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An innovative sustainability assessment for urban wastewater infrastructure and its application in Chengdu, China

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ABSTRACT

Sustainability assessments are an increasingly common tool for measuring progress towards sustainable development. Despite their popularity, sustainability assessments and the indicators that compose them are said to have had little impact on the policy arena. In this paper we discuss four attributes that we contend will improve the use of sustainability assessments to guide decision making: non-compartmentalization, site specificity, built-in guidance for target setting, and ability to measure active sustainability. We present a novel assessment tool for wastewater treatment infrastructure that illustrates these attributes. The assessment is composed of two-dimensional indicators we call "burden to capacity" ratios, that reveal and quantify the local value of resources embodied in wastewater and treatment byproducts, and the tradeoffs between designing systems for disposal versus reuse. We apply the sustainability assessment framework to an existing treatment plant in Chengdu, China and discuss the results.

1. Introduction

Since the 1990s, sustainability indicators have emerged as a common device for measuring progress towards sustainable development. Governments, international agencies, cities, non-governmental organizations, and researchers have all contributed to the development of indicators that can aid stakeholders in making sound decisions. Despite these efforts, several researchers conclude that, thus far, indicators have done little to contribute to sustainable development (Kates et al., 2005; Sahely et al., 2005; Wilson et al., 2007). Part of the failure can be attributed to the financial and political barriers to applying sustainability assessments to their full potential. However, part of the problem lies in a failure to design indicators that fulfill their intended purpose of measuring the *impacts* of development on the environment, and of the environment on future development (Alberti, 1996).

Perhaps it is the desire to appeal to a very broad set of interests that has led to the development of indicator frameworks that position economic, environmental, and social indicators as separate and equally interchangeable tradeoffs (Lele, 1991; Satterthwaite, 1997). This "competing objectives" view is a widespread interpretation of sustainability; however, the lack of interaction among these three dimensions in existing indicator frameworks suggests the need for a format that explicitly shows the positive and negative feedbacks between the environmental, social, and economic components of sustainability. Each of these elements is an important measure of human well-being. But much of the added value of applying a sustainability assessment is lost if a multi-objective framework fails to show that a deliberate change along one dimension of sustainability inevitably impacts other dimensions. Thus, there is a need for indicators that shed light on how human designed and driven systems interact with environmental systems, and for indicators that can measure the extent to which economic and social development occurs in harmony with, and not at the expense of, the environment (Alberti, 1996 The urban wastewater treatment sector has been the focus of several sustainability assessments; Collados, 1999).

(Hellstrom et al., 2000; Balkema, 2001, 2002; Hospido et al., 2004; Lundin, 2004; Sahely, 2005; Muga and Mihelcic, 2008). This paper introduces a framework of assessment for wastewater treatment infrastructure that: (1) conveys relationships between environmental, social and economic dimensions of sustainability, and (2) specifically evaluates how well tailored the infrastructure is to the context in which it functions. The Burden to Capacity Sustainability Assessment (B2C SA) builds upon the contributions of previous research; it is intended to enhance the impact and influence of sustainability indicators in decision making associated with designing, implementing and operating a viable sanitation

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scheme. In this article we explain the novel features of the B2C SA and provide the results of an application in China to demonstrate the new insight that can be gained through applying the framework to existing sanitation infrastructure.

2. Theory

A number of scholars have proposed sets of necessary criteria for indicator frameworks to be influential in the policy realm. Cash et al. (2003) argue that three attributes are essential: saliency, meaning relevance to actual policy choices; credibility, meaning scientific plausibility and technical accuracy; and legitimacy, meaning unbiased and politically fair (Cash et al., 2003). Lundin et al., 1999 pose six criteria for useful sustainability indicators: they should be able to demonstrate a move towards or away from sustainability; they should be applicable to a broad range (type and scale) of systems; they should have the ability to provide warning of potential problems; they should be amenable to existing data; they should be comprehensive; and they should be cost-effective (Lundin, 1999). In this paper, we argue that the above characteristics, while important, are not sufficient. Adhering to them does not necessarily render a set of indicators that expose tradeoffs, and the relative costs and benefits, of decisions. We suggest four different attributes that we believe are necessary for a set of indicators to become embedded in the policy-making process. Those attributes are non-compartmentalization, site specificity, built-in guidance for target setting, and ability to measure active sustainability, each of which is detailed below.

Table 1
The traditional layout and make-up of sustainability assessments for wastewater treatment systems.

