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Sustainability assessment of urban water planning using a multi-criteria analytical tool – a case study in Ningbo, China

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Abstract

Sustainable urban water infrastructure planning has become one of the major concerns when facing the growing urbanization pace and challenges in China. The paper aims to integrate the modern decision support tools in urban water supply system (WSS) planning and programing. A case study of Ningbo, China is presented to assess the cost-effectiveness and sustainability of the selected WSS. A multi-criteria sustainability analysis (MCSA) approach is adopted for dealing with the trade-off among a spectrum of criteria including those related to life-cycle costing and the triple bottom line concept. The results show that the three options for the WSS have the priority values 0.571, 0.632, and 0.631 and the second option is the best fit, while the first is least preferred owing to the high water–energy nexus. The analysis on the sensitivity is conducted revealing that decision-making is susceptible to the criteria weights and some quantification issues when assessing environmental and social sustainability. The third option might be a reversal of decision, against the second, depending partly on the criticality of relevant criteria weights. Finally, the MCSA approach is demonstrated to be employed not only for planning but for detailed design options' comparison later on and for managerial decision-making during operation.

Keywords: Carbon footprint; Least cost; Multi-criteria sustainability analysis; Ningbo; Water supply system

Abbreviations and acronyms

Beidu	Option A of Beidu and Jiangdong Combination, a water supply system
Xi'ao	Option B of Xi'ao and Xiaozhen Combination
Zhoumen	Option C of Zhoumen and Jiangdong Combination
AHP	Analytical hierarchy process

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AIFC	Average incremental financial cost (RMB/m^3)
Capex	Capital expenditure (RMB)
CDP 3.0	Criterium DecisionPlus software version 3.0
CF	Carbon footprint (Ton CO_2)
CI	Consistency index
EASY	Enabling-avoid-shift-yield route for policy orientation
GEF	Global environmental facility
GHG	Greenhouse gases
LCA	Life-cycle analysis
MCA	Multi-criteria analysis
MCSA	Multi-criteria sustainability analysis
NWEP	Ningbo Water Environment Project
Opex	Operational expenditure (RMB/yr)
O&M	Operation & maintenance
PV	Priority value
RMB	Renmin Chinese Yuan
TBL	Triple bottom line
TA	Technical assistance
WSS	Water supply system
WTW	Water treatment works

1. Introduction

1.1. Sustainable water planning

The growing perspectives of environmental, social, and economic sustainability in the water sector have been witnessed in recent years (Xu *et al.*, 2012). It is well recognized that worldwide water infrastructure planning calls for balancing economic, social, and environmental factors, which is referred to as a protocol of triple bottom line (TBL) (Coffman & Umemoto, 2010; Valipour, 2015). Actually, it means that the planning process should be in line with the goals for achieving sustainable development, meanwhile providing reliable and high-quality water provision to the city. For example, Novotny *et al.* (2010) envisaged this idea with the water–energy nexus as a premise for sustainability metrics' measurement. The TBL can be useful for comparing each option in a sustainable manner. The essence of such a protocol requires the planners to determine the preferred option that could provide the optimal mix of financial, social and environmental outcomes for stakeholders throughout the project lifespan. Moreover, a life-cycle impact evaluation approach is initially selected to allow for analysis of newly developed environmental indices, such as the emission of harmful greenhouse gases, the release of emerging toxins such as endocrine disrupters, and the resilience for adapting to climate change for social and ecosystems (Silva *et al.*, 2010; Ostfeld *et al.*, 2012). In addition, realizing the TBL requirement needs a suite of logical assessment frameworks such as cost-effectiveness analysis with proper valuation techniques to address quantification issues, and multi-criteria analysis (MCA) for screening and ranking the potential schemes (Zhuo *et al.*, 2013).

In terms of cost-effectiveness analysis, least-cost planning is a fundamental life-cycle costing approach for evaluating cost-effectiveness in implementation of any planning or project, which has been used for decades in China (Wu *et al.*, 2012). Recently the green-development initiative, including reduction of carbon footprint (CF) and adoption of low impact development, has been advocated by the Chinese government (Jia *et al.*, 2013; Wen *et al.*, 2014). The related paradigm shift should be incorporated into the life-cycle approach in China progressively.

Taking the climate change issue for example, due to the lack of both relative regulation and an assessment regime for incorporation of climate change impact into the life-cycle environmental impact assessment, the incorporation of the new consideration in emerging climate change issues is still ignored in the planning and implementation process (Baeumler *et al*., 2012; Wu *et al*., 2015). Hence, this presents the fact that proactive action is essential to implement and develop synergic planning to encompass sustainability and resilience factors into practices and decision-making. We then choose the hierarchical MCA approach as a primary tool, since not only can it integrate both quantitative and qualitative indices for assessment, through selection of an appropriate algorithm and other analytical tools (Valipour & Montazar, 2012; Bach *et al*., 2013), but also the architecture of MCA can accommodate more indices to be added in to meet the evolutionary requirements of new criteria.

1.2. Overall conception

Given the trend that sustainable urban water infrastructure planning has become one of the major concerns when facing the growing urbanization pace and challenges in China, the study therefore tries to first review the context of water supply planning assessment, with Ningbo, China as a case study showing the trajectory of setting up sustainable performance indicators and assessment goals for water supply planning in Section 1 and Section 2.1. The study then presents the related assessment process on planning for a specific water supply system (WSS) for Ningbo during China's 11th Five-Year Plan period, with emphasis on the use of integrated assessment tools by combining least-cost planning with the MCA approach, in Section 2.2. The methodology and the results are illustrated in Section 3.1–3.2, and Section 4.1–4.2, respectively. Furthermore, the study elaborates the methodology in Section 3.3–3.6 under the multi-criteria sustainability assessment (MCSA) approach and assessment rationale developed during the 12th Five-Year Plan period, giving more attention to low-carbon context and performance indicators linking TBL. A specific planning case on the selection of WSS priority is conducted and discussed afterwards including sensitivities and uncertainty factors. These are demonstrated with the results shown in Section 4.2–4.3. The implication, scaling-up and dissemination possibility of the integrative approach are discussed in Section 4.4 including actions to take in the future in Ningbo. Finally, the study gives the conclusions through Section 5 on the key points revealed while using the MCSA approach on the trade-off of a spectrum of criteria.

2. Study area

2.1. Study area and the evolution of planning criteria

Ningbo is located in the south of the Yangtze River Delta, with a land area of 9,816 sq.km and a permanent population of 7.7 million in its metropolitan area. It is a major international port city on the south-eastern coast of China, an economic center in the south of the Yangtze River Delta (Figure 1). The Ningbo Municipal Government has pushed forward major investments designed to strengthen the urban water supply and related eco-environment sector development with support from the World Bank, global environment facility (GEF) (World Bank, 2012) and other international finance institutions (Asian Development Bank (ADB), 2014) since the early 1990s. However, prior to the mid-2000s, only the traditional single-dimensional criteria, mainly from financial and engineering-economy indices, were used to implement the least-cost

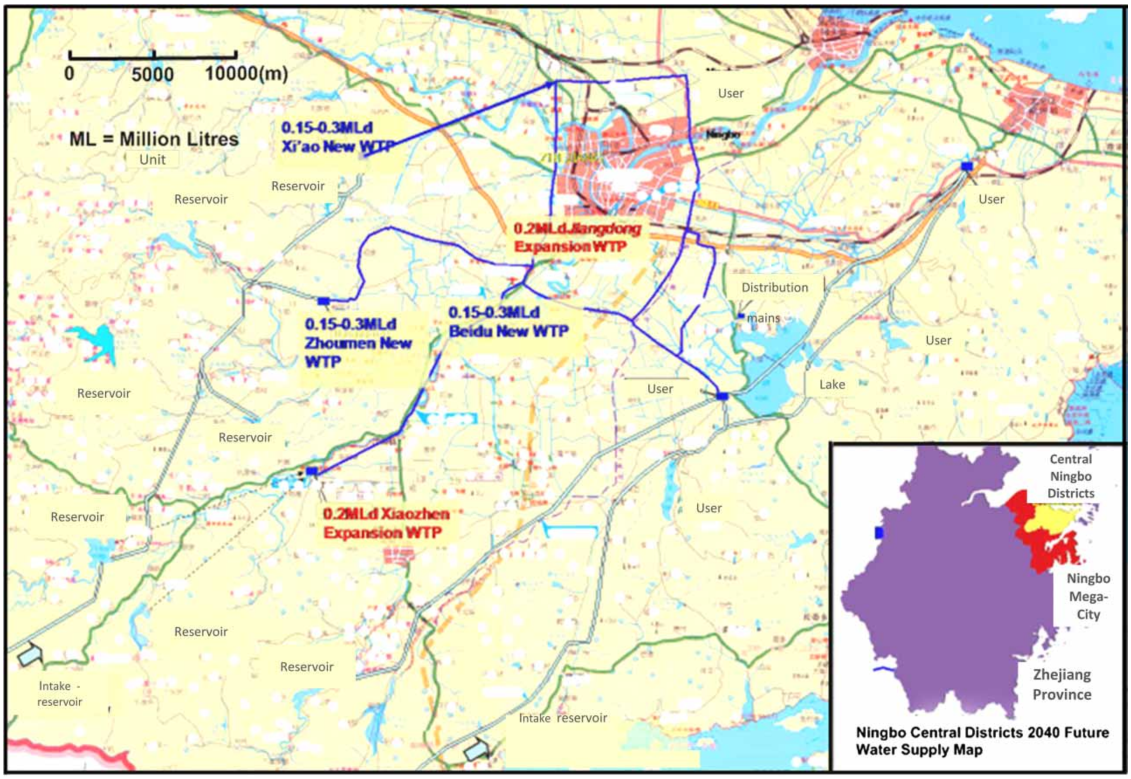

Fig. 1. Ningbo Central Districts Water Supply Planning 2008–2040.

