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Indicator-based Water Sustainability Assessment – A Review

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Abstract: In the past few decades, there have been extensive efforts on measuring sustainability. One example is the development of assessment tools based on sustainability indicators. Several individuals and organisations have suggested various indices for assessing sustainability. This paper focuses on the review of water sustainability assessment using the indicator-based approach. It discusses major definitions of sustainable development that have been proposed and more specific concepts of sustainability based on sustainability principles and criteria. It then proceeds with the review of existing definitions, principles and guidelines on sustainable water resource management. The paper then explores elements of indicator-based water sustainability assessment. These elements include the selection of components and indicators, obtaining sub-index values, weighting schemes for components and indicators, aggregation of components and indicators, robustness analysis of the index, and interpretation of the final index value. These six elements are explored considering four existing water sustainability indices and two other sustainability indices that are thought to be useful for the development and use of water sustainability indices.

The review presented in this paper on indicator-based water sustainability assessment can provide significant inputs to water stakeholders worldwide for using existing indices, for customising existing indices for their applications, and for developing new water sustainability indices. These indices can provide information on current conditions of water resources, including identifying all factors contributing to the improvement of water resources. This information can be used to communicate the current status of existing water resources to the wider community. Also, the water sustainability indices can be used to assist decision makers to prioritise issues, challenges and programs related to water resource management.

Keywords: *Sustainable development; Sustainability principles; Water sustainability index; Components; Indicators*

1. INTRODUCTION

The United Nations Conference on the Human Environment in 1972 sparked environmental awareness globally. The conference also inspired the publication of the Brundtland Report (also known as Our Common Future), where the notion of sustainable development was first introduced by the Brundtland Commission (Brundtland, 1987). Since the publication of this Report, studies and efforts to define sustainability and sustainable development have been extensively carried out by various institutions and organizations at all levels: local, national, regional and international. According to Harding (2002), sustainability is the ultimate goal of sustainable development. In the last few decades, there have been extensive efforts on measuring sustainability. One example is the development of assessment tools based on sustainability indicators, known sustainability indices. These sustainability indices have common purposes: to measure the sustainability.

Some authors have developed general sustainability indices, such as the Environmental Sustainability Index (Esty et al., 2005), Corporate Sustainability Indicators (Spangenberg & Bonniot, 1998), the Barometer of Sustainability (Prescott-Allen et al., 1997), Environmental Pressure Indices (Jesinghaus, 1999), Taking Sustainability Seriously (Portney, 2003), Sustainability Indicator Systems (Spangenberg & Bonniot, 1998) and Pressure-State-Response (PSR) based sustainability indicators (Spangenberg & Bonniot, 1998). Some sustainability indices are field-specific, such as indicators for environment (Esty et al., 2005), agriculture (Parris, 1998; Van Ittersum et al., 2008), fossil fuel (Ediger et al., 2007) and water resources. Indices for water resource sustainability, for example, are the Water Poverty Index – WPI (Lawrence et al., 2003), Canadian Water Sustainability Index – CWSI (Policy Research Initiative, 2007), Watershed Sustainability Index – WSI (Chaves & Alipaz, 2007) and West Java Water Sustainability Index – WJWSI (Juwana et al., 2010a). All these indices have the same goal to measure sustainability, which can further be used to assist decision makers and other stakeholders in achieving sustainability. Further, the indices can also be used to communicate the progress of sustainability to wider community. For example, the applications of a water sustainability index in one catchment for different years can be used to show the community how the catchment has progressed towards water sustainability.

The above-mentioned sustainability indices were developed based on existing definitions of sustainable development and sustainability principles, proposed by various individuals and institutions. These definitions re-affirm the definition of sustainable development in the Brundtland Report (Brundtland, 1987), which highlighted the concerns for future generations. The following sub-sections discuss some of these sustainable development definitions and sustainability principles, followed by definitions, principles and guidelines on sustainable water resource management. Later, the elements of an indicator-based sustainability assessment are also presented. Then, four existing water sustainability indices and two other indices are analyzed to provide an in-depth understanding of how such indices are applied in actual cases.

2. SUSTAINABLE DEVELOPMENT DEFINITIONS AND SUSTAINABILITY PRINCIPLES

Liverman et al. (1988) states that efforts to measure sustainable development can only be achieved when this concept is clearly defined. Since it was introduced in 1987 (Brundtland, 1987), there have been extensive studies to define sustainable development. The first definition of sustainable development was proposed by the Brundtland Commission (Brundtland, 1987), which defined sustainable development as:

...development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (Brundtland, 1987, p. 87)

This definition was followed by other definitions, such as the followings:

...to maximize simultaneously the biological system goals (genetic diversity, resilience, biological productivity), economic system goals (satisfaction of basic needs, enhancement of equity, increasing useful goods and services), and social system goals (cultural diversity, institutional sustainability, social justice, participation). (Barbier, 1987)

...meeting human needs while conserving the Earth's life support systems and reducing hunger and poverty. (Palmer et al., 2005, p. 5)

Even though the above definitions are presented in different forms, the messages are comparable. These definitions urge human actions to concern about present and future environments, while at the same time utilising natural resources to fulfil human needs. The Brundtland definition focuses on the balance of present and future generations, while the other two definitions further address the need for concern for environmental, social and economic interests.