Indicator	Source
Environment	
Percent removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) (%)	Otterpohl et al., 1997; Lundin, 1999; Bracken, 2005
Energy consumed/water treated	Dutta, 2003; Bracken, 2005
Solids production (mass/person equiv./time)	Lundin, 1999
N, P discharged to water (mass/person equiv./time)	Hellstrom, 2000
Human health	
Coverage (sewage connection) (%)	World Health Organization, 2005
Risk of waterborne infection (no. of outbreaks/unit population)	Finnson and Peters, 1996; Hellstrom, 2000; Bracken, 2005
Economic	
Operation and maintenance (O&M) cost per water produced (cost/flow rate)	Marques, 2001
Employees per water produced (no./flow rate	Marques, 2001
Social	
Households with water bill >3% of their income	Water UK, 2006
Social acceptance	Hellstrom, 2000; Palme, 2005
Technical function	
System robustness (no. sewer stoppages/flow rate)	Bracken, 2005
Complexity of construction and O&M	Bracken, 2005
Flexibility/adaptability	Hellstrom, 2000; Bracken, 2005

Indicators are organized by the dimension of sustainability they represent (i.e. environment, human health) and a selection of indicators commonly found in each category is shown.

2.1. Non-compartmentalization

It was said more than a decade ago that "indicators will not help address urban sustainability problems unless clear linkages can be established between urban patterns and the state of the natural resource base" (Alberti, 1996). Today, one of the most common criticisms of sustainability indicators is still the failure to link economic and social metrics to environmental metrics. Without these linkages, indicators fail to send clear signals regarding policy interventions to improve sustainability (Alberti, 1996; Farell and Hart, 1998; Collados and Duane, 1999; Wilson, 2007). The disconnect between different dimensions of sustainability is fostered by the common practice of compartmentalizing indicators into separate categories, leading to the same "fragmented view of the world that caused the problems" (Farell, 1998). For example, the indicators developed by Ashley and Hopkinson for assessing sanitation systems in the UK, and those developed by Balkema et al. for wastewater treatment systems more broadly, are divided into three components: economic, environmental and social (Ashley and Hopkinson, 2002; Balkema et al., 2002). Similarly, Hellstrom et al. as well as Bracken et al. suggest five categories of indicators for assessing urban water systems: health and hygiene, socio-cultural, environmental, economic, and functional and technical (Hellstrom et al., 2000; Bracken et al., 2005). Table 1 shows the typical categorization of indicators and a selection of those that are often used.

In the SA construct depicted in Table 1, there is no predictable relationship between any of the indicators, particularly those in different categories. We contend that SAs have potential to be far more effective if, rather than segregating different components of sustainability, those components are explicitly coupled. Categorical segregation may perpetuate a false notion that an indicator level in one category can change without consequence to indicators in other categories. For example, in Table 1, an effort to decrease eutrophication could be achieved by an increase in several other indicators including energy consumed, solids production, operation and maintenance (O&M) cost, and flexibility of O&M. However, these interrelationships are not captured in the conventional indicators.

2.2. Site specificity

Due to site-specific environmental, social, and economic landscapes, indicators with the same value may have different implications in different regions. For example, it is not sufficient to measure and compare the percentage of BOD or nutrients removed; from one watershed to another, there can be dramatic differences in the influent concentrations and in the impacts that organic and nutrient discharges have on ecosystems based on the receiving water's assimilation capacity. Similarly, it is not adequate to measure and compare how much energy is used to treat one cubic meter of wastewater: the environmental impacts of energy intensive treatment systems are highly dependent on the local energy portfolio, and the social impact is largely dependent on users' ability to pay or the government's willingness to subsidize energy. SAs are often used for comparative analyses between cities, regions, or nations. However, to contrast two locations based on the results of an SA with uni-dimensional components makes for an apples-to-oranges comparison. A more useful comparison would be between the *impacts* of the results, not the raw numbers. Thus, indicators should be designed with what might be called local impact factors, a type of benchmark that clearly reveals not just a raw number but how the number manifests itself locally. For example, a benchmark for user fees could be average household income.

2.3. Guidance for setting target values

Users have a wide range of knowledge bases that they employ in the process of conducting sustainability assessments and making decisions based upon their results. While developing and applying SAs is often lauded as a participatory, community-building experience, relying on consensus-based targets results in goal setting that is socio-political and not necessarily scientific (Sikdar, 2003). It cannot be assumed that the stakeholders involved in the target setting process possess the background necessary for making fully informed decisions about an indicator's appropriate target. This problem of arbitrary target setting can be eliminated by implementing the suggestion made in Section 2.2, that indicators have built-in benchmarks relevant to the local context. The benchmarks would serve to translate the results of indicators requiring specialized knowledge into easily understood local consequences by revealing an explicit impact or tradeoff. For example, a benchmark for the global warming impact (GWI) of the treatment process, a common indicator in sustainability assessments, could be the potential for offsetting the GWI through energy capture at the facility. Users can then negotiate over and establish target indicator values based on the local impact they are willing to accept or determined to avoid, a decision that properly belongs in the socio-political realm.