planning solution. The TBL thinking was absent from keeping pace with growing concerns about broader environment criteria related to the urban hydrological regime and climate change in practice.

Since 2006 when the 11th Five-Year Plan started, Ningbo city (generally referring to the six urban districts of the city proper) and its surrounding urban area have experienced rapid economic and population growth, with many new housing and industrial developments being completed. A set of criteria with multiple dimensions but limited scale (for example, absence of greenhouse gas (GHG) impacting factors) has been developed to reflect regional and local concerns with the aid of a technical assistance (TA) program under the World Bank (2011) loan project, Ningbo Water and Environment Project (NWEP), entitled 'Ningbo Water Regulatory, Planning and Management'.

An eco-sustainability strategy for urban infrastructure was initiated in the subsequent 12th Five-Year Plan to reflect global concern and is being implemented effectively in the 13th Five-Year Plan which starts this year. Simultaneously, Ningbo has gained growing attention from the international finance institutions. It was included in the first group of pilot cities of climate change resilience in China, to be developed into a low-carbon city (Silva *et al.*, 2010; Baeumler *et al.*, 2012); another two programs in implementation – Ningbo New Countryside Development Project (World Bank, 2010) with a series of TA and Ningbo Low-Carbon Development with capability development TA (ADB, 2014); and another program in preparation – Ningbo Sustainable Urbanization Demonstration Project with sustainable local development and planning TA (World Bank, 2016). The focal points were to overcome the above-mentioned constraints, and develop a multi-dimensional and multi-scale criterion assessment tool for global concern evolved for supporting low-carbon and green urban initiatives with urban livability.

2.2. Scope of case study

Our core case study is based on part of Ningbo municipal water infrastructure planning throughout the period of the 11th and 12th Five-Year Plans (The World Bank, 2011). The program in the case covered the design of the provision of potable water services and facilities for a population reaching 1,860,000 in the six districts of the city proper. The targets were to choose a WSS that can augment the water production capacity, as well as the associated water delivery pipelines and distribution networks. There were three options for the WSS after coarse screening, each containing twin water treatment works (WTW) (one candidate selected from Beidu, Xi'ao or Zhoumen; the other from Jiangdong or Xiaozhen) and associated distribution networks connecting existing pipelines, as shown in Figure 1.

- Option A: Beidu & Jiangdong (hereinafter called Beidu)
- Option B: Xi'ao & Xiaozhen (hereinafter called Xi'ao)
- Option C: Zhoumen & Jiangdong (hereinafter called Zhoumen)

There are at least four key water supply elements that have been proposed and balanced in the planning rationale setting:

- Water quantity – including technical output and social satisfaction;
- Water quality – including environmental and social safeguard;
- Cost constraints – including effectiveness and efficiency indicators; and
- Risk and uncertainty management in relation to strategic/tactical water management – including operation & maintenance and adaptive management.

In particular, much attention needs to be paid to the planning in the introduction of MCA, a subjective weighting and scoring approach which has not been universally accepted in China planning practice (World Bank, 2011).

In addition, we examine and discuss the consequences and way forward facing the planning development and implementation. Compared with the core case study, we also trace and examine the subsequent projects and capital improvement programs related to water resource management and infrastructure development aided by TA from international finance institutions. We hence analyze the related policy strategy and route for the planners and decision-makers in our case study.

3. Methods and data

3.1. Life-cycle costing: financial indices

Sustainable water planning is usually subject to life-cycle analysis. In this study, we go through the following steps for measuring the financial indices on a basis of life-cycle costing: (i) calculation and assessment of capital cost (Capex), (ii) calculation and assessment of operation & maintenance cost

(Opex) and its key breakdown, and (iii) definition of a least-cost formula incorporating the two above – namely, minimization of average incremental financial cost (AIFC) (Asian Least-cost Greenhouse Abatement Strategy (ALGAS), 1999).

$$AIFC = \frac{\sum_T (Capex_t + Opex_t) \times (1+r)^{-t}}{\sum_T Q_t \times (1+r)^{-t}} \quad (1)$$

where, *Capex* and *Opex* are added to form total cost; Q_t is the incremental output in year j, T is the span of life cycle, and r is the discount rate.

3.2. TBL basic: selecting MCA structure

As mentioned above, TBL thinking is the foundation of MCA. In our study, the least-cost solution stated in Section 3.1 is only one form of TBL, which only focuses on the economic or financial dimension. Thus, the multi-criteria decision assessment approach is further applied as an additional tool, including assessment of the environmental consequences of alternative water development programs as well as estimation of the magnitude of environmental damage and social impacts.

A number of affecting factors were constructed by putting together the relative indices chosen for MCA, including the financial, social and environmental indicators as well as the water quality assurance indicator (International Finance Corporation (IFC), 2012). Some indicators within the candidate options might have a competing or conflicting direction with others. However, those might be reconciled to some extent through MCA analysis for attaining the mutual trade-off.

MCA has been used to deal with both quantitative and qualitative problems since the 1970s, especially solving the conflicting nature of planning problems. The simplest MCA is the additive weighting method. The ranking can be attained by the operation of assigned weights and evaluation scores after normalization, which was used by Qi & Chang (2013) for water service planning. A similar case was seen in the study by Zhuo *et al*. (2013). More sophisticated MCA uses complex tools like ELECTRE (Infante *et al*., 2013). In many cases, a decision model using the analytical hierarchy process (AHP) via logical generation of the hierarchy has been applied widely, presenting many advantages in assisting the decision-making process (Young *et al*., 2010). In our study, we use Criterium DecisionPlus 3.0 (CDP 3.0) software as the AHP tool in which the MCA architecture was designed for WSS option assessment and selection (Infoharvest, 2012). In detail, a set of criteria with multi-dimensional factors was formulated and has been continuously reviewed among stakeholders since 2009, as shown in Table 1. In this table, the majority of influential factors were in place except the impacting factor of GHG.

Using analytical hierarchy processes and multi-criteria rating techniques, CDP 3.0 can obtain immediate graphical feedback from ‘what if’ analyses and there are several merits of usage, such as easily establishing pair-wise comparison of relative importance and evaluating the robustness of a decision through sensitivity analysis. Table 2 shows pair-wise AHP rating and scoring regime at high hierarchy in CDP 3.0 for Ningbo WSS assessment.

Table 1. Initial AHP framework for MCA in previous Ningbo water planning.

Goal (Level 1): Rating set for WSS priority selection	Level 2 Criteria	Level 3 Attributes
	Quantity Reliability	Universal*
	Operational	Energy consumption
		Influence on pressure, water age in mains
		Quantity resilience and flexibility
	Cost/Financial	Capital cost
		O&M – over 30 years
		AIFC
	Social Impact	Universal*
	Environmental/Water Quality	Raw water's reliability and flexibility
		Risks on distribution network

*Universal means considering no significant impacts on rating in limited cognition.

Table 2. Pair-wise AHP intensity and scoring regime selection.

