the variables presented positive effects on the TEI. Variables with significant effects included the river functions, EQL alternatives, and downstream cross-section distance. River functions demonstrated the most significant effect (5.935). Following the river functions, EQL alternatives were the second influential parameter, and the significance of this parameter (3.272) was approximately 23% higher than that of the downstream cross-section distance (2.656). Moreover, the self-purification coefficient was the least influential parameter (0.593), while both the river velocity and the weighting factors presented relatively small influences, with values of 1.087 and 0.785, respectively.

The two variables, the downstream cross-section distance (x) and river velocity (u), possessed similar environmental connotations, i.e., both of them represented the time periods experienced by pollutants when transporting to the cross-section. However, the aforementioned results showed that the two variables presented the strikingly different relative importance, with one being significant (x), while another being not influential (u). The most likely reason was related to the initial assigned ranges of variables for PB design. Probably, the change of variable x (ranging from 200 m to 39,200 m) exerted more significant effect on the modelling results than the change of variable u (ranging from 0.04 m/s to 0.64 m/s).

Further, we investigated whether and to what extent altering the initial ranges would impact the rankings of the main effects. Results indicated that (with u fixed), once the range of x reduced from (200 m, 39,200 m) to (200 m, 19,200 m), less significance was observed (Fig. 6). With a further decrease to (9200 m, 19,200 m), significance value continued decreasing, which relatively pulled up the significance of variable u. In the range of x (9200 m, 19,200 m), we narrowed the u range from (0.04 m/s, 0.64 m/s) to (0.04 m/s, 0.12 m/s) and examined the change of significance. Results showed that both x and u became barely influential to the results of modelling.

3.3. Refined case investigation

To compare the three EQL alternatives, Fig. 7 shows the changes of TEI and REI at different downstream cross-section distances (x) and

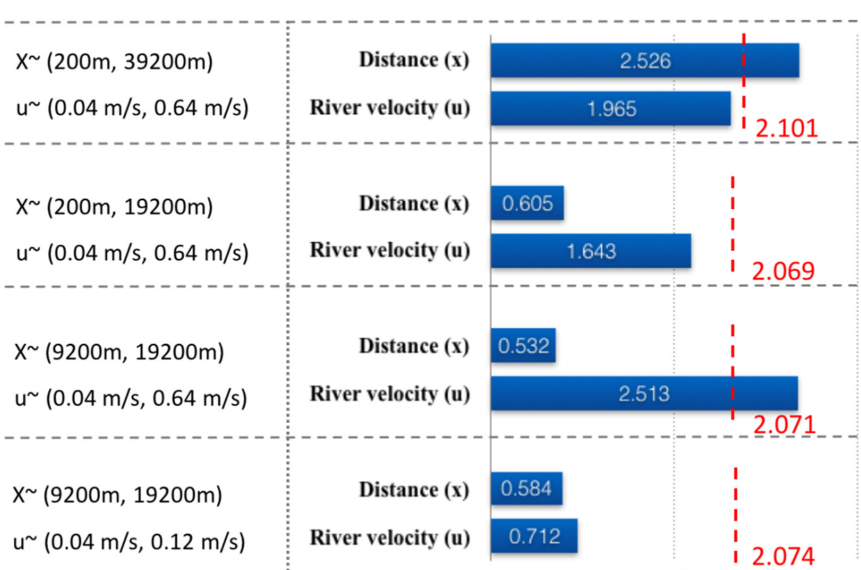


Fig. 6. Impact of the changing initial ranges on the significance extents of two variables: downstream cross-section distances (x) and river velocity (u).