2.4. Measure active sustainability

With few exceptions, indicators that populate wastewater treatment sustainability frameworks assess what can be termed the 'passive' sustainability of sanitation infrastructure. That is, these indicators measure the extent to which, and how efficiently, the system is *preventing* human waste from spreading disease and degrading the environment. Examples of such indicators include: coverage (% of population with access to wastewater treatment, % of population with sewer connections), nutrient removal (phosphorous discharge, % nitrogen removal), pathogen removal (% pathogen removal, risk of waterborne disease), cost ($ per m^3 of treated water, operation and maintenance cost per customer) (Finnson, 1996; Lundin, 1999; Marques and Monteiro, 2001; Samuel-Johnson and Esty, 2001; Tsagarakis et al., 2003; World Health Organization, 2005). However, wastewater and fecal sludge can be valuable resources if managed properly, and the reuse of embodied nutrients, energy, and wastewater itself are fundamental to sustainable sanitation (SANDEC, 2000; IWA Sanitation 21 Task Force, 2007; Mara et al., 2007). Thus SAs must capture both passive sustainability, and this additional dimension of 'active' sustainability, a measure of how a sanitation scheme is *contributing* to or *adding value* to the local environment, social well-being, and economy. It is true that some existing SAs include indicators that measure the degree of reuse of a given sanitation system (e.g., % of wastewater reused, % of nutrients reused, etc.,) but the local benefits of reuse and/or the costs of disposal-oriented sanitation, including direct damage costs and opportunity losses, are never revealed or even implied.

3. Results

The B2C SA that resulted from this research attempts to incorporate the four characteristics described above that are critical but often lacking in existing sustainability assessments. The framework satisfies many of the criteria posed by Cash and Lundin et al. including using indicators that can be evaluated in a scientifically and technically accurate fashion; that demonstrate a move towards or away from sustainability; that have the ability to provide warning of potential problems; and that are comprehensive (Lundin, 1999; Cash, 2003). There are several features of the B2C SA (Table 2) that set it apart from existing frameworks, in particular, its organization, indicator format, and overall content. We emphasize that the particular indicators presented in this research are tailored to the Chengdu context and thus will not be universally appropriate.

3.1. Novel attributes of the Burden to Capacity Sustainability Assessment

3.1.1. Life cycle approach to SA organization

The structure of the B2C framework is unique, as indicators are not grouped according to the dimension of sustainability that they measure, but rather the phase of wastewater treatment that they are relevant to, thus avoiding the compartmentalization of different components of sustainability. The categorization used for this framework was chosen to reflect the life cycle analysis approach; the three categories – production phase, treatment phase, and end use phase – provide a comprehensive picture of the treatment scheme (Table 2). The organization of the indicators facilitates analysis of which segment of the wastewater life cycle is the weakest or has the greatest opportunity for improvement.

As a starting point for developing the content of the B2C SA, we used the most common conventional indicators (such as those shown in Table 1) as a guide to ensure that each dimension of sustainability was represented in the new framework. Consequently, many of the B2C ratios have conventional counterparts but deliver the information in a manner that better facilitates responsive decision making. For example, B2C #26, "Effluent BOD concentration: BOD standard for receiving water or user", replaces the typical indicator, "% BOD removal" (Table 2, Table 1). Similarly, B2C #5, "Electricity used to treat wastewater: empirical energy value of wastewater", replaces the typical indicator, "Energy consumed/water treated" (Table 2, Table 1).

3.1.2. Indicator format

Each indicator is formulated as a ratio with the "burden" on the left-hand side, and the "capacity" on the right-hand side. The burdens are in the form of economic costs (e.g., operation and maintenance costs (B2C #12)), environmental stressors (e.g., environmental water shortage (B2C #3)), or resource demands (e.g., local demand for nutrients (B2C #24)). The capacities are either a measure of the extent to which the associated burden is adequately managed or abated in the local context (e.g., user fee collection (B2C #12), available GWI offset via energy capture (B2C #6)), or a measure of the extent to which the scheme is suitable for, or receptive to, a given burden (e.g., replacement value of existing infrastructure (B2C #14), amount of treated wastewater used for agricultural irrigation (B2C #19)), (Table 2). The dual function of the "capacity" reflects the give-and-take relationship that exists between a sanitation scheme and the landscape it functions in, and measures the extent to which they are in balance.

One purpose of two-dimensional indicators is to expose the linkages between different dimensions of sustainability (e.g., environmental, social and economic). Each of the three life cycle categories in this framework consists of indicators that address economic, environmental and social facets of sustainability; many of the B2C ratios address more than one of these dimensions simultaneously (see Table 2 for the dimensions reflected through each indicator). For example, B2C #5 (Energy used to treat wastewater: empirical energy value of wastewater,) simultaneously captures economic and environmental information, while B2C #7 (Facility electricity use per person equivalent: average local per capita electricity use,) captures both economic and social information (Table 2). The extent to which any one dimension of sustainability is represented in the B2C SA is not necessarily different from frameworks organized by category, as the content ultimately depends on the interests and priorities of the makers and users of the assessment.