Standard AHP	Decision Narration	Scoring Criterion
9	Absolutely Better	+9
8	Critically Better	+8
7	Very Strongly Better	+7
6	Strongly Better	+6
5	Definitely Better	+5
4	Moderately Better	+4
3	Weakly Better	+3
2	Barely Better	+2
1	Equal	±1
½	Barely Worse	−2
⅓	Weakly Worse	−3
¼	Moderately Worse	−4
⅕	Definitely Worse	−5
⅙	Strongly Worse	−6
⅐	Very Strongly Worse	−7
⅛	Critically Worse	−8
⅑	Absolutely Worse	−9

3.3. Water–energy nexus: CF

CF assessment can be used to convey the impacts on global warming and climate change caused by the development of a program or planning. Normally, so-called CF accounting is divided into the top-down (environmental input–output table often used) and bottom-up method (through CF inventory and impact analysis). A number of CF tools have been developed for calculation of GHG emissions resulting from the utilization of all energy and material resources, comprising three scopes of CF inventories, as per the ISO standard, and adopted by the World Resource Institute China program (Wen *et al.*, 2014).

Among them, Scope 2 CF refers to indirect emissions from purchased utilities, e.g. electricity, gas and heat, which are the major sources of operational CF in the water supply sector. In our study the differences between different options are from Scope 2 emissions, a result of the water–energy nexus. For more details of the WSS, electric energy consumption is the main source that should be split into sequential water cycle steps: transportation through abstraction and conveyance of source water, water processing in WTW, and transportation through distribution of treated water.

Quantified CF, especially at the programing stage in water supply planning, can be assessed by the bottom-up formula, as below.

Energy use CF in Scope 2 quantifies CF s_2 by the formula:

$$CFs_2 = \sum F_i * E_i \quad (2)$$

where, F_i is carbon emission factor of energy type i and E_i is secondary consumption of energy type i. Energy type includes coal power, hydropower, and/or renewable energy from wind/solar system.

The following formula of electricity demand is applied in transportation and lift of water:

$$\mathrm{Ee-trans} = \frac{(\sum \mathrm{Headequivalent(m)} * \mathrm{Flow(L/s)} * \mathrm{Gravity(m/s^2)})}{\mathrm{Pumping\ efficiency}} \quad (3)$$

where, head equivalent is an aggregate of both static head and friction-caused head and pumping efficiency is assumed as 73–83%.

The following formula of electricity demand is applied in water processing:

$$\mathrm{Ee-proc} = \mathrm{Energy\ intensity\ for\ unit\ water\ processing}\left(\mathrm{kWh/m^3}\right) * \mathrm{Flowrate}\left(\mathrm{m^3}\right) \quad (4)$$

3.4. TBL in-depth: development of MCSA

We define a series of new indices after a baseline decision MCA tool from CDP 3.0 was built in the study, in particular, the CF, as well as its derivative, CF induced externality, to be embedded into the previous MCA analysis. As a result, the framework of MCSA has been developed through revisiting TBL after the planning became effective. Development of the framework before and after revisiting the relevant framework configuration has been conducted. In the former configuration, the CF issue is simply considered and categorized into its parent criteria, environmental sustainability at level 2 in AHP. The planning objective for this is to maximize the global benefits and reduce the CF profile over the planning horizon, whilst in the latter, the new MCSA reshapes the CF profile by categorizing it into social sustainability at level 2, named social carbon damage costs, or societal costs of CF (Ogden *et al*., 2004; IFC, 2012). MCSA for Ningbo WSS is shown in Table 3, with three ranking levels from goal level to the lowest individual level, with sensitivity and uncertainty configuration included. Compared with Table 1, the level 2 criteria of the MCSA remain relatively unchanged but the level 3 sub-criteria are augmented and adjusted in line with green and sustainable infrastructure rationale. By software testing, we can balance targets of economic sustainability and socio-environmental sustainability, and know the magnitude and robustness of related impacts in

Table 3. MCSA framework with AHP weighting method.

Goal Level	Level 2: Rating Set	Weights Priority Determinant	Level 3: Rating Set	Weights Priority Rating
	Output safeguard & reliability	Pair-wise & CI	Quantity assurance/technical easement for output	Critical
	Operational sustainability	Pair-wise & CI	Lower power energy consumption	Very Important
			Less influence of burst and leakage	Important
			Max. water quality assurance	Important
WSS priority	Financial sustainability	Pair-wise & CI	Min. capital cost	Important
			Min. O&M – over 30 years	Very Important
			Min. AIFC	Critical
	Social sustainability	Pair-wise & CI	Min. social carbon damage costs	Important
			Access assurance for all dwellers	Important
	Environmental sustainability	Pair-wise & CI	Max. regional benefit – raw water's eco-value	Important
			Max. global benefits – less CF profile	Important
			Fewer environment risks on distribution network	Important

CI, consistency index; Min., minimizing; Max., maximizing.

a candidate water infrastructure system. Therefore, the following key steps are taken: pair-wise method for weight assignment at level 2, quantification and non-quantified parameters judgment at level 3, scoring using lowest criterion against each option, normalization of all indicator scores, consistency test and adjustment, influential factor analysis, sensitivity analysis, and final ranking.

3.5. Key elements for measurement in MCSA

From Table 3, we consider the key elements for measuring criteria in relation to the water–energy nexus and its externality (Ogden *et al.*, 2004; Australia Government National Water Commission (AGNWC), 2011). The related objective setting comes from the following five key attributes:

- Lower power consumption – in category of operational sustainability;
- Minimize the lifespan Opex – that of financial sustainability;
- Minimize the AIFC – that of financial sustainability;
- Minimize the social carbon damage costs – that of social sustainability; and
- Maximize the global benefits – Less CF profile – that of environmental sustainability.

Of the above five attributes, lower power consumption and less CF profile are physical measurements while others are monetized ones. During option comparison, we can directly give the scores according to the relative rating method and the absolute values regarding physical attributes. The other three attributes are in a monetary setting and we should consider the financial and economic parameters.

Moreover, considering data availability and the assumptions set by WSS stakeholders, the data to construct the model are obtained from various sources (Wen *et al.*, 2014; Wu *et al.*, 2015) with significant parameters as below:

- Discount factor: in China 6% is the normal discount factor in water supply projects when calculating AIFC.
- Scoping of CF and the intensity (only referring to power-induced operational CF owing to its overwhelming contribution) – the Grid emission factor in Ningbo is 0.719 ton/CO_2 (renewable energy use from wind or solar systems in the area is negligible).
- The magnitude of social carbon damage costs depends on the societal carbon cost in economic analysis given the accounted CF. The selection of this will not affect the scoring of options as the CF profile of each option has been determined, and thus would not affect mutual comparison in this regard.

3.6. MCSA configuration and tool calibration

The consistency issue should be taken into account in advance. The consistency ratio, as a measure of consistency (Young *et al*., 2010), can be calculated directly from individual pair-wise comparisons over the rating set. When the consistency ratio is larger than 0.10, comparisons may be inconsistent. In addition, if the number of pairs is no more than three, the consistency ratio is more than 0.10 by direct comparison in most cases. Therefore, as indicated in Table 3, we establish the relative importance of the level 3 sub-criteria by directly setting their relative trade-offs, whereas the level 2 criteria, the parents of the related sub-criteria, need full pair-wise comparison and test by the consistency ratio.

The consistency ratio is defined as:

$$\text{Consistency Ratio}\,\text{N}*\text{N} = \frac{\text{Consistency Index}}{\text{Random Index}\,\text{N}*\text{N}} \tag{5}$$

where, N means number of pairs (Random Index equals 1.12 when $N = 5$).

4. Results and discussion

4.1. Quantitative assessment

4.1.1. Comparison of financial least-cost. As an important pillar for traditional TBL, the financial viability with the promise of water supply functioning is taken into prime account among city infrastructure regulators and the asset operators as well as other stakeholders, such as city dwellers. Table 4 gives the results of Ningbo WSS option assessment in the delivered report of Ningbo water supply planning in 2009 based on the consulting report when three candidate WSS options were considered.

Among them, Beidu WTW is located near the downtown area while Xi'ao and Zhoumen WTW are both in hilly peri-urban areas. To choose the optimal new WTW from them and the associated distribution mains was a key component of the planning. Besides, the existing Xiaozhen or Jiangdong WTW needed an expansion for contribution to the whole WSS configuration since twin-WTW are

Table 4. Capex, Opex and AIFC cost estimates proposed WSS options: 2010–2040.

WSS Option	Capex (Million RMB)	Opex Annual (Million RMB)	AIFC (RMB/'000 m^3)
Beidu	1,338	147	1,481
Xi'ao	1,517	112	1,462
Zhoumen	1,521	113	1,465

References: World Bank (2011); Wu *et al.* (2015).

required for a measure of reliability. Which sites were better depended on financial-led attributes: (i) benefiting the whole system in terms of system trade-off between short-term Capex and long-term Opex (Table 4), (ii) minimization of the composite index, namely, AIFC, and (iii) satisfying the merits of low energy intensity and ensuring low emissions in the whole WSS which could otherwise cause monetized burden.