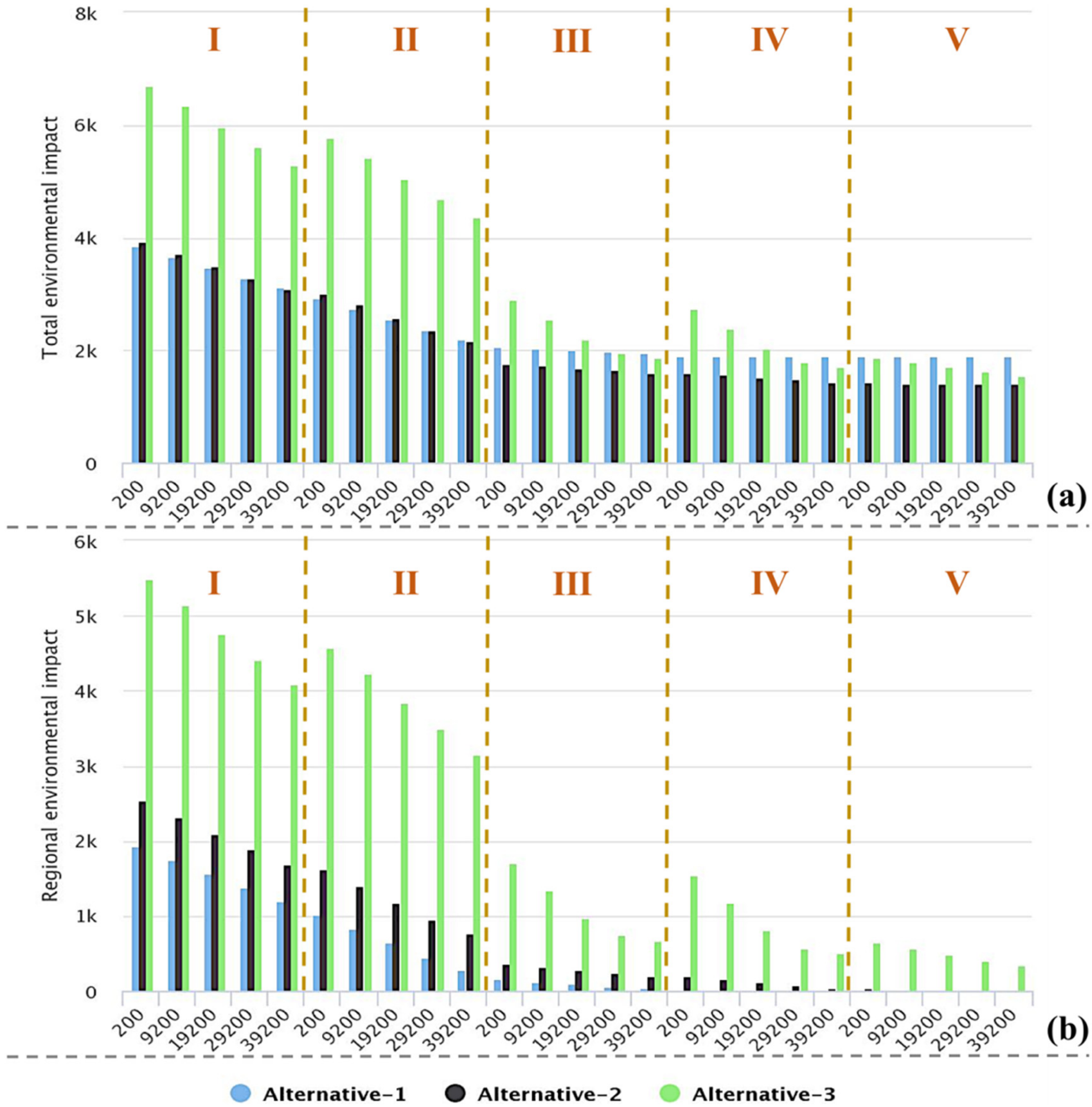


Fig. 7. Refined case investigations: dynamic comparisons between EQL alternatives under different downstream distances (from 200 m to 39,200 m) and different river functions (from Grade I to Grade V).

different river functions. For each EQL alternative, the decreases in overall tendencies were observed for both TEI and REI, either as the *x* increased from 200 m to 39,200 m or as the river functions switched from Grade I to Grade V. The decreases were originated from the fact that longer distances allowed degradation of more pollutants by the self-purification process, and the fact that river functions changing from Grade I to Grade V represented the increased maximum acceptable amount of pollutants. Both of the facts would relatively decrease the environmental impacts of discharged sewage.

In spite of the similar overall tendency mentioned above, the declined ranges of environmental impacts (both TEI and REI) were different. Gradual reduction was observed at all river functions, while a remarkable decrease was demonstrated at all downstream distances as river function was altered from Grade II to Grade III. This finding confirmed the previous PB results that river function presented more significant effects on modelling output, compared to the downstream cross-section distance.

With regard to the comparisons of the three EQL alternatives, the results were not static stereotypes, but altered according to varied conditions. At Grade I and Grade II, the results remained consistent at all downstream distances, i.e. both the highest TEI and REI were presented in Alternative-3 and the lowest ones were observed in Alternative-1. However, changing from Grade II to Grade III a fluctuation of TEI and REI was noticeable. In terms of TEI, Alternative-3 exerted greater impact when *x* was ranging from 200 m to 19,200 m. With a further increase of *x* to 29,200 m and 39,200 m, Alternative-1 presented the highest environmental impact.