These definitions on sustainable development were further explained by the growing studies on sustainability principles. One of the most well-known sustainability principles is the "triple bottom line approach", which includes the environmental, economic and social aspects of sustainability (Farsari & Prastacos, 2002; Ekins et al., 2003; Cui et al., 2004). Spangenberg (2004) proposes similar principles labelled as challenges, namely environmental, social and institutional challenges. The environmental challenge emphasises the degradation of natural resources for human use; the social challenge highlights the unequal distribution of wealth and poverty; and the institutional challenge focuses on peace and security.

Other sustainability principles are presented in different forms. Parkin (2000) introduced the capital flow concept, which stated that any development for achieving sustainability needs to manage different capital flows. These capital flows are natural, human, social, manufactured and financial. Any development proposal has to contribute to improving, or at least maintaining, these five different capital flows (Parkin, 2000).

Spangenberg & Bonniot (1998) labelled their sustainability principles as "sustainability dimensions". These dimensions are packed in the so-called "prism of sustainability", as presented in Figure 1. This prism, reflecting sustainability, has four dimensions, which are institutional, environmental, social and economic. Each dimension is then further explored to identify relevant indicators. For example, for the institutional dimension, the sustainability indicators are participation, justice and gender balance. For the environmental dimension, resource use and state indicators are identified. For the social dimension, the indicators are health care, housing, social security and unemployment. Finally, for the economic dimension, the indicators are Gross National Product (GNP), growth rate, innovation and competitiveness (Spangenberg & Bonniot, 1998).

Apart from the indicators of individual dimensions, the prism of sustainability also offers a framework to identify the inter-linkage indicators between dimensions. The inter-linkages can be two, three or even four dimensional, which seek to compromise and synergise dimensions. Indicators based on two-dimensional inter-linkages are also illustrated in Figure

1. For example, the Human Development Index (HDI) indicators are derived from the inter-linkage between economic and social dimensions. Similarly, distribution of access to environmental resource and transport intensity are indicators derived from the interaction of environment and social dimensions. Furthermore, the inter-linkage of environment and economic dimensions has resulted in indicators such as jobs, services and resource intensity of production (Spangenberg & Bonniot, 1998).

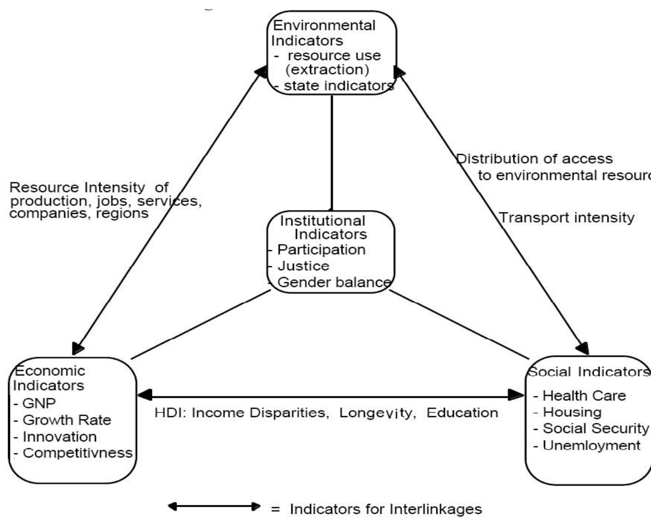

Figure 1 The prism of sustainability (Spangenberg & Bonniot, 1998)

3. SUSTAINABLE WATER RESOURCE MANAGEMENT: DEFINITIONS, CRITERIA AND GUIDELINES

As the complexity of issues related to water resources has increased, there have been extensive studies to combine the concept of sustainability with water resource management issues (Loucks & Gladwell, 1999; Loucks et al., 2000; Ashley et al., 2004; Starkl & Brunner, 2004; Giuppponi et al., 2006; Mays, 2006; Policy Research Initiative, 2007). By applying sustainability principles, it is expected that available water resources can be responsibly utilised, not only by the current generation, but also by future generations.

Loucks & Gladwell (1999) define water resource sustainability as:

> *…water resource systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity. (Loucks & Gladwell, 1999, p. 30)*

Other authors have defined water resource sustainability as:

> *…the ability to provide and manage water quantity so as to meet the present needs of humans and environmental ecosystems, while not impairing the needs of future generations to do the same. (Mays, 2006, p. 4)*

> *…the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life. (Mays, 2006, p. 4)*

> *…a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. (GWP-TAC, 2000, p. 1)*

These definitions on water sustainability urge any water-related decision maker and/or other stakeholders to consider every impact of their water-related programs on both present and future generations. Considerations on purely technical criteria are no longer sufficient as the complexity and uncertainty of water-related issues intensify. Inclusion of environmental, economic and social criteria is critical to address such complex and uncertain water-related problems (Loucks & Gladwell, 1999).

The above definitions also clearly indicate that sustainable water resource management can only be achieved through the integration of water-related issues and stakeholders. Savenije & Van der Zaag (2002) highlight the importance of Dublin principles on integrated water resource management, in the International Conference on Water and the Environment (ICWE) (United Nations Conference on Environment and Development, 1992), which state that:

> Water is an essential resource, to be used and managed appropriately, (2) All relevant stakeholders should be involved in the development and management of water resources, (3) The central role of women in the provision, management and protection of water resources is recognized and acknowledged, and Economic value of water in all uses should be emphasized and taken into account in the decision making.

Mays (2006) accentuates three domains of integrated water resource management, which include scope, scale and governance. Scope covers social and developmental issues related to water resources, its related sectors, gender empowerment, poverty eradication and fairness among the community. Scale ranges from local to national, and also possibly the river basin level. Governance needs to include public sector, business community and wider community representation.