Another purpose of the two-dimensional ratios is to provide site-specific context, and thus to provide guidance in setting target values. For each indicator, either the burden or the capacity – and in some cases both – is a decision-making variable, meaning that local

Table 2
Burden to Capacity Sustainability Assessment for wastewater treatment infrastructure.

Burden		Capacity	Dimension of sustainability[a]
Production phase			
1.	Domestic wastewater produced	Domestic wastewater conveyed to treatment plant	EN, S
2.	Growth rate in water usage	Growth rate in wastewater treatment	EN, EC
3.	Environmental water shortage	Surface water withdrawal[b]	EN
Treatment phase			
4.	Current wastewater flow to facility	Design capacity of facility	
5.	Electricity used to treat wastewater	Empirical energy value of wastewater[c]	EN, EC
6.	Net global warming impact (GWI) caused by WW treatment process[d]	Available GWI offset via energy capture	EN, EC
7.	Facility electricity use per person equivalent	Average local per capita electricity use[e]	EC, S
8.	Acidification associated with wastewater treatment	Eutrophication avoided by wastewater treatment	EN, EC
9.	Cost of nutrient treatment and removal	Local retail value of influent nutrients for productive use	EN, EC, S
10.	Land area used for wastewater treatment facility	Habitat created by wastewater treatment facility[f]	EN, EC, S
11.	Influent concentration of pathogens	Ability of treatment scheme to remove endemic pathogens	EN, S
12.	O&M costs (recurring costs)	User fee collection	EC, S
13.	User fee	Average household income	EC, S
14.	Annual investment in maintenance	Replacement value of wastewater treatment infrastructure	EC, S
15.	Person hours per day skilled operator present at facility	Number days in previous year facility shutdown	EN, EC
16.	Sludge handling cost	Total cost of wastewater handling	EC
17.	Daily average sludge production	Daily sludge wasting	EN, EC
End-use phase			
18.	Wastewater treated	Wastewater reused	EN, S
19.	Agricultural land within 3 km radius	Amount of treated wastewater used for agricultural irrigation	EN, S
20.	Local value of resources embodied in wastewater	Value of wastewater being captured	EN, EC, S
21.	Average metal concentration in sludge	Metal standard for sludge land application	EN, EC
22.	Local value of resources embodied in sludge	Value of sludge being captured	EN, EC, S
23.	Sludge disposed in landfill	Daily tipping capacity of landfill	EN
24.	Local demand for nutrients	Unutilized nutrient content in wastewater and sludge	EN, EC, S
25.	Effluent nutrient concentration	Nutrient standard for receiving water or user	EN
26.	Effluent BOD concentration	BOD standard for receiving water or user	EN

The framework for Chengdu consists of 26 indicators (in the form of ratios) categorized by the three phases of the wastewater life cycle: production, treatment, and end use.
[a] EN (environmental), EC (economic), and S (social).
[b] Where the magnitude of surface water withdrawal vs. that of environmental water shortage is intended to indicate the potential *capacity* of reductions in surface water withdrawal to abate water shortage.
[c] Where empirical energy value is a measure of the wastewater's capacity to provide energy.
[d] Value does not include biogenic CO_2.
[e] Where average per capita electricity use is a measure of the *relative* local capacity to operate a treatment scheme with a given electricity intensity. The goal should always be to minimize electricity consumption.
[f] Where habitat created is a measure of the capacity of the treatment plant to optimize land use by serving multiple purposes.

stakeholders must make choices that determine its value. Target values or limits are not pre-determined in the B2C SA. Those choices are left to the users of the SA, but the opportunities revealed by the ratios are intended to foster more informed goal setting.

To use B2C #6 as an example of how the B2Cs provide guidance in target setting, decision makers can use the right-hand side of the ratio, available GWI offset via energy capture, as a benchmark of the degree to which GWI could be reduced (Table 2). Thus the GWI offset potential can help SA users set realistic targets for the allowable GWI caused by the wastewater treatment process, either for the facility in question or for future facilities. Rather than arriving at arbitrary target values for each indicator, users of the B2C framework can make decisions based on how they leverage the inherent relationship in each of the B2C ratios. Furthermore, these capacities are designed to be easily understood by any user. Thus, while decision makers may lack the training to adequately manage or abate "burdens" associated with wastewater from a scientific perspective, the simple but multi-dimensional relationships revealed by the B2C ratios are intended to facilitate decisions that favor a sustainable development trajectory.

The B2C SA is designed to be sensitive to a sanitation scheme's performance in particular contexts. The capacity in the burden to capacity ratio is operationalized such that its value is based on local environmental, economic, and social conditions. Using B2C #9 as an example, the cost of nutrient removal (for disposal) is juxtaposed against the local retail value of nutrients in the influent as a benchmark for the rationality, and the social, economic, and environmental sustainability of handling nutrients as waste as opposed to a resource (Table 2). In regions with agriculture in the immediate vicinity, the opportunity cost of nutrient removal and disposal is far greater than in regions where there is no easily accessible productive end user of nutrients.