The TEI of Alternative-1 and Alternative-3 alternately ranking the highest also appeared at Grade IV. However, for Grade V, Alternative-1 remained the highest one at all downstream cross-section distances. The most likely reason was that the maximum acceptable amount of pollutants in Grade V was higher than other functions, which could relatively decrease the REI to the most extent. As such, all the three EQL alternatives presented low levels of REI, e.g. with values of 0, 41.69 and 654.42 for Alternative-1, Alternative-2 and Alternative-3, respectively when $x = 200m$. Combined with the site-specific impacts, Alternative-1 generated the highest TEI (1911.84), following by Alternative-3 (1862.85), and Alternative-2 (1445.12).

3.4. Stakeholder participation

To facilitate the participation of stakeholders in the evaluation of EQL alternatives, CA was employed in the *HIT.WATER* scheme to promote stakeholders to decide the most preferred alternative and present the intrinsic decision criteria quantitatively. After collecting the preference data from all the respondents, which referred to the stakeholders from the context of sewage treatment, three results were obtained: (1) utility estimate for each attribute and level, (2) total utility for each alternative, and (3) relative importance of each attribute. Based on the PB results that river functions presented significant effects on modelling output, two decision scenarios were established by employing the LCA characterization results of Grade-I and Grade-V, respectively.

Table 1 shows the utility estimates for all attributes associated with all levels. Generally, the higher value of utility estimate represented the greater extent of preference. For instance, with regard to the utility estimates of ADF under Grade-I, the highest preference was on the Alternative-3 corresponding with the highest utility of −1.00; and the lowest preference was on the Alternative-1 corresponding with the lowest utility of −3.00. It was worth noting that different tendencies of preference for the selected impact categories (attributes) were demonstrated under different river functions. With emphasis on the paradigm shift from Alternative-3 to Alternative-1, the Grade-I showed decreasing tendencies of preferences for the attributes of ADF, GW and HT, but increasing tendencies for A, PO and BDO. For the Grade-V, however, the increasing tendency was only demonstrated on the attribute of BDO, and decreasing tendencies were embodied on all other attributes. The difference in the utility estimates was a representation of how different decision situations would substantially impact the decisions of stakeholders. Specifically, the difference indicated that the change from Grade-I to Grade-V was capable of altering the preferences of stakeholders on the impact categories.

With the utility estimates for each attribute level, the total utility that represented the overall preference for each alternative could be calculated. Under different river functions, the stakeholders showed substantially different judgments or preferences between the three alternatives, as shown in Fig. 7. When at Grade-I, Alternative-1 was the most preferred option with the highest total utility of 6.44 ± 0.15, followed by the Alternative-2 (3.62 ± 0.34), and Alternative-3 (1.52 ± 0.11). With the shift to Grade-V, the most preferred option was the Alternative-3 with the highest overall preference of 6.76 ± 0.20, and the least preferred option was the Alternative-1 with the lowest overall preference of 1.67 ± 0.22.

To further understand the preferences of stakeholders, the relative importance of each attribute could be derived via CA to measure how important each attribute was to the overall preferences of stakeholders. In other words, the relative importance to certain extent equates with