The need for the integration of water-related issues is also noted by Loucks & Gladwell (1999). They state that water sustainability endorses water-related programs to be directed towards a more integrated or holistic approach. Water-related projects can no longer be emphasised from a purely technical view, ignoring social and economic concerns (Loucks & Gladwell, 1999). Towards a better understanding of water sustainability principles, Loucks & Gladwell (1999) provide water sustainability guidelines, which include the importance of water infrastructure, environmental quality, economics and finance, institutions and society, human health and welfare, as well as planning and technology. In line with these guidelines, Mays (2006) introduces seven requirements to ensure the sustainability of water resource systems. They are basic water needs to maintain human health; minimum standard of water quality; basic water needs to maintain ecosystem health; long-term renewability of available water resources; accessible data on water resources for all parties; institutional schemes to resolve water conflict; and democratic water-related decision making.

Jakeman et al. (2005) introduce issues to be addressed in integrated water resource management, which include water supply and demand, poverty alleviation and subsistence production, agricultural land use, and environmental issues such as erosion and forest maintenance. All these issues are essential because they can be used as the basis for developing water resource improvement programs to consider how these different issues impact present and future generations.

4. ELEMENTS OF INDICATOR-BASED SUSTAINABILITY ASSESSMENT

In general, the indicator-based sustainability assessment seeks to identify indicators to measure sustainability. An indicator is a measure, either qualitative or quantitative, of facts or conditions of particular issue(s). If the indicators are observed regularly, they can analyse changes during the observation period (Nardo et al., 2005). Some indicators might be grouped to form a component, or particular indicator(s) might be further explained by having sub-indicators. A group of indicators and/or components, which are combined together, is called an index or composite indicator. Nardo et al. (2005) emphasise that ideally an index should measure multi-dimensional ideas that cannot be explained by one indicator.

To apply the indicator-based sustainability assessment, common elements to be considered include component and indicator selection, obtaining sub-index values of components and indicators, weighting of components and indicators, aggregation of components and indicators, and robustness analysis of the index. The components and indicators provide a framework for indicator-based sustainability assessment, as it identifies all the components and indicators of the index. To assess sustainability using this approach, all identified indicators must have common unit values. The values of the indicators in common units are known as sub-index values. After all the sub-index values of the indicators are obtained, they can be aggregated to a single index value. In the aggregation, the indicators might be assigned equal or non-equal weights. The robustness analysis of the index is conducted to study the uncertainty of inputs on the index.

4.1. Selection of components and indicators

Components and indicators are the main constituents of an index. Therefore, in developing an index, the selection of components and indicators is extremely important. Components and indicators for an index are commonly selected through a literature review on previous sustainability frameworks and existing sets of components and indicators (Chaves & Alipaz, 2007; Policy Research Initiative, 2007; Sullivan & Meigh, 2007; Juwana et al., 2010b). Generally, an initial set of components and indicators is identified, based on those reviews. This initial set is then refined through discussion with key stakeholders (Policy Research Initiative, 2007; Sullivan & Meigh, 2007; Juwana et al., 2010a).

Liverman et al. (1988) suggest the following characteristics for the selection of indicators:

- *Sensitive to change in time*

  A reliable indicator must be observable throughout the particular time series of data; otherwise the indicator will not be able to provide information on how the issues related to the indicator have changed over time.

- *Sensitive to change across space or within groups*

  An indicator should reflect the changes occurred across space or within groups. If not, the indicator will be less useful to measure a condition. The Gross National Product (GNP) is an example of an economic indicator which is not sensitive to change within groups. The GNP value may increase even though for the majority of community groups the economic condition worsens. In this case, such an indicator might be replaced by one that measures the distribution of income.

- *Predictive or anticipatory*

  With regard to sustainability, reliable indicators should be able to predict or anticipate the signs of unsustainable conditions. Then, once the signal is received, the indicators can be traced to identify the main causes for the unsustainable signal. The water stress indicator by Falkenmark et al. (1989a), for example, is an indicator which can provide an early signal, if water availability in a particular area is under threat. As this indicator is derived from two variables – population and available fresh water – further analysis can demonstrate which variable has caused the stress to water resources. Once specific causes of the unsustainable condition are identified, appropriate action to address these causes can be deployed.

- *Reference or threshold values available*

  Indicators which have been identified will be less useful when reference or threshold values to assess the indicators are not available. Therefore, if the data or reference value is not available for an indicator, the indicator might have to be replaced by a 'similar' indicator, for which its data is available. In developing countries, this is a major concern as required data to assess the identified indicators might not be available or inaccurate (West Java Environmental Protection Agency, 2008). Therefore, it is important that during the indicator selection process, the issue of data availability is included as one of the selection criteria.

- *Unbiased*

  Biases in the selection of sustainability indicators may occur due to various reasons, such as the existing knowledge of the index developer, political interests, and the background given in the existing literature. It might not be possible to eradicate these biases. Therefore it is important, for the index developer, to identify the potential sources of biases and take necessary measures to minimise them.

- *Appropriate data transformation*

  For most indicators, the identified indicator is not the raw data. Therefore, to obtain the value for the indicator, appropriate data transformations or calculations are needed. It is important to carefully develop or adopt the appropriate method for transforming the data into the meaningful indicator value.

- *Integrative*

The importance of integrative or composite indicators is to provide the signs on relative conditions that are not sustainable. Senior decision makers need to be informed on the conditions based on these signs, which will be analysed to trace the main causes that lead to conditions that are not sustainable.