3.1.3. B2C SA content

This assessment is designed recognizing that wastewater and wastewater treatment byproducts are resources with quantifiable economic and social benefits. The overall framework puts significant emphasis on assessing the degree to which the embodied energy, nutrients and the wastewater itself are put to productive and valuable use in the region. The plausibility of collecting the necessary data, and of determining a sound calculation or approximation, was also taken into account so as to improve the usability and adoption of the framework. Finally, sustainability assessments require us to think of systems as closed-loop, and we have to make choices about where the boundaries of any system lie. In this assessment, the unit of analysis is the treatment plant and the municipality it operates in, but it is certainly possible to extend the B2C approach upstream or downstream of this boundary, or to apply it at the watershed level.

3.2. B2C SA application in China

The B2C SA was applied to Wastewater Treatment Plant (WWTP) #2, located in the south of Chengdu, the capital of Sichuan

Province, China. The facility was built in 2004, has a design capacity of 300 000 m^3 per day, and is situated on approximately 140 000 m^2 of land. WWTP #2 is a secondary treatment facility with two-stage activated sludge and UV disinfection. The treated effluent discharges to the FuNan River which flows south out of the city. Table 3 presents the numerical results and brief interpretation of the B2C SA application to WWTP #2. The "brief interpretation" column also includes references to other indicators in the framework that are related to the one in question. Co-analyzing the results of several indicators in the B2C SA brings out additional tradeoffs and complementarities that can lead to more informed decisions.

4. Discussion

4.1. Key outcomes of the B2C SA application in China

The application of the B2C SA to WWTP #2 signals several key policy responses for decision makers; these signals can be used to set priorities for water and wastewater management, and to inform the design of future treatment facilities in the vicinity. One significant outcome of the assessment is that a 20% reduction in surface water withdrawals (6.4×10^8 m^3/yr) would alleviate environmental water shortage between the outtake and point of discharge back to the river after treatment, and would also enhance the assimilation capacity and water quality of the local rivers within the city and downstream. Achieving this reduction can be approached via water conservation and/or wastewater reuse. At its current level of operation, reusing all of the wastewater from WWTP #2 would contribute to a nearly 9% reduction in demand for surface water withdrawals; if the untreated wastewater from the drainage district were conveyed to the WWTP, and it were operating at its full capacity of 300 000 m^3/d, reusing the effluent would reduce demand for freshwater by 17%. The assessment also reveals that the installation of anaerobic digesters for sludge digestion and biogas capture would offset nearly 20% of its electricity demand, and simultaneously decrease the volume of sludge by approximately 20%, helping to reduce the burden on the local landfill (Table 3, B2C #23) and the costs of sludge handling (Table 3, B2C #16). Anaerobic digestion would also contribute to pathogen inactivation which is required for some reuse options.

The results of the B2C SA also reveal that the nutrient effluent quality from WWTP #2 is not sufficient to meet the Chinese standards for waters with low capacity for natural remediation such as the FuNan River. Several possible policy options are signaled including enhancing nutrient removal to achieve environmental discharge standards. While there is not agricultural land in the immediate vicinity of WWTP #2 (Table 3, B2C #19), the effluent quality meets Chinese reuse standards for industry and urban landscape, thus those reuse options could be explored. The additional infrastructure cost of improving nutrient removal versus implementing reuse should be compared, keeping in mind the possibility of harnessing the economic value of the wastewater through fees to end users if the latter option is chosen.

B2C #13 reveals that user fees for wastewater treatment account for approximately 1% of average household income (total water fees account for about 2.6% of household income) (Table 3). According to the Asian Development Bank's National Guidelines for Wastewater Tariffs, 5% of household income is recommended as the affordability threshold for the combined costs of water and wastewater (ADB, 2001). Raising user fees from 0.8 RMB/m^3 to 1.2 RMB/m^3 would raise the fee to 1.5% of average household income and would increase annual revenues to WWTP #2 to just over $7 000 000. This fee increase would improve cost recovery for O&M (Table 3, B2C #12) and enable more adequate investment in maintenance (Table 3, B2C #14). However, 1.5% of household income may be deemed politically unpalatable. The role of the B2C SA is to reveal these relationships and opportunities, and it is left to the users and the political process to decide how they will negotiate the implicit tradeoffs.

4.2. Data needs for applying the B2C SA

At first glance, the B2C SA may appear highly data intensive. Collecting the necessary information will require time and resources, but most of these data are regularly collected in cities where basic wastewater and socio-economic monitoring occurs. Examples of data routinely collected include influent flow, BOD, and average household income. A subset of the data require local investigation, such as determination of the retail value of nutrients as fertilizer, and the extent of farmland in the vicinity of the treatment facility. Another subset may require approximation using the best available information. For example, GWI can be estimated based on the local energy portfolio, and the treatment scheme's ability to remove pathogens can be approximated using performance data from comparable facilities.