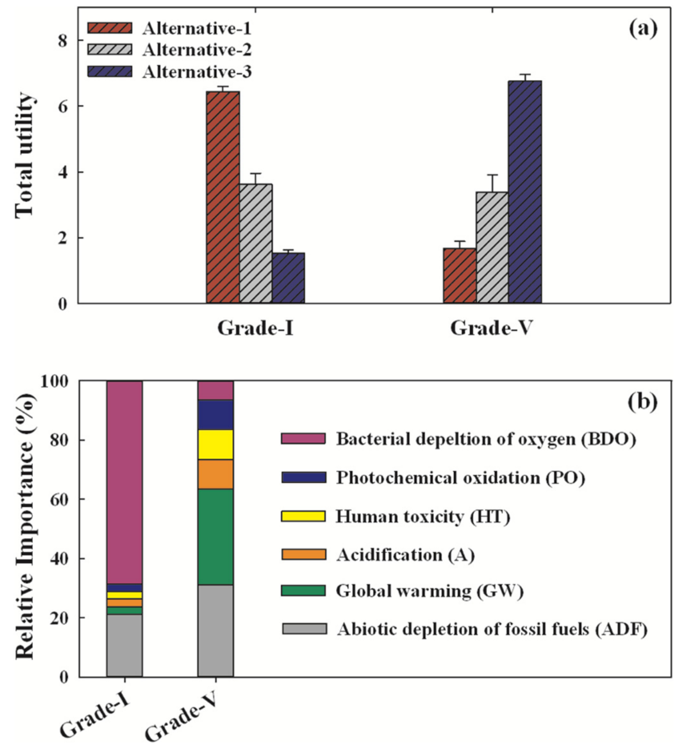


Fig. 8. Estimation of total utility (overall preference) and relative importance (judgment criterion) of stakeholders under two decision scenarios (Grade-I and Grade-V).

the stakeholders' intrinsic decision criteria. The attribute with higher importance score played a more important role than that with lower score. As shown in Fig. 8, BDO presented the highest relative importance (68.6%) for the Grade-I, implying the highest environmental priority for stakeholders to determine the appropriate EQL alternative. ADF was the second-highest importance (21.1%), while the aggregated importance of other attributes was 10.3%. Further, switching from Grade-I to Grade-V the changes of relative importance were evident. At this point, GW presented the highest importance (32.3%), followed by a slightly lower importance of ADF (31.2%). The aggregated importance

Table 1
Utility estimates for each level of attributes.

Attributes	Levels	State	Grade I		Grade V	
			Utility estimates	Std. error	Utility estimates	Std. error
ADF (MJ)	7.66E+04	Scenario-3	−1.00	0.196	3.00	0.288
	8.63E+04	Scenario-2	−2.00	0.191	2.00	0.393
	1.17E+05	Scenario-1	−3.00	0.187	1.00	0.434
GW (kg-CO_2-eq.)	1.05E+04	Scenario-3	−0.17	0.073	3.00	0.073
	1.22E+04	Scenario-2	−0.33	0.095	2.00	0.095
	1.57E+04	Scenario-1	−0.50	0.121	1.00	0.121
A (kg-SO_2-eq.)	5.43E+01	Scenario-3	0.08	0.012	0.50	0.014
	6.05E+01	Scenario-2	0.17	0.023	0.33	0.032
	8.41E+01	Scenario-1	0.25	0.033	0.17	0.045
COD (kg-NO_3-eq.)	5139.17	Scenario-3	3.00	0.004	0.016	0.014
	2324.44	Scenario-2	6.00	0.012	0.020	0.025
	1754.26	Scenario-1	9.00	0.017	0.032	0.037
HT (kg-1,4-dB-eq.)	1.74E+03	Scenario-3	−0.25	0.13	0.75	0.17
	2.08E+03	Scenario-2	−0.50	0.25	0.50	0.22
	2.86E+03	Scenario-1	−0.75	0.471	0.25	0.41
PO (kg-ethylene-eq.)	2.77E+00	Scenario-3	0.01	0.011	0.50	0.019
	3.11E+00	Scenario-2	0.02	0.015	0.33	0.021
	4.21E+00	Scenario-1	0.03	0.023	0.17	0.033

Note: Higher value indicates higher preference. Each value of utility estimate represents the collective preference of all the stakeholders engaged in this study. Two decision scenarios were constructed herein based on two different conditions: Grade I and Grade V. Attributes in the table were selected from the impact categories of LCA.

of A, HT, and PO, was 30%, while BDO contributed the least importance with the lowest score of 6.5%.

4. Discussion

This study established the *HIT.WATER* scheme, which integrated life cycle assessment (LCA), water quality model (WQM), conjoint Analysis (CA), and statistical Plackett–Burman (PB) design. The aim of establishing this scheme was to facilitate the evaluation of effluent quality limit (EQL) by means of jointly considering the estimation of sustainability, watershed planning, and stakeholder participation.

Despite its development under the context of Chinese wastewater management, application of the *HIT.WATER* scheme can be extended to multiple regions and broader scales where the evaluation of paradigm shifts (technological advancement or effluent standard changes) in sewage systems is necessary. Indeed, this scheme provides a platform that allows the evaluation conducted from various perspectives. On the one hand, it enables the screening of appropriate EQL alternatives under a given circumstance that represents a certain situation in reality. The given circumstance can be constructed by transforming various realistic elements (e.g. water velocity) into the model parameters. On the other hand, the *HIT.WATER* scheme provides a participation system for stakeholders such that they can present their preferences and determination in scientific and feasible formats, in which their professional judgment and the prior evaluation results are combined.