Some concerns regarding the importance of indicator selection are presented by Nardo et al. (2005), who emphasise the quality of basic data for indicators and procedures to carry out the selection of indicators. The concerns for quality of basic data include their relevance, accuracy, timeliness, accessibility, interpretability and coherence. The concerns for procedures include design of the theoretical framework, obtaining sub-index values, linkage to other indicators and robustness analysis.

4.2. Obtaining sub-index values

In general, the identified indicators for an index have their own units. For example, the Water Availability indicator of the Canadian Water Sustainability Index (CWSI) has the unit of m^3/cap/year. The amount of available water for one person per year in a certain area (presented in m^3/cap/year), is known as the actual value of *Water Availability* indicator. As the actual values of indicators of an index are presented in different unit values, they cannot be aggregated or compared. The indicators can only be aggregated or compared when they have the same unit value. The values of indicators, which have the same unit, are known as sub-index values in indicator-based assessment. Different methods to obtain the sub-index value of indicators are currently available. The selection of the most appropriate method will be based on properties of the data and the purpose of developing the index (Nardo et al., 2005). Special attention and careful analysis is needed, as different methods may result in different outcomes (Ebert & Welsch, 2004). Some of these methods are discussed below.

a) Ranking method

The ranking method is the simplest method, as the sub-index is obtained, based on the relative importance of identified indicators. This method is used to compare the values of a particular indicator for different areas. Once the values are obtained, they are simply arranged in ascending or descending order, and the rankings are defined. In some cases (Jencks et al., 2003), the values for the indicator for different areas across different years are also compared. The equation to calculate sub-index values using this method is:

$$S_i = Rank\ (X_i) \quad \textbf{(1)}$$

where S_i is the sub-index value for indicator *i* and X_i is the actual value for indicator *i*.

This method was used in assessing the Medicare Beneficiaries Indicators (Jencks et al., 2003) and applications of the Technology Achievement Index (TAI) to obtain the sub-index values of TAI indicators (Cherchye et al., 2007). In these applications, this method was useful in prioritising the identified indicators. Based on the prioritisation, relevant policy actions were formulated to each indicator.

The advantage of using this method is its simplicity. However, once the rankings are presented, the information attached to each indicator becomes less meaningful (Nardo et al., 2005). Consequently, a comparative analysis between indicators cannot be achieved in absolute terms of their values; rather it is based on relative importance.

b) Continuous re-scaling

The continuous rescaling method is used to produce an identical range for the values of indicators, e.g., 0–1 or 0–100. These values assist decision makers to better understand the performance of respective indicators, and allow them to formulate more specific action plans to address the issues related to certain indicators.

This method has been widely used in the development of various indices, such as the Canadian Water Sustainability Index (Policy Research Initiative, 2007), Water Poverty Index (Lawrence et al., 2003), Human Development Index (Rodríguez, 2011), Environmental Sustainability Index (Esty et al., 2005) and West Java Water Sustainability Index (Juwana et al., 2011). The general equation to calculate the sub-index values using this method is as follows:

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad \textbf{(2a)}$$

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \times 100 \quad \textbf{(2b)}$$

where S_i is the sub-index value for indicator *i*, X_i is the actual value for indicator *i*, and X_{min} and X_{max} are the minimum and maximum threshold values of the indicator.

Eq. (2a) gives the sub-index value in 0–1 scale, while Eq. (2b) provides a 0–100 scale.

These two equations are used when the X_{min} is the least preferred value and the X_{max} is the most preferred value. If X_{min} and X_{max} are the most and least preferred values respectively, Eq. (2a) and Eq. (2b) are modified to:

$$S_i = 1 - \left(\frac{X_i - X_{min}}{X_{max} - X_{min}}\right) \quad \textbf{(3a)}$$

$$S_i = 100 - \left(\frac{X_i - X_{min}}{X_{max} - X_{min}} \times 100\right) \quad \textbf{(3b)}$$

In order to use the continuous rescaling method, maximum and minimum threshold values for each indicator must be defined. The actual values for the indicator are then re-scaled, based on the threshold values using the appropriate equation (i.e. 2a, 2b, 3a or 3b).

c) Percentage of annual differences over two consecutive years

This method calculates the sub-index value of a particular indicator based on the difference of an actual value in a particular year compared to the previous year. The use of this method is subject to time-series data availability for the identified indicators (Nardo et al., 2005).

The general equation for this method is:

$$S_i = \frac{X_{i,t} - X_{i,t-1}}{X_{i,t}} \quad \textbf{(4)}$$

where S_i is the sub-index value of indicator *i*, $X_{i,t}$ is the actual value of indicator *i* at time *t* , $X_{i,t-1}$ is the actual value of indicator *I* at time *t-1*.

This method was used in the application of the Internal Market Index (Nardo et al., 2005).

d) Categorical scaling

The categorical scaling method assigns categories for indicators based on some defined criteria. The categories can be numerical (values such as 1–5) or qualitative (such as ‘very good', 'good' or 'poor'). Compared to the continuous rescaling method, instead of having the sub-index values in continuous form, this method produces the sub-index values in categories.