In China, nearly all of the necessary data for applying the B2C SA are already collected by various government agencies. (See Supplementary Information Table S3 for an assessment of the quality of the data used in this analysis.) Collating this information within the B2C framework adds value and purpose to the ongoing data collection, as data are often collected as a formality and archived, rather than used to drive decision making and policy analysis. Also, as stated above, the particular indicators used in the Chengdu application of the B2C SA will not be suitable for all locations. In lower income countries, where there is a dearth of data and limited capacity to establish a reliable monitoring scheme, or where there exists a very different set of challenges and priorities, the local ecology and economy can drive the design and selection of indicators that fit within the B2C SA.

4.3. B2C SA transferability

To test the adaptability of the B2C SA framework to different contexts, we are piloting the approach to the urban sanitation sector in Ghana. The Ghanaian context is very different from Chengdu: cities rely on fecal sludge collection, are lower income, and suffer from widespread treatment plant failure. However, using a different set of B2C ratios, the overall approach appears promising with respect to revealing information that can help to explain and rectify the chronic failure of treatment plants in the country. The B2C SA framework can also be used outside of the wastewater treatment sector, e.g., the electricity and solid waste sectors, and even products, where the format of the multi-dimensional indicators as well as the life cycle approach could be applied to sustainability assessments to improve their utility

One characteristic of the B2C SA that is both a strength and a limitation is that the life cycle organization needs to be adapted for particular products and sectors. Therefore, a single B2C SA would not be suitable for a regional sustainability assessment that covers several sectors. For the B2C ratios to reveal new information, and draw attention to policy-relevant tradeoffs and relationships, developers of the B2C SA require knowledge of local priorities and constraints, as well as specialized knowledge of the sector or product in question. Thus, the process of developing the B2C indicators is not as amenable to multi-stakeholder participation as conventional sustainability assessments. However, once the indicators are developed, evaluating the ratios and responding to their outcomes invites broad community and stakeholder engagement.

Table 3
Results of the Burden to Capacity Sustainability Assessment (B2C SA) for urban wastewater for WWTP #2 in Chengdu, Sichuan Province, China.