4.1. Implications from the case analysis

From the demonstrative case study, this work presented the processing procedures and scientific interpretations for the complicated results obtained from the scheme.

Given the case outcome derived from PB-design, the first finding was that the initially assigned ranges of parameters led to an obvious influence on the modelling output. Understanding the relation was important to establish refined case investigations because the changing ranges of parameters usually represent the changing characteristics in environmental conditions. For example, the variation of water velocities possibly corresponds to the seasonal changes, and the variation of downstream cross-section distances is closely related to the officially monitored river reach. Thus, upon the results of PB design, the *HIT.WATER* scheme delivered a foundation for the refined case investigations by means of varying the embedded variables and constructing different decision situations.

By the refined case investigations, we further discovered that the TEI and REI of different EQL alternatives altered with the varying environmental conditions. Indeed, it was the unique ability of the *HIT.WATER* scheme that could enable the presentation of dynamic comparisons on a quantitative basis. This would be more advantageous to provide insightful decipherment of the evaluation of the paradigm shifts in sewage plants. For instance, substantial WWTPs in China are currently facing with a decision situation whether or not to upgrade EQL from intermediate treatment (Alternative-2) to tertiary treatment (Alternative-1) (Zhang et al., 2016). Hereby, we assumed that the WWTP in this case analysis faced the same challenge. According to the results (Fig. 7), the upgradation would be appropriate when the river function of monitored river reach was defined as Grade-I or Grade-II. This was due to the almost similar TEI of the two alternatives and the lower REI of Alternative-1, meaning that upgrading to Alternative-1 could reduce the water pollution potential but not at the expense of incurring more environmental burdens. However, once the defined river function ranged from Grade-III to Grade-V, the upgradation would be unfavorable, because the slight reduction of REI was not enough to offset the increased burdens of other environmental categories, finally resulting in the TEI of Alternative-1 higher than that of Alternative-2.

In the end, based on the estimation results of CA, a decision-making process could be derived herein to describe how stakeholders proceed with their judgments facing the three EQL alternatives under the two decision scenarios (Grade-I and Grade-V). Considering that those stakeholders belonged to the context of sewage treatment, intuitively they would pay more attention to the effects of enhanced removal of pollutants, which could be reflected by the BDO attribute. However, BDO played the most important role only in the scenario of Grade-I, and the least significant role in the scenario of Grade-V (Fig. 8). This observation indicated that the removal of pollutants was not the sole criterion when evaluating the appropriateness of EQL alternatives. In fact, with shift to Grade-V, the stakeholders became more concerned about the unintended environmental implications, such as the resource consumption and climate change.

4.2. Future direction for refinement of the HIT.WATER scheme

To represent the regional aquatic pollution potential of sewage discharge, the present study introduced a site-specific category named BDO (Bacterial Depletion of Oxygen). It was the foundation for linking WQM with LCA in current *HIT.WATER* scheme. The focus of this category was on the potential growth of microorganisms, and it was different with the eutrophication category emphasizing the algae growth caused by nitrogen and phosphorus. Despite the independence of one another in current scheme, the bacteria growth and algae growth are closely related in reality (Amin et al., 2015; Ramanan et al., 2016; Ren et al., 2018). As such, in order to cover more cases on water pollution, the refinement in future will be on synthetization of the two categories by characterizing the combined effects of COD, nitrogen, and phosphorus to the growth of bacteria and algae.

Associated with the incorporation of WQM, several elements related to watershed planning became the essential ingredients of the *HIT.WATER* scheme. The watershed planning in reality often involve interactions of multi-factors such as the synergy between self-purification effects and dilution effect, the coordinated management of multiple river reaches, and the comprehensive improvement of various emission points as well as the joint consideration of background concentration and non-point source pollution (Guo and Jia, 2012; Lei et al., 2015). Whilst most of the factors have been included in the current scheme, the case study in this present work dealt with a simplified situation that had only one river reach and one pollution point. To advance the practical application, future refinement ought to select more concreted watershed case with complicated factors affecting the sustainability estimation.

Moreover, this study revealed one of the functions of PB design in identifying the significance of individual parameters. However, besides the "main" effect of individual parameters, the modelling output could reasonably be impacted by the 2-way "interactions" of pairs of parameters or the notable higher order interactions (3-way, 4-way, etc.). Taken into account the fact that environmental impacts of EQL alternatives were determined by the combined effects of many factors, investigation of the "interactions" of multi-factors would be of great importance. This is another critical function of the PB design (Beres and Hawkins, 2001), and should be particularly explored in future studies using the *HIT.WATER* scheme.