This method can also be used to obtain the sub-index values of certain indicators for which quantitative data are not available. For example, to assess the *Institutional Capacity* indicator of the WSI, there was no quantitative information available. Thus, the WSI developer suggested two indicators to assess the *Institutional Capacity*; they were *Legal Framework* and *Participatory Management*. Each of these two indicators has a criterion, which was divided into five scales (very poor, poor, medium, good and excellent) (Chaves & Alipaz, 2007). Each criterion corresponded with a sub-index value. The sub-index value for the Institutional Capacity was the average of sub-index values of *Legal Framework* and *Participatory Management.* In the WJWSI, this method was used to obtain the sub-index of three indicators, namely the *Information Disclosure, Governance Structure* and *Law Enforcement* (Juwana et al., 2011).

The general equation for using this method is:

$$S_i = \begin{matrix} Z_j & if & X_i \; meets \; criteria \; 1 \\ Z_j & if & X_i \; meets \; criteria \; 2 \\ \dots & & \dots \\ Z_n & if & X_n \; meets \; criteria \; n \end{matrix} \quad \textbf{(5)}$$

where S_i is the sub-index value of indicator *i*, X_i is the actual value of indicator *i*, Z_j is the category for X_i that meets criteria *j*, and n is the number of categories.

e) Distance to a reference

Nardo et al. (2005) discussed the use of this method by Parker (1991) in 'Concern About Environmental Problems'. In this application, the values of indicators of one country (or the average values of different countries) are used as a reference. The sub-index values of respective indicators of other countries are assessed, based on their relative conditions to the reference value(s).

The general equation to use this method is:

$$S_i = \frac{X_i}{X_r} \tag{6}$$

where S_i is the sub-index value for the indicator i, X_i is the actual value for the indicator, and X_r is the actual value used as reference.

4.3. Weights

In the index development, weights are used in the indicator aggregation, allowing index developers (or users) to assign different weights on the indicators. In general, Nardo et al. (2005) classify weighting techniques in two broad categories, which are statistical-based methods and participatory-based methods. In the former method, weights are assigned based on the analysis on the data of the indicators. In the latter method, weights are given based on opinion from experts or the general public. As the selection of experts might involve subjective judgment, justifications for the selection of these experts are required.

Methods such as Factor Analysis (FA) / Principal Component Analysis (PCA) and Unobserved Component Model (UCM) are examples of the statistical-based weighting approach. In general, the FA/PCA assigns weights based on the loading factor of each indicator to the final index. The use of FA/PCA to determine weights involves four steps. The first step is to analyse the correlation of the indicators. If no correlation exists, it is likely that the indicators do not share common factors. Then, in such cases where the indicators are not correlated, the indicators are assigned equal weights. However, it is unlikely that the indicators completely have no correlation. If the correlation existed, the second step is to identify common factors, representing group(s) of indicators. In PCA, the factors are known as (principal) components. Each factor indicates how well the factor in explaining the overall variance. The third step is to determine the contribution of each indicator to its corresponding factor using the factor loading analysis. Then, the final step is to compute the weights based on the common factor and factor loading analysis. Higher weights are given to the indicators with high loading factor, and high percentage in explaining the overall variance (Nardo et al., 2005). In any cases, whether strong or weak correlations existed, interpretations on the correlations need to be presented based on clear and documented criteria.

The UCM method assumes that indicators of an index are dependent on other unknown factors. These factors are labelled as unobserved component(s) (Harvey & Koopman, 2000; Nardo et al., 2005). The dependency on the unobserved component(s), as well as errors associated with each indicator of an index, is shown by the variance of each indicator. To use this method, the first step is to calculate the variance of each indicator of the index. Then, the sum of variance of other indicators is calculated. The weight for an indicator increases as the variance of that indicator decreases, and as the sum of variance of other indicators increases (Nardo et al., 2005).

In the participatory-based approach, methods such as Budget Allocation (BAL), Analytical Hierarchical Process (AHP) and Revised Simos' Procedure are available. The BAL method is used to assign weights for different indicators based on allocation of budget by selected experts. The experts are requested to allocate certain budgets to each indicator. Once the budget is allocated, weights are calculated based on the budget. If necessary (optional), the budget allocation is repeated until convergence among experts is reached (Nardo et al., 2005).

The AHP method is a multi-criteria decision-making technique used in different fields such as customer service (Kwong & Bai, 2002), operational design (Macharis et al., 2004) and water conservancy (Zhang, 2009). This method is used to determine weights of different criteria in decision making. Using AHP, weights are determined through pair wise comparison of the identified criteria. The method was found to be useful to determine weights of criteria where qualitative judgment from experts or the general public was involved.

The Revised Simos' Procedure seeks to assign weights to different indicators based on the preference of selected decision makers - DMs (Kodikara et al., 2010). Using this method, weights for different indicators were assigned by distributing cards to the selected DMs. Each card represented one indicator. Along with the cards to represent each indicator, the DMs are also given blank cards. Then, the DMs are asked to arrange the cards in order of importance, from the least important to the most important. The weights of the indicators are computed, based on card order. An example of this method can be found in the study of multi-objective operation of urban water supply systems by Kodikara (2008) and Kodikara et al. (2010).

4.4. Aggregation

In developing an index, aggregation may occur in sequential stages, as illustrated in the example in Figure 2, assuming that the index has components, indicators and sub-indicators. In this figure, the values of sub-indicators are aggregated to obtain the values of the indicators. The values of the indicators are then aggregated to obtain the values of components. Finally, the values of components are aggregated to obtain the final index value.

In some cases the final index is not obtained from the aggregation of the components. Instead it is obtained from the aggregation of indicators or sub-indicators. The Environmental Sustainability Index (ESI) is such an example. Even though the ESI has five components, the final index value is obtained through the aggregation of 21 sub-index values, instead of the aggregation of sub-index values of components (Esty et al., 2005).