	Burden			Capacity			Brief interpretation
Production phase							
1.	Domestic WW produced			Domestic WW conveyed to treatment plant			Approximately 30% of the domestic wastewater generated in the drainage district served by WWTP #2 is treated. The treatment deficit indicates an enormous need for expanded sewer capacity (see B2C #4)
	m^3/d	220000		68000			
2.	Growth rate water usage (urban core)			Growth rate wastewater treatment (urban core)			In 2004 and 2005, rates of increase in wastewater treatment significantly outpaced increases in water usage; however, supply of wastewater treatment still does not meet demand (see B2C #1). Rates of increase in wastewater treatment capacity that are greater than rates of increase in water usage must continue for several years until supply of wastewater treatment meets demand. Ultimately, sustainability will be depicted by approximately equal rates of increase in water usage and wastewater treatment
		%	m^3/yr		%	m^3/yr	
	2004	7.4	1.7×10^7	2004	16	2.6×10^7	
	2005	3.1	7.6×10^6	2005	49	9.2×10^7	
	2006	5.2	1.3×10^7	2006	−6.7	-1.9×10^7	
	2007	1.1	3.0×10^6	2007	6.6	1.7×10^7	
3.	Environmental water shortage (Chengdu Municipality)			Surface water withdrawal (Chengdu Municipality)			A 20% reduction in surface water withdrawal could mitigate environmental water shortage. Wastewater reuse is one means of reducing withdrawals (see B2C #18–19). Increases in annual fresh water usage would further strain aquatic ecosystems (see B2C #2)
	m^3/yr	6.3×10^8		3.2×10^9			
Treatment phase							
4.	Current WW flow to facility			Design capacity of facility			It is not uncommon to design treatment plants with a larger capacity than they will initially serve in anticipation of future demand. However, if the unsewered domestic wastewater in addition to the current mix of industrial and domestic wastewater were conveyed to the facility, the WWTP would operate close to capacity (see B2C #1). Expansion of the sewer network in this drainage district (#3) should be prioritized to maximize the utility of the existing wastewater treatment infrastructure
	m^3/d	150000		300000			
5.	On-site electricity used to treat WW			Empirical energy value of WW (as electricity)			The potential electricity yields embodied in the wastewater, and its economic value, underscore the substantial energy recovery opportunity that exists in Chengdu's wastewater and sewage sludge. The anaerobic pond and UASB would replace existing activated sludge treatment systems whereas anaerobic sludge digestion would be added to the existing treatment scheme. The latter would not change the energy consumption at the plant but could be used as an on-site energy source
	MJ/yr	5.2×10^7		An Pond	UASB	An. Dig.	
	$1000/yr	630		1.1×10^7	2.9×10^7	1.1×10^7	
				210	550	210	
6.	Net GWI caused by WW treatment process			Available GWI offset via energy capture			Anaerobic sludge digesters can be installed to provide more comprehensive sludge treatment than exists at the facility, and to generate biogas for carbon-neutral heat or electricity production to offset the GWI (see B2C #5). Numerous other opportunities, not included in this indicator, exist for reducing or offsetting the global warming impact (GWI) of the treatment process. Installing continuous dissolved oxygen monitoring devices for tailoring aeration levels to the real-time oxygen demand of the wastewater, and adding anaerobic selectors to the activated sludge system would reduce the GWI
	kg CO_2-eq/yr	4.3×10^6		2.7×10^6			
	Damage cost ($)/yr	61000		37000			
7.	Facility electricity use per person equivalent			Average household per capita electricity use			Electricity intensity of wastewater treatment in Chengdu is equivalent to more than 50% of the average per capita household electricity consumption. By comparison, this ratio is equivalent to about 2% for the state of California because of substantially higher household electricity use. Electricity for wastewater treatment in Chengdu represents a significant burden on total consumption in the municipality
	kWh/p.e. yr	26		49			
8.	Acidification associated with WW treatment			Eutrophication avoided by WW treatment			This indicator reveals the air quality expense at which eutrophication is being avoided. The adequacy of the current level of nutrient removal in the context of assimilation capacity of the receiving water or user is quantified in B2C #25
	kg SO_2-eq/yr	1600		kg PO_4-eq/yr	3.54×10^{10}		
	Damage cost ($)/yr	5000		Damage cost ($)/yr	NA		
9.	Cost of nutrient treatment and removal[a]			Local retail value of influent nutrients for productive use			The opportunity cost associated with current nutrient handling at WWTP #2 is equivalent to more than $1 M/yr, the sum of the total treatment cost and value of the nutrients if used productively
		Marginal	Average				
	$/yr	18000	340000	900000			
10.	Land area used for WW treatment facility			Habitat created by WW treatment facility			None of the space used for wastewater treatment is simultaneously used for park or habitat space
	m^2	140000		0			
11.	Influent concentration of pathogens			Ability of treatment scheme to remove endemic pathogens			Removal of bacteria, virus and protozoa is probably sufficient, due to the UV disinfection step. However, helminths, specifically *Ascaris* are endemic in the Chengdu Municipality. *Ascaris* eggs are resistant to UV, and only partial removal will occur by sedimentation. Adding coagulant to achieve advanced primary treatment may be a cost-effective solution to improving removal of helminth eggs. Acceptable effluent concentrations of each pathogen type will vary by end use
	Bacteria	1.0×10^6 CFU/L		Log removal	3–>7		
	Virus	NA		Log removal	1–6		
	Protozoa	NA		Log removal	>3		
	Helminths	100 eggs/L		Log removal	1–2		
12.	O&M costs			User fee collection			The estimated user fee collection covers approximately 85% of the invested O&M costs of the facility. Full cost recovery may be possible with an increase in user fees that still falls within the Asian Development Bank's (ADB) affordability threshold (see B2C #13)
		$/m^3$	$/yr	$/m^3$	$/yr		
	Spent	0.13	7000000	0.11	6000000		

Table 3 (*continued*)