As for the application of CA, the sample size of the invited stakeholders has been considered as an important factor (Orme, 1998). In the *HIT.WATER* scheme, the selection of sample size would be highly corresponded with the purpose of promoting the participation of stakeholders. There would be no such question when the investigation aimed to explore the similarities and differences between the preferences and criteria of the individuals, or when the group of stakeholders had a limited number of individuals and all their participation in the CA was feasible (like the way handled in the present study). However, If the purpose was to derive collective opinions of groups with specific backgrounds (e.g. the whole population in a country), it will be important to ensure that the chosen sample size is statistically representative (Itsubo et al., 2004). This is an important research theme in future, especially if we plan to promote the involvement of stakeholders with a broader community and larger population size.

5. Conclusions

To have a sustainability evaluation of EQL alternatives for sewage systems, this current study established the *HIT.WATER* scheme - an integrated LCA-based decision-support platform that integrates the currently available LCA system, Water Quality Model, Plackett–Burman design, and Conjoint Analysis. By means of synthesizing various types of fundamental data input (e.g. energy and material flows, emissions into air, water and soil, natural factors of downstream watershed, human factors of official watershed planning, etc.), this system could produce dynamic comparisons of environmental impacts between EQL alternatives. It would contribute to the preclusion of "one-size-fits-all" decisions that was identified without systematic consideration of sustainability. Simultaneously, the participation of stakeholders could be achieved by a transparent decision-making process, with clear quantitative presentations of their options and judgment criterions concerning the evaluation of appropriate of EQL.

Moreover, via a demonstrative case study, the following findings were obtained.

a). The *HIT.WATER* scheme delivered a platform that evaluations of EQL could be investigated from various perspectives by varying the embedded variables to construct different decision situations.
b). For the WWTP in the present case study, it is not in all cases that net environmental improvement can be achieved when determining to upgrade from intermediate treatment to tertiary treatment.
c). With the change of decision scenarios, stakeholders would shift their evaluation emphasis by adjusting the weights between different impact categories.

In future, we will extend the application of the *HIT.WATER* scheme to a broader scale where the evaluation of paradigm shifts (technological advancement or effluent standard changes) in sewage systems is necessary. Further, efforts will be spent to refine the scheme, covering e.g. the characterization of the combined effects of pollutants on growth of bacteria and algae, the investigation of more concrete watershed case with complex factors processed jointly, and the involvement of stakeholders with a broader community and high population size.

Acknowledgements

This work was supported by the National Key R&D Program (No. 2016YFC0401105) and State Key Laboratory of Urban Water Resource and Environment (Harbin Institute of Technology) (No. XQ2018002), and the National Natural Science Foundation of China (Grant No. 31870110).

Competing financial interests

The authors declare no competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.209.

References

Amin, S., Hmelo, L., Van Tol, H., Durham, B., Carlson, L., Heal, K., Morales, R., Berthiaume, C., Parker, M., Djunaedi, B., 2015. Interaction and signalling between a cosmopolitan phytoplankton and associated bacteria. Nature 522 (7554), 98.

Bai, S., Wang, X., Huppes, G., Zhao, X., Ren, N., 2017a. Using site-specific life cycle assessment methodology to evaluate Chinese wastewater treatment scenarios: a comparative study of site-generic and site-specific methods. J. Clean. Prod. 144, 1–7.

Bai, S.W., Wang, X.H., Zhang, X.D., Zhao, X.Y., Ren, N.Q., 2017b. Life cycle assessment in wastewater treatment: influence of site-oriented normalization factors, life cycle impact assessment methods, and weighting methods. RSC Adv. 7 (42), 26335–26341.

Bai, S., Wang, X., Zhao, X., R, N., 2018a. Characterizing water pollution potential in life cycle impact assessment based on bacterial growth and water quality models. Water 10 (11), 1621.

Bai, S., Zhao, X., Wang, D., Zhang, X., Ren, N., 2018b. Engaging multiple weighting approaches and conjoint analysis to extend results acceptance of life cycle assessment in biological wastewater treatment technologies. Bioresour. Technol. 265, 349–356.

Bai, S., Zhu, X., Wang, X., Ren, N., 2018c. Identify stakeholders' understandings of life cycle assessment results on wastewater related issues. Sci. Total Environ. 622, 869–874.