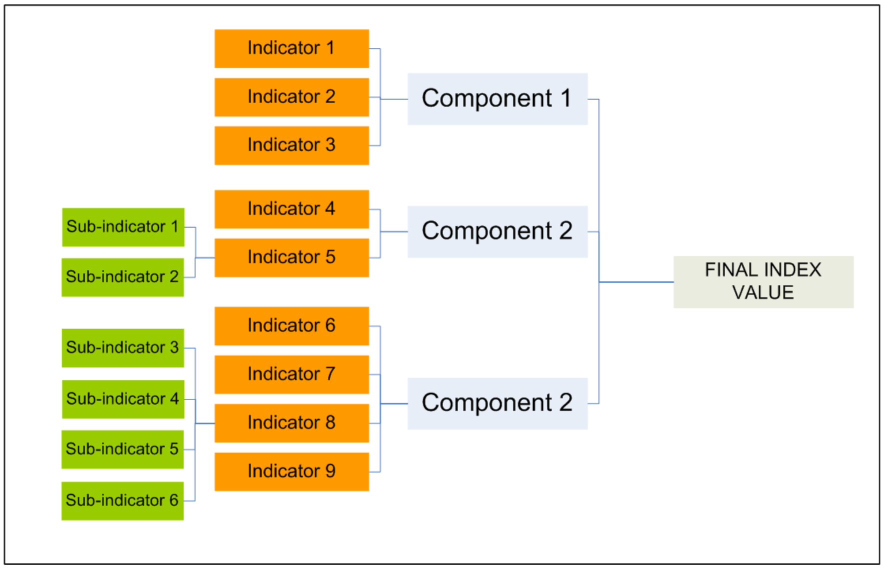

Figure 2. Stages of aggregation of an index

The two most common methods for aggregation of sub-indices are the arithmetic and geometric methods. The arithmetic method is widely used to aggregate sub-indices of various indices including the existing water sustainability indices of CWSI, WPI and WSI (Sullivan, 2002; Chaves & Alipaz, 2007; Policy Research Initiative, 2007). This method is applied through the summation of weighted sub-index values (Nardo et al., 2005), as given in Eq. (7).

$$I = \sum_{i=1}^{N} w_i S_i \qquad \textbf{(7)}$$

where I represents the aggregated index, N is the number of indicators to be aggregated, S_i is the sub-index for indicator i and w_i is the weight of indicator i.

With this method, perfect substitutability and compensability among all sub-indices occurs (Nardo et al., 2005). This means low values of some sub-indices are compensated with high values of other sub-indices. Consequently, it is possible for an index to have the same aggregated index values for different cases, even if the sub-index values for each of these cases differ quite considerably, but the weighted average sub-index values of all cases are identical. Consider the following example of an index with two indicators and different sets of values of indicators. In the first case, the sub-index values of the two indicators are 40 and 40 (maximum scale of 100) and in the second case, they are 10 and 70. If the arithmetic method with equal weights is applied to aggregate the indicators, both cases will have aggregated index values of 40. The extreme difference in sub-index values of the two indicators (10 and 70) in the second case compensated each other to produce the average value of 40 for the index.

The other common method used for aggregation is the geometric method. This method is used by multiplying weighted sub-index values, as shown in the following equation (Swamee & Tyagi, 2000):

$$I = \prod_{i=1}^{N} S_i^{W_i} \qquad \textbf{(8)}$$

the symbols for Eq. (8) are the same as those for Eq. (7).

In contrast to the arithmetic method, the geometric method does not create perfect substitutability and compensability among the sub-index values of the indicators. Consequently, two cases with a significant difference in their sub-indices will have different aggregated index values, even if their weighted average sub-index values are identical. If the above hypothetical example is used with the geometric method with equal weights, both cases will have different aggregated index values. The aggregated index value is 40 for the first case and 26.5 for the second case. Here, the low sub-index value (10) of the second case is not fully compensated by the high value of the other sub-index (70). Rather, the difference of these two sub-indices is reflected in the aggregated index value.

The above hypothetical example is extended with first indicator values changing linearly from 0 – 100, while at the same time the second indicator value changing linearly from 100 – 0. The results from the two aggregation methods are shown in Figure 3. Both methods use equal weights for the two indicators. In the arithmetic aggregation method, regardless of extreme differences between the two sub-index values, the aggregated index values remain constant. This is because the average values of the two sub-indices are the same. However, in the geometric aggregation method, the aggregated index values varied according to differences between sub-index values. A higher difference on the sub-index values results in lower aggregated index values.