It is shown that the values of AIFC had no remarkable difference actually. The table merely reveals a weak advantage in choosing the Xi'ao WSS followed by the Zhoumen WSS option under the assumption of a 6% discount rate. Option A, Beidu WSS, was the least preferred option because both its AIFC and annual Opex were the highest although its Capex was the lowest.

4.1.2. Comparison of the CF profiles and impacts. The results of CF accounting are the basis of the power-induced externality. As shown in Figure 2, from the conveyance of water sourcing and water processing to distribution of treated water, the annual aggregate CF of Beidu is 10,739 ton, while for the same service areas in Xi'ao and Zhoumen, the values are 5,021 ton and 5,087 ton, respectively. The

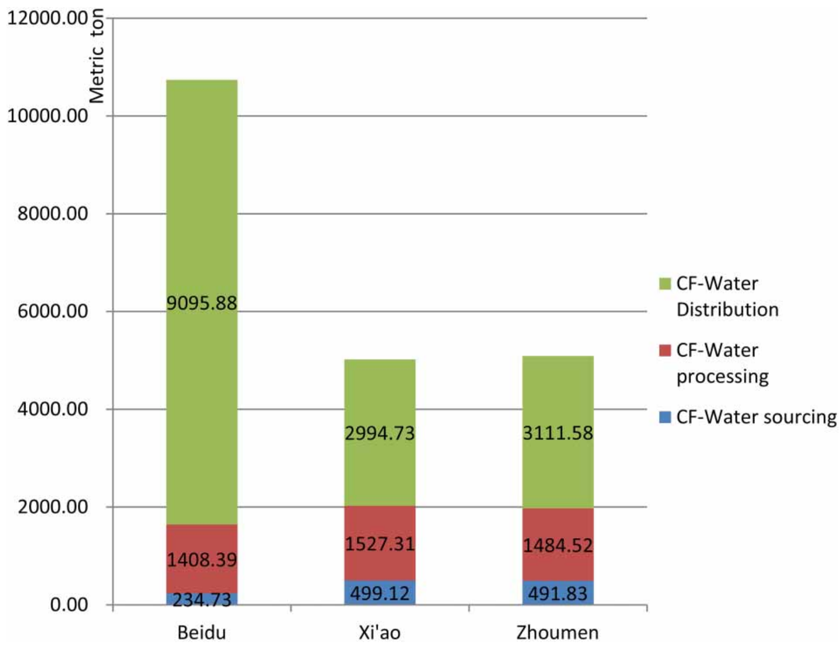

Fig. 2. CF estimation (metric ton) on a yearly basis and the breakdown of the three options.

Beidu option has a much higher CF profile from the component of distribution of potable water. The other two options have slightly higher CFs from raw water sourcing to WTW than Beidu because in dry seasons, when the reservoir water level approaches the lowest guarantee supply level, the stand-by lifting pump will be triggered, contributing to the power consumption. The slight gaps only exist at the water processing stage among the three options, and account for medium contribution in the water supply loop.

The significant distinctions were caused by the CF amount from the treated water distribution stage. It was shown that the pumping pressure was huge before potable water was distributed to all end-users at Beidu site, while in other sites, potable water was reachable mostly by gravity and only a minority of end-users relied on pumping. Therefore, from the water–energy nexus perspective, Beidu was the worst option.

In terms of the global GHG impacts, the significant CF gaps during the WSS evaluation might be meaningful from either the societal or environmental dimension. Both the physical means of the CF and the monetized means of it can reveal the impacts; hereby we categorize the former in environmental criteria while the latter is enlisted in the societal criteria in MCSA framework. Hence, the MCSA approach strengthens high CF-induced impacts by added weight, enhancing the efficacy of sustainability assessment.

4.2. Combined quantitative and qualitative assessment

The output 'safeguard & reliability' and 'AIFC' are endowed with playing the most critical roles while 'minimization of min. O&M cost over 30 years' and 'lower power energy and chemical consumption' occupy the second tier of importance seen from Table 3. Most of them are quantitative; however, compared with financial features and a tangible asset database, the social and environmental issues are the most complex and case-specific, which could result in difficulties in quantification or valuation. Other difficulties with quantification include some unforeseen or uncertain issues in relation to the reliability and productivity during WSS operation, which hinder proactive evaluation (World Bank, 2011). Based on the nature of the specific Ningbo WSS case study, MCSA could solve this through a combined quantitative and qualitative assessment. Table 5 presents the AHP weight scale estimates with regard to level 3 sub-criteria assessment against each WSS option under the MCSA framework, among which four indices can be physically determined for comparison, followed by two indices in terms of quasi-physical determination, whilst the remaining indices should be qualitative in judgment and comparison.

4.3. MCSA results

4.3.1. MCSA results on level 2 pair-wise comparison. Although the consistency test is not strictly required (Infoharvest, 2012), we logically figure out the detailed weight matrix at the level 2 pair-wise comparison (derived from the preliminary setting in Table 3). As shown in Table 6, financial sustainability has the highest aggregate significance against the other four criteria. Despite this, all pair-wise comparison values are ranging from 0.25 to 4, allowing social and environmental sustainability to be well involved.

Table 7 demonstrates the results of the MCSA for the three options under the AHP structure beginning from lowest criteria – level 3 – as developed and stated in the designated methodology. It can be

Table 5. AHP indices rating lowest level – a verbal description.

Level 3-Rating Indices	Beidu	Xi'ao	Zhoumen
Water quantity assurance/technical easement for output	Very important & uncertain	Important & uncertain	Important & uncertain
Lower power energy and chemical consumption	Quasi-physically determined	Quasi-physically determined	Quasi-physically determined
Less influence of burst and leakage	Very important & uncertain	Very important & uncertain	Very important & uncertain
Max. water quality assurance	Fair important	Important	Important
Min. capital cost	Physically determined following Table 3		
Min. O&M cost – over 30 years	Physically determined following Table 3		
Min. AIFC	Physically determined following Table 3		
Min. social carbon damage costs	Quasi-physically determined & uncertain	Quasi-physically determined & uncertain	Quasi-physically determined & uncertain
Access assurance for all dwellers	Very important & intangible	Very important & intangible	Very important & intangible
Max. regional benefit – raw water's eco-value	Very important & intangible	Critical & intangible	Critical & intangible
Max. global benefits – less CF profile	Physically determined following Figure 2		
Fewer environment risks on distribution network	Very important & uncertain	Unimportant	Important & uncertain

Table 6. Pair-wise test – Level 2.

Level 2	Output safeguard – reliability	Operational sustainability	Financial sustainability	Social sustainability	Environmental sustainability
Output safeguard – reliability	1	3	0.3333	4	2
Operational sustainability	0.3333	1	3	2	1
Financial sustainability	3	0.3333	1	4	3
Social sustainability	0.25	0.5	0.25	1	3
Environmental sustainability	0.5	1	0.3333	0.3333	1
Consistency Index =		0.0378			
Consistency Ratio =		0.0337			

seen that the level 2 criteria, with the consistency ratio of 0.0337, have the following contributions: (1) financial sustainability 43%; (2) output safeguard & reliability 25.1%; (3) environmental sustainability 12.8%; (4) operational sustainability 12%; and (5) social sustainability 7.1%. To sum up, the overall ranking in terms of aggregate priority value under this rating set (depicted in Figure 3) is 0.632 in score for Xi'ao; (slightly) >0.631 for Zhoumen (causing overwhelming advantage); and >0.571 for Beidu (Figure 3). The score (priority value) of Beidu WSS is shown to be 10% lower than those of Xi'ao and Zhoumen.

Table 7. Ranking and level 3 sub-criteria breakdown on scores of three WSS options.

Lowest Level (Level 3) Criteria	Beidu	Xi'ao	Zhoumen	Breakdown Weights
Quantity assurance/technical easement for output	0.6	0.54	0.54	0.251
Lower power energy consumption	0.55	0.78	0.78	0.051
Max. water quality assurance	0.25	0.5	0.51	0.034
Min. capital cost	0.5	0.45	0.44	0.095
Min. O&M cost – over 30 years	0.72	1.00	0.99	0.143
Min. AIFC	0.5	0.52	0.51	0.191
Min. social carbon damage costs	0.4	0.75	0.75	0.035
Max. regional benefit – raw water's eco-value	0.75	1	0.95	0.043
Less influence of burst and leakage	0.75	0.75	0.7	0.034
Fewer environment risks on distribution network	0.75	0.25	0.5	0.043
Max. global Impact – less CF profile	0.25	0.5	0.48	0.043
Access assurance for all dwellers	0.75	0.75	0.65	0.035
Aggregate PV of goal level (Ranking)	0.571(3rd)	0.632(1st)	0.631(2nd)	

PV = priority value of option.