Beres, D.L., Hawkins, D.M., 2001. Plackett–Burman technique for sensitivity analysis of many-parametered models. Ecol. Model. 141 (1–3), 171–183.

Beres, D., Swartzman, G., Clark, C., Starfield, A., 2001. Truth in modeling. Nat. Resour. Model. 14 (3), 457–464.

Churchill, G.A., Iacobucci, D., 2006. Marketing Research: Methodological Foundations. Dryden Press, New York.

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: state of the art. Water Res. 47 (15), 5480–5492.

Ebenstein, A., Fan, M., Greenstone, M., He, G., Yin, P., Zhou, M., 2015. Growth, pollution, and life expectancy: China from 1991-2012. Am. Econ. Rev. 105 (5), 226–231.

Floresalsina, X., Corominas, L., Snip, L., Vanrolleghem, P.A., 2011. Including greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies. Water Res. 45 (16), 4700–4710.

George, B., 1978. Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building.

Glucker, A.N., Driessen, P.P., Kolhoff, A., Runhaar, H.A., 2013. Public participation in environmental impact assessment: why, who and how? Environ. Impact Assess. Rev. 43, 104–111.

Gonzalez, S.O., Almeida, C.A., Calderon, M., Mallea, M.A., Gonzalez, P., 2014. Assessment of the water self-purification capacity on a river affected by organic pollution: application of chemometrics in spatial and temporal variations. Environ. Sci. Pollut. Res. Int. 21 (18), 10583–10593.

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., 2009. A new planning and design paradigm to achieve sustainable resource recovery from wastewater. Environ. Sci. Technol. 43 (16), 6126–6130.

Guo, Y., Jia, H., 2012. An approach to calculating allowable watershed pollutant loads. Front. Environ. Sci. Eng. 6 (5), 658–671.

Guven, H., Eriksson, O., Wang, Z., Ozturk, I., 2018. Life cycle assessment of upgrading options of a preliminary wastewater treatment plant including food waste addition. Water Res. 145, 518–530.

Hadjimichael, A., Morera, S., Benedetti, L., Flameling, T., Corominas, L., Weijers, S., Comas, J., 2016. Assessing urban wastewater system upgrades using integrated modeling, life cycle analysis, and shadow pricing. Environ. Sci. Technol. 50 (23), 12548–12556.

Han, D., Currell, M.J., Cao, G., 2016. Deep challenges for China's war on water pollution. Environ. Pollut. 218, 1222–1233.

Huang, D., Liu, X., Jiang, S., Wang, H., Wang, J., Zhang, Y., 2018. Current state and future perspectives of sewer networks in urban China. Front. Environ. Sci. Eng. 12 (3), 2.

Itsubo, N., Sakagami, M., Washida, T., Kokubu, K., Inaba, A., 2004. Weighting across safeguard subjects for LCIA through the application of conjoint analysis. Int. J. Life Cycle Assess. 9 (3), 196–205.

Kabisch, N., Korn, H., Stadler, J., Bonn, A., 2017. Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Springer.

Lavee, D., 2011. A cost–benefit analysis of alternative wastewater treatment standards: a case study in Israel. Water Environ. J. 25 (4), 504–512.

Lei, K., Zhou, G., Guo, F., Khu, S.-T., Mao, G., Peng, J., Liu, Q., 2015. Simulation–optimization method based on rationality evaluation for waste load allocation in Daliao river. Environ. Earth Sci. 73 (9), 5193–5209.

Li, W., Li, L., Qiu, G., 2017. Energy consumption and economic cost of typical wastewater treatment systems in Shenzhen, China. J. Clean. Prod. 163, S374–S378.

Lu, B., Du, X., Huang, S., 2017. The economic and environmental implications of wastewater management policy in China: from the LCA perspective. J. Clean. Prod. 142, 3544–3557.

Meng, F., Fu, G., Butler, D., 2016. Water quality permitting: from end-of-pipe to operational strategies. Water Res. 101, 114–126.

MEP, 2002a. Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918-2002). China Environment Press, Beijing.

MEP, 2002b. Surface Water Quantity Standards (GB8938-2002). China Environment Press, Beijing.

MEP, 2014. Action Plan for Water Pollution Prevention and Control.

MEP, 2017. Report on the State of the Environment in China.

Molinos-Senante, M., Hanley, N., Sala-Garrido, R., 2015. Measuring the CO2 shadow price for wastewater treatment: a directional distance function approach. Appl. Energy 144, 241–249.

Montgomery, D.C., 2017. Design and Analysis of Experiments. John wiley & sons.