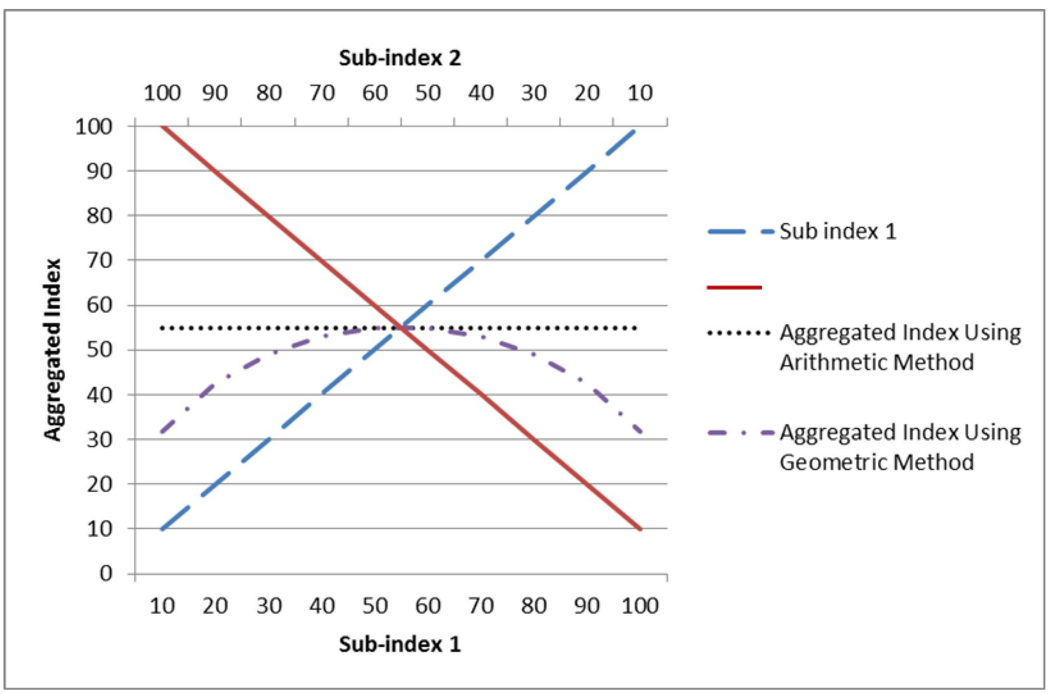

Figure 3 Comparisons of arithmetic and geometric aggregation methods

The geometric aggregation method takes into account the differences in the sub-index values when aggregating indicators, while the arithmetic aggregation method does not take these differences into account. Therefore, if the difference of sub-index values is important, the geometric method is more appropriate. Poor indicator performances, shown by the low sub-index values, will be reflected in the aggregated index value in the geometric aggregation method. In contrast, when the arithmetic aggregation method is used, poor indicator performances will not be reflected in the aggregated index value if other indicators perform well.

Note that in Eq. (7) and Eq. (8), the aggregated index is obtained from the indicators. However, the same form of equation(s) can be used at different levels of aggregation.

4.5. Robustness analysis

The robustness analysis of the index is concerned with the ability of the index to be applied under different circumstances, such as different locations, sets of indicators, and methods involved in calculating the final index. The robustness analysis is useful to provide a better understanding to relevant stakeholders, particularly users of the index, on the strengths and weaknesses of the index. The robustness analysis is commonly carried out by undertaking uncertainty and sensitivity analysis on the index.

Uncertainty analysis deals with uncertainties, related to the index development, affecting the final index value. Uncertainty analysis aims at identifying input variables that are varied, and potentially lead to error or uncertainty in the outputs (Esty et al., 2005; Nardo et al., 2005). It attempts to analyse the effects of uncertainties in the input on the output values (Saisana et al., 2005).

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Sensitivity analysis aims to assess and apportion the effects of variation in input variables on outputs (Saltelli et al., 2004; Nardo et al., 2005). It seeks out, mostly quantitatively, which input variation has mostly affected the output variation (Saltelli et al., 2004; Esty et al., 2005). The sensitivity analysis will provide information on how much the variation in output is influenced by input uncertainty (Nardo et al., 2005).

The Monte Carlo technique performs both uncertainty and sensitivity analysis. It operates by randomly considering different input variables, based on their range and appropriate probability distribution, and simulating the corresponding output values (Clemen & Reilly, 2001). With this technique, all uncertainties in the input factors can be taken into account simultaneously or individually (Saisana et al., 2005). The factors to improve the accuracy of Monte technique includes performing more simulations and reducing uncertainty ranges in the input variables (Clemen & Reilly, 2001).

5. EXISTING WATER SUSTAINABILITY INDICES

The indicator-based sustainability assessment approach has been used in the past to develop water sustainability indices. Widely used indices are: the Water Poverty Index (WPI) by Sullivan (2002), Canadian Water Sustainability Index (CWSI) by the Policy Research Initiative (2007), Watershed Sustainability Index (WSI) by Chaves & Alipaz (2007) and West Java Water Sustainability Index (WJWSI) by Juwana et al., (2010a).

The Water Poverty Index (WPI) was developed to assess the link between poverty and water availability (Sullivan, 2002). The developers of WPI believed that there is a strong correlation between water availability and poverty. The indicators of WPI were developed to assess this correlation. The first pilot project was conducted internationally in 2003, involving 147 countries worldwide (Lawrence et al., 2003). The results from the application were compared with the results of other indices such as the Falkenmark Water Stress Indicator and HDI.

The application of WPI in 2003 on an international scale, involving most countries in the world, had inspired the Policy Research Initiative (PRI) to develop the CWSI. In the application of WPI in 2003, Canada was ranked second (of 147 participating countries). Even though the performances of Canadian water resources were considered excellent at that time, PRI believed that Canada still had water resource issues, particularly among its rural communities. It was believed that the benefits from these water resources, received by local communities, were compromised. The CWSI was developed to specifically point out these disparities. Similar to WPI, the development of the CWSI framework seeks to integrate physical, environmental and socio-economic aspects of water resources in Canada. The application of CWSI in various Canadian communities is expected to identify important water issues and prioritise water-related issues, to communicate the conditions of Canadian water resources to the wider public, and to raise awareness of the Canadian stakeholders about water resources at the community level.