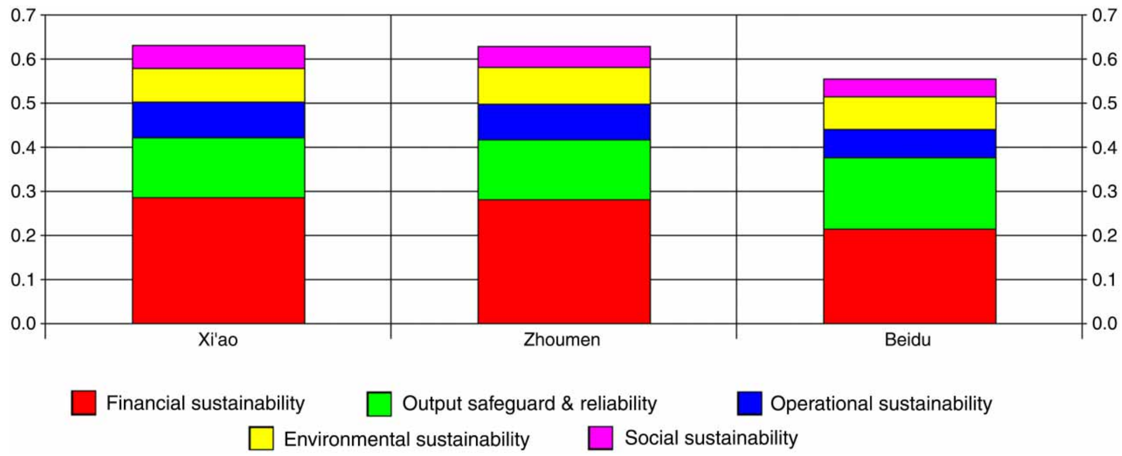

Fig. 3. Snapshot of final scores and the criteria contribution. (The level 2 criteria contribution to final scores are differentiated.)

4.3.2. Contribution of MCSA – breakdown analysis. Full breakdown and contributions of each WSS option are given regarding each sub-criterion at the lowest level of AHP, indicated from Table 7 and depicted explicitly in Figure 4(a). The top-three sub-criteria with great contributions to scores of the three WSS options are: (i) the Opex – an index for financial sustainability; (ii) quantity assurance plus technical easement for output – an index quantifying output safeguard meeting functional requirement; and (iii) the AIFC – another index for financial sustainability. Although the index of 'maximizing global benefits by reducing CF' and that of 'minimizing social carbon damage costs' only account for 4.3% and 3.5% in weighting, respectively, they still can considerably affect the final rating scores. Finally, the overall scores of the WSS decision are 0.632 for Xi'ao, 0.631 for Zhoumen, and 0.571 for Beidu, mainly due to the fact that Beidu has a much lower rating on the index of 'Min O&M over 30 years',

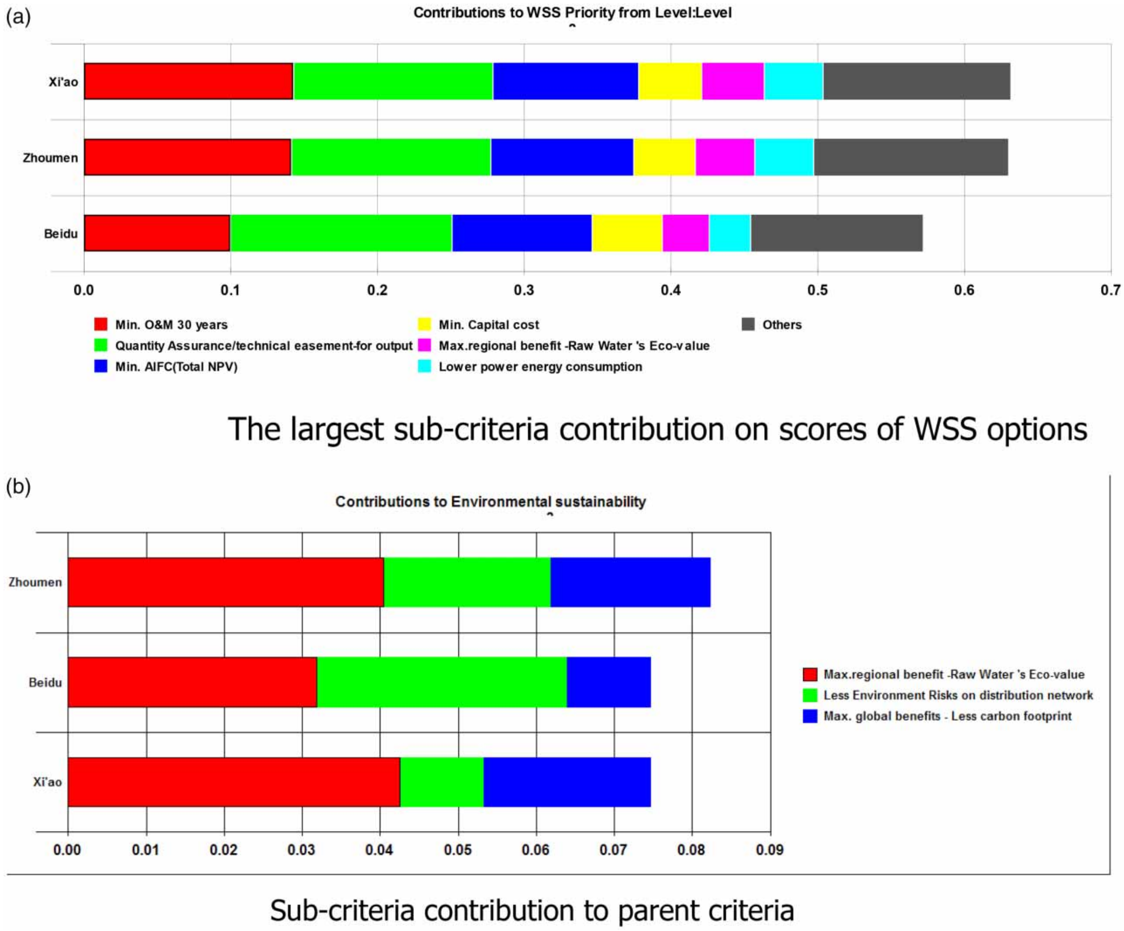

Fig. 4. Snapshot of breakdown charts of main attributes in AHP CDP 3.0.

although ‘quantity assurance plus technical easement for output’ can partially offset such a disadvantage since the employees might be keen on working downtown and the turnover of skilled staff is low.

Figure 4(b) indicates the sub-criteria regarding contributions at the lowest level of AHP in relation to their respective parent criteria. Taking environmental sustainability as an example, though Beidu has a very good score of rating on the contribution to reducing risk of distribution network burst and associated environmental issues (because of risk automation system in place at pumping stations), the CF incurred is the highest; they are a competing pair. The Zhoumen WSS is the best from the environmental sustainability perspective because all the three sub-criteria of environmental sustainability for it are superior to the average of the three options.

4.3.3. Sensitivity of MCSA and policy implications. The sensitivity analysis not only determines how sensitive the decision is to the change in relative importance assigned to the criteria, but also tests the extent of variation of the sub-criterion value that would affect the aggregate decision score. We select the parent criteria – environmental, social and financial sustainability – for analysis. From the diagrams