Orme, B., 1998. Sample size issues for conjoint analysis studies. Sawthooth Software Research Paper Series. Sawthooth Software Inc., Squim, WA, USA.

Plackett, R.L., Burman, J.P., 1946. The design of optimum multifactorial experiments. Biometrika 305–325.

Qu, J., Fan, M., 2010. The current state of water quality and technology development for water pollution control in China. Crit. Rev. Environ. Sci. Technol. 40 (6), 519–560.

Rahman, S.M., Eckelman, M.J., Onnis-Hayden, A., Gu, A.Z., 2016. Life-cycle assessment of advanced nutrient removal technologies for wastewater treatment. Environ. Sci. Technol. 50 (6), 3020–3030.

Rahman, S.M., Eckelman, M.J., Onnis-Hayden, A., Gu, A.Z., 2018. Comparative life cycle assessment of advanced wastewater treatment processes for removal of chemicals of emerging concern. Environ. Sci. Technol. 52 (19), 11346–11358.

Ramanan, R., Kim, B.-H., Cho, D.-H., Oh, H.-M., Kim, H.-S., 2016. Algae–bacteria interactions: evolution, ecology and emerging applications. Biotechnol. Adv. 34 (1), 14–29.

Ren, N., Wang, Q., Wang, Q., Huang, H., Wang, X., 2017. Upgrading to urban water system 3.0 through sponge city construction. Front. Environ. Sci. Eng. 11 (4), 9.

Ren, X., Zeng, G., Tang, L., Wang, J., Wan, J., Liu, Y., Yu, J., Yi, H., Ye, S., Deng, R., 2018. Sorption, transport and biodegradation–an insight into bioavailability of persistent organic pollutants in soil. Sci. Total Environ. 610, 1154–1163.

Renou, S., Thomas, J.S., Aoustin, E., Pons, M.N., 2008. Influence of impact assessment methods in wastewater treatment LCA. J. Clean. Prod. 16 (10), 1098–1105.

Shao, M., Tang, X., Zhang, Y., Li, W., 2006. City clusters in China: air and surface water pollution. Front. Ecol. Environ. 4 (7), 353–361.

Shen, Z., Qiu, J., Hong, Q., Chen, L., 2014. Simulation of spatial and temporal distributions of non-point source pollution load in the Three Gorges Reservoir region. Sci. Total Environ. 493, 138–146.

Wang, X., Liu, J.X., Ren, N.Q., Yu, H.Q., Duujong, L., Guo, X.S., 2012. Assessment of multiple sustainability demands for wastewater treatment alternatives: a refined evaluation scheme and case study. Environ. Sci. Technol. 46 (10), 5542.

Wang, X., Wang, X., Huppes, G., Heijungs, R., Ren, N., 2015. Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China. J. Clean. Prod. 94, 278–283.

Wang, H., Yang, Y., Keller, A.A., Li, X., Feng, S., Dong, Y.-N., Li, F., 2016. Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. Appl. Energy 184, 873–881.

Wang, D., Pillai, S.C., Ho, S.-H., Zeng, J., Li, Y., Dionysiou, D.D., 2018. Plasmonic-based nanomaterials for environmental remediation. Appl. Catal. B Environ. 237, 721–741.

Wu, Y., Chen, J., 2013. Investigating the effects of point source and nonpoint source pollution on the water quality of the East River (Dongjiang) in South China. Ecol. Indic. 32, 294–304.

Zhang, Q., Yang, W., Ngo, H., Guo, W., Jin, P., Dzakpasu, M., Yang, S., Wang, Q., Wang, X., Ao, D., 2016. Current status of urban wastewater treatment plants in China. Environ. Int. 92, 11–22.

Zhao, X., Yang, J., Zhang, X., Wang, L., Ma, F., 2017a. Evaluation of bioaugmentation using multiple life cycle assessment approaches: a case study of constructed wetland. Bioresour. Technol. 244, 407–415.

Zhao, X.Y., Wang, L., Du, L.N., Yang, J.X., Dong, J., Ma, F., 2017b. Optimization of culturing conditions for isolated Arthrobacter sp ZXY-2, an effective atrazine degrading and salt-adaptive bacterium. RSC Adv. 7 (53), 33177–33184.

Zhou, J., Chang, V., W, C., Fane, A.G., 2011. Environmental life cycle assessment of reverse osmosis desalination: the influence of different life cycle impact assessment methods on the characterization results. Desalination 283, 227–236.