	Burden			Capacity		Brief interpretation
13.	User fee			Average household income		On average, about 1% of average household income is spent on wastewater treatment. The ADB's combined affordability threshold for water and wastewater services is 5% of household income. See B2C #12, #14 to assess motivation for raising user fee
	\$/mo hh	2.6		265		
14.	Annual investment in maintenance			Replacement value of wastewater treatment plant		The treatment plant appears to be keeping a fair maintenance schedule. The facility is investing slightly less than 2% of the replacement value of the facility per year. The US General Accounting Office recommends a minimum investment in maintenance of 3%, and ideally 6% of the replacement value. Feasible investment in maintenance may be limited by user fee collection (see B2C #12)
	\$/yr	430000		23000000		
15.	Person hours per day skilled operator present at facility			Number days in previous year facility shutdown		The facility has a superior annual operation record which can be partially attributed to adequate staffing of skilled labor.
	Person h/d	24		0		
16.	Sludge handling cost			Total cost of WW handling		Due to the absence of on-site sludge treatment prior to disposal, sludge handling accounted for only 3% of the capital cost of the facility, but accounts for 21% of the operating costs.
	Capital (\$)	1700000		57000000		
	O&M (\$/yr)	490000		2400000		
17.	Daily average sludge production			Daily sludge wasting		WWTP #2 has a design sludge retention time (SRT) of 5 days. The facility is wasting approximately 85% of the necessary amount to maintain steady state. Insufficient wasting can increase aeration requirements and decrease BOD removal
	Dry ton/d	22		18.5		
End-use phase						
18.	WW treated			WW reused		This indicator reveals uncaptured opportunity to reuse wastewater effluent to help mitigate water shortage by offsetting demand for surface water withdrawal and to capture the local value of the wastewater (see B2C #3, 9–10)
	m^3/d	150000		0		
19.	Agricultural land within 3 km radius			Amount of treated wastewater used for agricultural irrigation		There is no opportunity to reuse treated wastewater for irrigation in the immediate vicinity of WWTP #2. Other wastewater reuse options should be investigated such as for industrial or domestic purposes. See B2C #3 for sustainability of current surface water use
	ha	0		m^3/ha	0	
				m^3/yr	0	
20.	Local value of resources embodied in WW			Value of WW being captured		The local value of wastewater includes the value of embodied energy if biogas generated by anaerobic treatment (pond or UASB) is captured and converted to electricity plus the value of the treated wastewater if sold in place of potable water to industrial users. Since there is no agricultural land to discharge wastewater to (B2C #19), the nutrient value in wastewater is not included in the value of wastewater
	\$/yr	8000000		0		
21.	Average metal concentration in sludge			Metal standard for sludge land application		With the exception of nickel (Ni), the heavy metal content in WWTP #2's sludge is well within the State Environmental Protection Agency's (SEPA) standards for land application. Options for reducing Ni (like source control) would allow the sludge to be land applied, which could supply a portion of the local demand for fertilizer (see B2C #24) and divert sludge from the landfill (see B2C #23)
	Pb (g/m^3)	290		1000		
	Cr (g/m^3)	300		1200		
	Cd (g/m^3)	12		20		
	Ni (g/m^3)	1100		200		
22.	Local value of resources embodied in sludge			Value of sludge being captured		Here the resource value of sludge includes land application and on-site energy generation through anaerobic digestion. The potential economic value is larger than the existing O&M costs of sludge handling (see B2C #16). Sludge can also serve as an input (fuel or material substitute) to cement manufacturing, but may require prior heat-drying. Note, capturing energy in wastewater and sludge are mutually exclusive (see B2C #20)
	\$/yr	597000		0		
23.	Sludge disposed in landfill			Daily tipping capacity of landfill		Sludge from WWTP #2 accounts for about 3% of the total daily tipping capacity of the Longquan Landfill where it is being disposed. WWTP #2 is one of several WWTPs that dispose sludge at Longquan (totaling 400 t/d), and according to Chinese national policy, sludge tipping at landfills may not exceed 5% of total capacity. WWTP #2 and/or other facilities will have to seek alternative sludge handling options
	ton/d	93		3400		
24.	Local demand for nutrients			Unutilized nutrient content in WW and sludge		Demand for nutrients by the agricultural sector within the Chengdu Municipality is quite substantial and has potential to be partially satisfied by nutrients embodied in wastewater and sludge from WWTP #2. Capturing the resource value of the embodied nutrients can also increase revenue to the treatment facility (see B2C #12, 19, 21)
		TN	TP	TN	TP	
	ton/yr	1.6×10^4	5.2×10^3	2.9×10^3	180	
	\$/yr	4500000	2100000	840000	3300	
25.	Effluent nutrient concentration			Nutrient standard for receiving water or user		Treated wastewater from WWTP #2 is discharged to the FuNan River which is an extremely stressed ecosystem. The effluent nutrient concentrations exceed the wastewater discharge standards for surface waters with very limited nutrient assimilation capacity (GB18918-2002). Identifying alternative end uses for the wastewater is likely to be the most economical and environmentally beneficial option (see B2C #19–20)
	Total N (mg/L)	27		15		
	NH_4-N (mg/L)	4.6		5		
	Total P (mg/L)	1.5		0.5		
26.	Effluent BOD concentration			BOD standard for receiving water or user		On average, WWTP #2 is meeting discharge standards for BOD to waters with low assimilation capacity
	mg/L	8.5		10		

See Table S1 for a detailed summary of the methods, assumptions, and data sources.

[a] Marginal cost = operation and maintenance (O & M); average cost = O & M + capital cost (amortized over 20 year lifespan).

5. Conclusions

The objectives of this article were to present the newly developed B2C SA framework for wastewater treatment infrastructure and to convey its novel attributes. We believe that its two-dimensional format can provide more concrete decision and policy guidance than previously developed assessments that use uni-dimensional measures of sustainability. The B2C SA bears four characteristics that we contend are necessary but lacking from existing assessments: non-compartmentalization, site specificity, built-in guidance for target setting, and ability to measure active sustainability. The B2C SA does not capture all necessary wastewater treatment planning criteria; rather it is intended to supplement traditional engineering analyses. In particular, the unique feature of the B2C SA to quantify the local value of resources embodied in wastewater and treatment byproducts should facilitate more informed decision making with respect to designing wastewater handling schemes for reuse versus disposal.

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Appendix A. Supplemental material

Supplementary information for this manuscript can be downloaded at doi:10.1016/j.jenvman.2009.06.009.

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