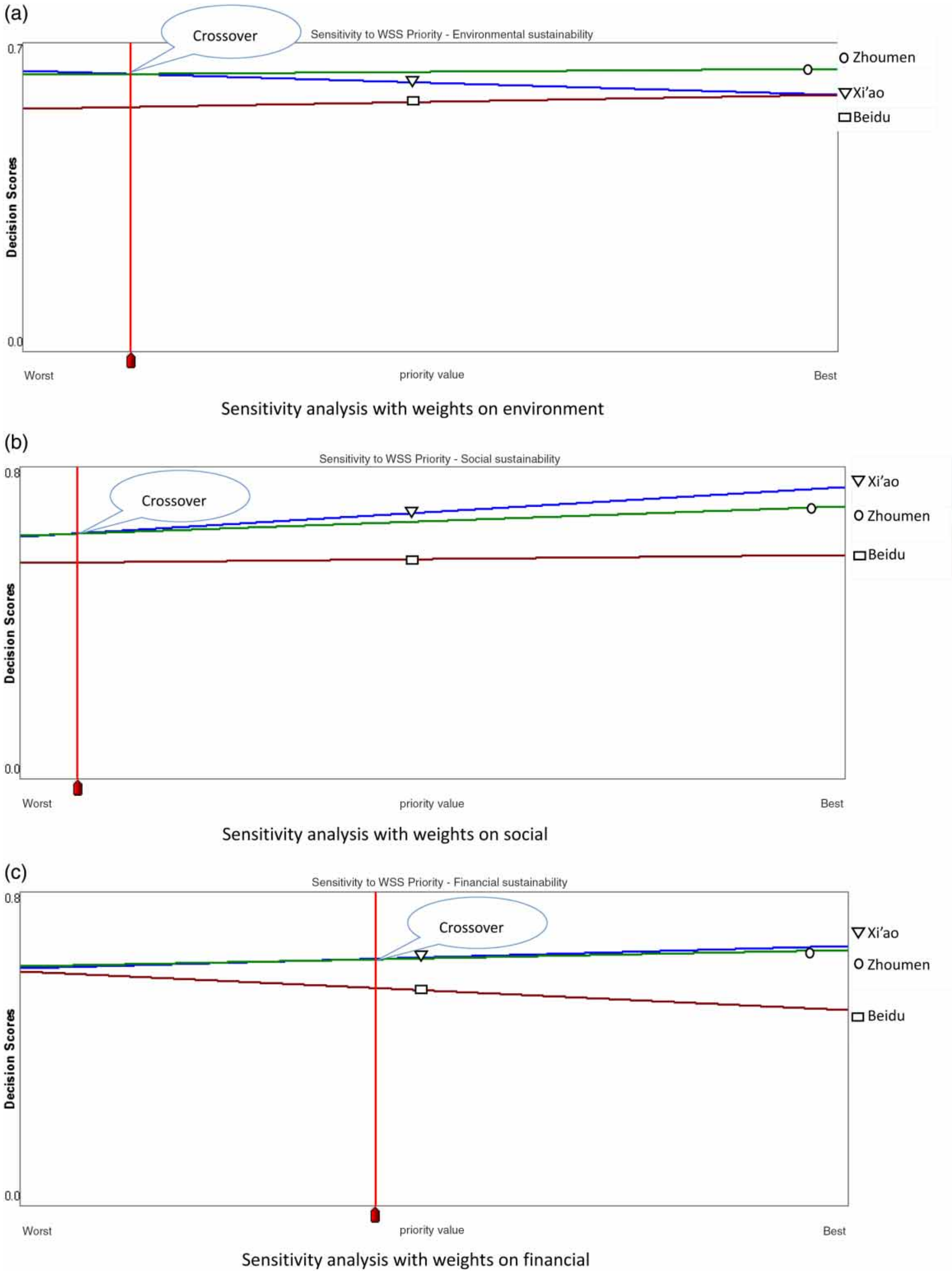

Fig. 5. Snapshot of sensitivity analysis with weights for TBL (Level 1) rating set in CDP 3.0.

(Figure 5) – sourced by snapshots from CDP 3.0 – we see that, regarding social sustainability, Beidu is almost never preferred for all weight combinations owing to its high societal damage cost. For Zhoumen and Xi'ao, the latter is preferred in most cases except when the social sustainability priority value is less than 0.07. The environmental sustainability sensitivity chart illustrates that the sustainability factor is various. In case of a priority value larger than 0.80, the gap between Beidu and Xi'ao will be bridged, but the score is still lower than that of Zhoumen by 10%; and in case of a priority value less than 0.32, Xi'ao will be slightly better than Zhoumen and much better than Beidu.

In addition, in terms of the sensitivity of the leading option – Xi'ao – regarding weights, a list of weights of sub-criteria with respect to their parent criteria is figured out, which measures the sensitivity resulting from the change of the value of a certain weight (Table 8). CDP 3.0 prioritizes such a list in an order from 'most critical' to 'least critical'. The 'most critical' means most sensitive when the weights change at the level 2 hierarchy. The level 2 TBL pillars of environmental, social, and financial sustainability have relatively low sensitivity to weights. Also, among all criteria and sub-criteria, no more than four of them would make the change of preferred option to the Beidu system as weight changes, including the criterion of output safeguard & reliability. This also implied that if the Xi'ao or Zhoumen system can make sufficient improvement in the output safeguard & reliability, such as through smooth construction in complex geographic conditions and mobilizing skilled people for safe operation in remote hilly areas for instance, it is inevitable that these systems could be used to achieve maximum water supply service in all aspects.

Despite this, when comparing the Xi'ao and Zhoumen options, the Xi'ao system is shown to be susceptible to a reversal of decision by Zhoumen, the impact extent of which depends on the criticality of relevant criteria weights. As shown in Table 8, there are four criteria with criticality less than 10% change, namely, environmental and social sustainability at criteria level, and fewer environment risks on distribution network and max. regional benefit – raw water's eco-value at sub-criteria level, which means the usurper will be Zhoumen displacing the Xi'ao option in this regard.

Moreover, we can confirm that the criterion of minimization of AIFC can influence the decision to the greatest extent. This implies that if AIFC calculation can stretch to CF monetization, it would rigorously strengthen the rationale for green and low CF mode water planning.

In reality, apart from sensitivity to weights, every lowest criterion has its own attributes in terms of valuation or scoring, which influences the priority value and its parent value. For example, minimizing capital cost is absolutely related to the water–energy nexus, especially for the large investment need of water supply assets, because there is an embedded CF from the perspective of life-cycle impact. If the embedded CF is excluded, the extent to which the calculation would be meaningful, by affecting the values of both Capex and AIFC, would be cautious for comparison. Another circumstance is that the carbon pricing mechanism was not formed until late 2010 in China (Wu *et al*., 2015). Under such circumstance, we adopt MCSA, which enables planners and decision-makers to weigh environmental economics' criteria with other aspects of selected scenario options in parallel. In our case, when the financial indices for all options are not sufficiently distinguishable, the addition of the direct energy saving and associated CF indices could help in sorting out preferred and robust planning configurations.

4.4. Evolutionary trajectory and the way forward – a discussion

Developing a multi-criteria sustainability tool that makes sense to planners and decision-makers is an evolutionary and adaptive process that can be implied in the selected WSS priority assessment. More and more sustainability parameters shall be added in a changing world and a holistic solution is required including integration of toolkits for accounting and measuring TBL indices while accommodating site/city-specific traits. An examination of the trajectory of the multi-criteria decision-making practices is

Table 8. Sensitivity of leading option [Xi'ao option] to weights.

Criterion	Sub-Criterion	Criticality	Usurper	Current PV	Current Weight	Crossover PV	Crossover Weight
WSS priority	Environmental sustainability	2%	Zhoumen	0.13	(Pair-wise)	0.15	(Pair-wise)
WSS priority	Social sustainability	−3%	Zhoumen	0.07	(Pair-wise)	0.04	(Pair-wise)
Environmental sustainability	Fewer environment risks on distribution network	4%	Zhoumen	0.33	(Important)	0.38	(Important)
Environmental sustainability	Max. regional benefit – raw water's eco-value	−7%	Zhoumen	0.33	(Important)	0.26	(Unimportant)
Environmental sustainability	Max. global benefits – less CF	−10%	Zhoumen	0.33	(Important)	0.23	(Unimportant)
WSS priority	Financial sustainability	−10%	Zhoumen	0.43	(Pair-wise)	0.33	(Pair-wise)
WSS priority	Operational sustainability	−14%	Zhoumen	0.12	(Pair-wise)	−0.02	(Off-scale)
Social sustainability	Access assurance for all dwellers	−22%	Zhoumen	0.5	(Important)	0.28	(Unimportant)
Social sustainability	Min. social carbon damage costs	22%	Zhoumen	0.5	(Important)	0.72	(Off-scale)
Operational sustainability	Less influence of burst and leakage	−24%	Zhoumen	0.29	(Important)	0.05	(Trivial)
WSS priority	Output safeguard & reliability	31%	Beidu	0.25	(Pair-wise)	0.56	(Pair-wise)
Financial sustainability	Min. O&M 30 years	−35%	Beidu	0.33	(Very Important)	−0.02	(Off-scale)
Operational sustainability	Max. water quality assurance	43%	Zhoumen	0.29	(Important)	0.71	(Off-scale)
Financial sustainability	Min. capital cost	64%	Beidu	0.22	(Important)	0.86	(Off-scale)
Operational sustainability	Lower power energy consumption	64%	Zhoumen	0.43	(Very Important)	1.07	(Off-scale)
Financial sustainability	Min. AIFC	68%	Beidu	0.44	(Critical)	1.12	(Off-scale)
Output safeguard & reliability	Quantity assurance/ technical easement for output	100%	Neither	1	(Trivial)	2	(Off-scale)

Note: Criticality is a metric/index of measuring the nearness of a reversal of preferences, namely, crossover, and implying that if one weight of criterion is varied and causes a crossover, the weight is critical to the decision. The higher the value, the farther and consequently less sensitive to the reversal of decision and less critical that weight is. Criticality/sensitivity degree: 100% for Quantity assurance/technical easement for output; 68% for Min. AIFC; 64% for Lower power energy consumption and Min. capital cost. Crossover Preference Value (PV – a reversal of preferences in options) – the following sub-criteria are greater than 1: 2 for Quantity assurance/technical easement for output; 1.12 for Min. AIFC; 1.07 for Lower power energy consumption.

thereby conducted. As Ningbo is a mega-city comprising six core districts, three counties and sharing a long coastline, we trace the following international projects on the traits of MCSA focal points and summarize lessons learned from the projects, namely, NWEP Xi'ao[1] WTW processing selection, Ningbo New Countryside Project WSS in Chunhu sub-project, and GEF-NWEP integrated urban and coastal watershed management schemes. Table 9 summarizes how those projects in Ningbo are employed with TBL thinking, from planning to implementation of the sustainable water infrastructure, with each having specific criteria and weights facing the selection of sustainability parameters. It is found that in-depth TBL thinking is helpful in the efficacy of sustainable water planning and management. For instance, by use of the multi-criteria TBL approach, sustainability can be assessed for detailed design options' comparison later on and for managerial decision-making such as assessing renewal working alternatives in the operational period. Notably, as a sub-component of our case system, site-specific topography and technical penetration of a gravity-driven membrane system into the China market have enabled Xi'ao WTW developers to adopt this novel water-processing approach, which is capable of meeting multi-sustainable criteria.

Site survey and verification as well as desktop review on literatures listed in Table 9 have revealed that TBL thinking is progressively gaining the consensus among stakeholders (because the borrowers, for instance, have a regular rating mission); based on such lessons learned and experiences gained, the route of EASY, i.e. enable-avoid-shift-yield, strategy is refined by key stakeholders, as presented in Figure 6. The route highlights that sustainable system design and evaluation are the most important for integrating functional, TBL thinking and operational factors in one. The top priorities for a water project or capital improvement program are to avoid the overexploitation of the water resource, reduce wastage of resources and societal capital, as well as lessen the societal and environmental damage from the system on a sustainable scale. On the basis of this, the TBL thinking should penetrate into the engineering cost-effectiveness assessment and life span system's component optimization process. Lastly, it is emphasized that 'enabling' is the driving force of the route. For a specific case for evaluation, the EASY route calls for enabling of TBL thinking as the driving force in scenario development and option assessment, since the enabling toolbox of technology or portfolio of incentives on policy could exert various impacts on the individual parameters, and finally the priority values and the enabling environment could move the sustainable alternative forward in the right place (World Bank, 2016). With regard to this, it should be emphasized that TA-mode is one of the effective enabling approaches that could generate diffusion and the scaling-up effect as described in Table 9. Moreover, as summarized in Table 9, all participants crucially need a consensus with least-bias assessment of applicable EASY strategies and with appropriate route mapping when facing versatile interest appeals, so as to facilitate a transition to sustainable water planning and management other than path dependence.

5. Conclusions

A new approach for decision support was developed for a complex urban system. It enables assessment of sustainability by use of the multi-criteria TBL approach, together with life-cycle assessment. The results show that the three options of the WSS have the aggregate priority values 0.571, 0.632, and 0.631 and the

[1] Xi'ao WTW is now given the name 'Taoyuan'.

Table 9. TBL features – Projects of NWEP, Ningbo New Countryside Project, and GEF-NWEP.

Theme/period	Concerned areas/ options	Route through TA/ dissemination	Focal points on TBL and the consequences	Major beneficiaries (institution, developer/taxpayer/ operator)	Source/ reference
WTW processing selection/ 2014 – ongoing	Suction mode ultra filtration (UF) membrane vs pressure-mode UF vs V-shape filtration for Xi'ao WTW design	NWEP loan TA: Singapore study tour; and manufacturer due diligence and pilot test	Ecological footprint, land footprint (floor area), and water–energy nexus indices given quantitative analysis, resulting in suction mode UF technology being awarded by a domestic manufacturer. Previously, existing Jiangdong WTW asset was retrofitted using the same product after the primary benefit and ancillary benefits were defined	Ningbo Water Supply Company; Yinzhou District Dwellers; Suction-type UF manufacturer; Ningbo Water Environment Project Management Office	World Bank (2011), Wu *et al.* (2015), and Ningbo Daily (2015)
Universal service plan for Ningbo New Countryside Project/2010 – ongoing	Alternative schemes on coastal water supply for township dwellers: decentralized township WTW vs conveyance from neighboring WTW	Ningbo New Countryside Project loan TA: appraisal through due diligence; stakeholders' consultation	Universal service target at societal dimension as additional index while given more weights – resulting in building local WTW being replaced by imported potable water product, with merits of shortening the commissioning phase and facilitating water conservation. Other key indices also include cost-effectiveness and climate resilience and vulnerability issue	Fenghua Investment Company; Chunlu Town Dwellers; Ningbo Water Environment Project Management Office	World Bank (2010) and Bach *et al.* (2013)

(*Continued.*)

Table 9. (*Continued.*)

Theme/period	Concerned areas/ options	Route through TA/ dissemination	Focal points on TBL and the consequences	Major beneficiaries (institution, developer/taxpayer/ operator)	Source/ reference
Integrated urban and coastal watershed management schemes/ 2007–2011	Technical options for wastewater reclamation and water resource management; developing constructed multi-purpose wetland and participant involvement and decision-making	GEF-NWEP loan TA: Study tour in Australia (Melbourne and Sydney); initiative on local resilience action plan; water reclamation GEF Grant TA: stakeholder meetings and conferences; TA on environment assessment (EA) and green design	The environmental assessment was integrated into financial performance assessment – the EA result forced the engineering feasibility study reshaping the preferred option considering more criteria on low impact development; key indices include environmental and ecological amenities and life-cycle cost-effective measures; however, fewer socio-economic sustainability indices not fully satisfactory due to procedural problem	Cixi Sewage Treatment Company; Hangzhou Bay New District Authority; Species; Tourist; Ningbo Water Environment Project Management Office	World Bank (2006, 2012), Wu *et al.* (2012), and GEF (2014)

first one, the Beidu option, is the least preferred, compared with the latter two, owing to the high degree of water–energy nexus. The second, the Xi'ao option, is shown as the leading decision preference, while it is susceptible to a reversal of this decision by the third, the Zhoumen option, the impact extent of which is dependent on the criticality of relevant criteria weights. Nevertheless, our MCSA shows, since adding weights on environmental and socio-economic criteria, the Xi'ao option, followed by Zhoumen, has rigorous priority over Beidu. The criticality analysis results have also showed that the weights' variation is not critical in affecting the WSS of Beidu as a main usurper to override the leading option.

Another conclusion we can draw is that insignificance or absence of environmental externality measurement might be critical to causing a reversal of the decision preference. A sensitivity analysis should be conducted to securitize the criteria robustness for decision support. This can also be complemented by the hierarchical MCSA approach and can hence be fed back as a driver for promoting environmental life-cycle analysis (LCA). In our case, from only the financial aspect, for instance the AIFC index, we could not distinguish between the three options because they are either capital cost intensive or operational cost intensive, thereby causing the values of AIFC to be almost the same. If

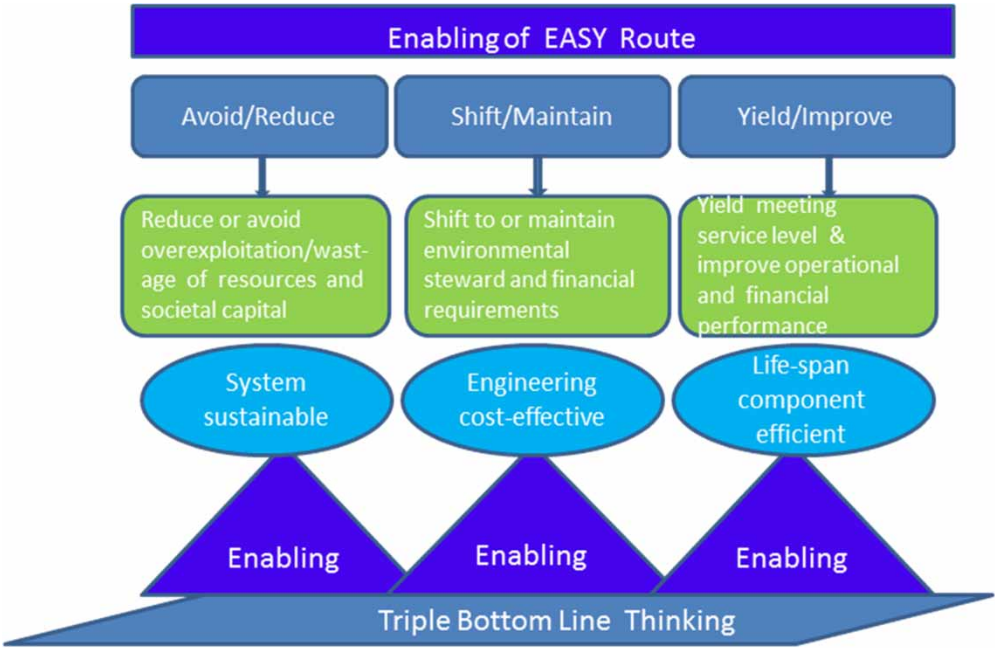

Fig. 6. TBL thinking route of EASY (enable-avoid-shift-yield).

complemented by factors such as direct energy saving and the associated magnitude of CF reduction, and further embedded in the MCSA tool, such a combination of selected indices will matter for pinpointing the direction of planning configuration preference. As aforementioned, it is good for sustainability thinking if the AIFC index can spread itself to CF monetization, as the rationale for sustainable water planning will be strengthened with greater robustness.

To date, the MCSA approach has not only been employed in Ningbo for planning but can also be used in detailed design options' comparison later on, as well as for managerial decision-making such as assessing renewal working alternatives in the operational period. The MCSA performance reviewed in Ningbo recommends that adoption of MCSA follows an EASY strategy, which first enables planners and decision-makers to weigh environmental and socio-economic criteria with other aspects of selected scenario options in parallel, followed by accommodating an evolutionary process, for instance, to adopt appropriate toolkits making quantification and valuation easy to achieve. Finally, given complex external influences, long-term decision-making for WSS may entail trade-offs related to conflicting objectives, multiple options, and uncertainties mentioned as case study terms of reference in TA (World Bank, 2010) and always catering for the dynamic emerging perceptions and performance indicators embedded in the city resilience and urban low-impact development and planning (Jia *et al.*, 2013; World Bank, 2016).

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References

ALGAS (1999). *Asian Least-Cost Greenhouse Abatement Strategy, Summary Report*, ADB, Manila, Philippines.

Asian Development Bank (ADB) (2014). Capacity development technical assistance for Ningbo Low-Carbon Development Phase 1 report. Available at: http://www.adb.org/forms/request-information-formsubject=47055-001 (accessed 29 April 2016).

Australia Government National Water Commission (AGNWC) (2011). *Externality Pricing in the Australian Water Sector*, Waterlines Report Series No. 43, April 2011.

Bach, P. M., McCarthy, D. T., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & Deletic, A. (2013). A planning algorithm for quantifying decentralized water management opportunities in urban environments. *Water Science and Technology 64*(12), 2362–2369.

Baeumler, A., Vasquez, E. I. & Mehndiratta, S. (2012). *Sustainable Low-Carbon City Development in China.* World Bank, Washington, DC. Available at: http://siteresources.worldbank.org/EXTNEWSCHINESE/./low_carbon_city (accessed 2 May 2012).

Coffman, M. & Umemoto, K. (2010). The triple-bottom-line: framing of trade-offs in sustainability planning practice. *Environment, Development and Sustainability 12*(5), 597–610.

GEF (2014). Improving-water-and-wastewater-services. Available at: https://www.thegef.org/gef/news/improving-water-and-wastewater-services-residents-ningbo (accessed 6 November 2012).

Infante, C. E. D., Mendonça, F. M., Purcidonio, P. M. & Valle, R. (2013). Triple bottom line analysis of oil and gas industry with multi-criteria decision making. *Journal of Cleaner Production 52*, 289–300. doi:10.1016/j.jclepro.2013.02.037.

Infoharvest Inc. (2012). Criterium DecisionPlus (CDP) 3.0 Tutorial. Available at: http://infoharvest.com/ihroot/infoharv/304Tutorial.pdf (accessed 30 August 2012).

International Finance Corporation (IFC) (2012). *International Finance Corporation's Guidance Notes: Performance Standards on Environmental and Social Sustainability.* IFC, Washington, DC.

Jia, H. F., Yao, H. R., Tang, Y., Yu, S. L., Zhen, J. X. & Lu, Y. W. (2013). Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection. *Environmental Monitoring and Assessment 185*(9). DOI: 10.1007/s10661-013-3144-0.

Ningbo Daily (2015). Ningbo Tao yuan Water Treatment Works adopting gravity-driven UF membrane. Available at: http://www.nbwater.com/doc/nsxx/nsxw/2015-5-29/26023.shtml (accessed 29 May 2015).

Novotny, V., Elmer, V., Furumai, H., Kenway, S. & Phills, O. (2010). Water and energy framework and footprints for sustainable communities. In: *Proceedings of IWA World Water Congress 2010*, *Montreal, Canada*, 2010.

Ogden, J. M., Williams, R. H. & Larson, E. D. (2004). Societal lifecycle costs of cars with alternative fuels/engines. *Energy Policy 32*(1), 7–27.

Ostfeld, A., Barchiesi, S., Bonte, M., Collier, C. R. & Cross, K. (2012). Climate change impacts on river basin and freshwater ecosystems: some observations on challenges and emerging solutions. *Journal of Water and Climate Change 3*(3), 171–184.

Qi, C. & Chang, N. B. (2013). Integrated carbon footprint and cost evaluation of a drinking water infrastructure system for screening expansion alternatives. *Journal of Cleaner Production 27*, 51–63.

Silva, J., Kernaghan, S., Luque, A., Cook, S., Crawley, C. & Singleton, D. (2010). Cities and climate change adaptation: the role of rapid resilience. In: *The Proceedings of 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference*, *Sydney, Australia*, 2010.

Valipour, M. (2015). A comprehensive study on irrigation management in Asia and Oceania. *Archives of Agronomy & Soil Science 61*(9), 1247–1271.

Valipour, M. & Montazar, A. (2012). Optimize of all effective infiltration parameters in furrow irrigation using visual basic and genetic algorithm programming. *Australian Journal of Basic and Applied Sciences 6*(6), 132–137.

Wen, H., Zhong, L. J., Fu, X. T. & Spooner, S. (2014). Water Energy Nexus in the Urban Water Source Selection–A Case Study from Qingdao, 2014. Available at: www.wri.org.cn (accessed 30 November 2014).

World Bank (2006). *GEF NWEP- Project Appraisal Report: On US$5 million Fund Donor No. 36424*, June 2006, Washington, DC.

World Bank (2010). *China-Ningbo New Countryside Development Project, Project Appraisal Document.* World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/2010/01/11768237/china-ningbo-new-country-side-development-project (accessed 26 January 2010).

World Bank (2011). *NWEP Implementation Completion and Results Report*, Report No: ICR1747, p1-38, Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/08/18/000333038_20110818231548/Rendered/PDF/ICR17470ICR0Bo0fficial0Use0Only0090.pdf (accessed 28 August 2011).

World Bank (2012). *China -GEF-Ningbo Water and Environment Project. No: ICR2361*, Washington, DC. Available at: http://documents.worldbank.org/curated/en/2012/05/16626145/china-gef-ningbo-water-environment-project (accessed 29 May 2012).

World Bank (2016). *Ningbo Sustainable Urbanization Demonstration Project Information Document, No: PIDC12540*, Washington, DC. Available at: http://documents.worldbank.org/curated/en/124341468257968727/Project-Information-Document-Concept-Stage-Ningbo-Sustainable-Urbanization-Demonstration-Project-P149485 (accessed 01 November 2016).

Wu, L., Jiang, Q. & Yang, X. M. (2012). Procedia environmental sciences. In: *18th Biennial ISEM Conference on Ecological Modelling for Global Change and Coupled Human and Natural System*, Volume 13, 2012, pp. 582–589.

Wu, L., Mao, X. Q. & Zeng, A. (2015). Carbon footprint accounting in support of city water supply infrastructure siting decision making: a case study in Ningbo, China. *Journal of Cleaner Production 103*, 737–746.

Xu, M., Weissburg, M., Newell, J. P. & Crittenden, J. C. (2012). Developing a science of infrastructure ecology for sustainable urban systems. *Environmental Science & Technology 46*, 7928–7929.

Young, K. D., Younos, T., Dymond, R. L., Kibler, D. F. & Lee, D. H. (2010). Application of the analytic hierarchy process for selecting and modeling stormwater best management practices. *Journal of Contemporary Water Research & Education 146*(1), 50–63.

Zhuo, C., Ngo, H. H., Guo, W. & Wang, X. C. (2013). Analysis of Sydney's recycled water schemes. *Frontiers of Environmental Science & Engineering 7*(4), 608–615.

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