The Watershed Sustainability Index (WSI) was specifically applied at the basin level. It attempted to integrate issues of hydrology, environment, life and policy into a single and comparable number (Chaves & Alipaz, 2007). The developers of the index indicated that previous indices on water resources had not been specifically designed for use at the basin scale, and did not take into account the cause–effect relationship of their indicators. The application of sustainability indices at the basin level is important as the assessment of water resource sustainability cannot be bordered by jurisdictional frontiers (Chaves & Alipaz, 2007). To follow up on the cause–effect relationships among indicators, the WSI has used the Pressure-State-Response (PSR) model to address each of the HELP dimensions (Hydrology-Environment-Life-Policy) (Chaves & Alipaz, 2007).

The development of West Java Water Sustainability Index (WJWSI) is expected to benefit water stakeholders in West Java (1) to identify all factors contributing to the improvement of water resources, so that the resources can be used to fulfill present and future needs, (2) to assist decision makers to prioritise issues and programs related to water resource management, and (3) to communicate the current status of existing water resources to the wider community.

All the above four indices have common objectives, namely to provide information on current conditions of water resources, to provide inputs to decision makers and to prioritise water-related issues (Lawrence et al., 2003; Chaves & Alipaz, 2007; Policy Research Initiative, 2007; Juwana et al., 2010b). However, since each index is developed by taking the local environmental, social and economic characteristics into account, it may not be valid at other spatial scales (regional, national or international). Hence, these four reviewed indices also have some differences. In developing a new water sustainability index, consideration and analysis of similarities and differences with existing indices will be of utmost importance. In the following sub-sections, the four indices are critically reviewed under the various elements of index development.

5.1. Selection of component and indicators

The selection of components and indicators for WPI was based on the consensus of physical and social experts, water practitioners, researchers and other stakeholders (Lawrence et al., 2003). These experts were concerned about the relationship between water poverty and income poverty. Water poverty is illustrated in cases where people have access to water resources, but the availability of water is not adequate, whereas income poverty is shown when the availability of water is adequate, but people do not have access to the water resources. Therefore, assessing the performance of water resources cannot be achieved by ignoring socio-economic factors related to water resources (Lawrence et al., 2003). The final framework for WPI, resulting from expert consensus, is shown in Table 1.

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Table 1 Indicators of Water Poverty Index

Components	**Indicators**
Resources	Internal water resources
	External water resources
Access	Population with access to safe water
	Population with access to sanitation
	Irrigated land
Capacity	Gross Domestic Product (GDP)
	Under-5 mortality rate
	Education
	Gini coefficient
Use	Domestic water use
	Industrial water use
	Agricultural water use
Environment	Water quality
	Water stress
	Regulation and management capacity
	Informational capacity
	Biodiversity

The selection of components and indicators for CWSI was based on the literature review on water resource management and existing indicators of the Water Poverty Index (WPI). In the preliminary document of CWSI (Policy Research Initiative, 2007), indicators of WPI were modified to suit Canadian water resource characteristics. The document was then brought into a two-day workshop, and experts finalised the selection of components and indicators to be included in the final CWSI framework, as shown in Table 2.

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Table 2 Indicators of Canadian Water Sustainability Index

Components	**Indicators**
Resource	Availability
	Supply
	Demand
Ecosystem Health	Stress
	Quality
	Fish
Infrastructure	Demand
	Condition
	Treatment
Human Health	Access
	Reliability
	Impact
Capacity	Financial
	Education
	Training

The selection criteria used by these experts include scope, scale, applicability, relevancy, data and scoring (Policy Research Initiative, 2007). The scope criterion is concerned with the numbers of indicators to be included under each component. The experts believed that appropriate trade-off was made between a ‘too narrow’ and ‘too broad’ scope of indicators for each component. As for the scale, the concern was the difficulty in assessing the performance of water resources purely based on one particular community or area. In many cases, water conditions in one area are highly influenced by the other areas. Therefore, in CWSI, physical availability of water resources and ecosystem health are monitored at the river basin scale, instead of the community scale. For other issues such as education, poverty and infrastructure, they are assessed at the community scale (Policy Research Initiative, 2007). The next four criteria, which are applicability, relevancy, data and scoring, are highly related. They are concerned with the applicability of the index due to data availability, how the sub-index values of the indicators are obtained, and how meaningful these results are to the communities they serve. If an indicator will only be meaningful to particular communities, and much less meaningful for others, this indicator is replaced with another indicator (Policy Research Initiative, 2007).

The terminology used in WSI for components and indicators is different to the other indicators. In WSI, the components and indicators of the other indices are referred to as indicators and parameters respectively. The indicators of WSI were selected, based on the HELP platform, designed by UNESCO’s International Hydrologic Program (Chaves & Alipaz, 2007). For each indicator, different parameters (or sub-indicators) were developed using the PSR model of Smeets et al. (1999), which seeks to analyse the causality of the following three issues: (1) The *pressures* of human activities on various environmental issues, (2) How these pressures affect the *states* of the natural systems, and (3) The *responses* by governments and general communities to address the environmental changes through different policies and regulations.

Using the HELP platform and the PSR model, WSI indicators and parameters were developed. At the end of the selection process, the authors of the WSI proposed four different indicators: **H**ydrology, **E**nvironment, **L**ife and **P**olicy. *Pressures, states* and *responses* for each of these indicators were then identified and labelled as parameters. The Hydrology indicator comprises two *pressure* parameters, two *state* parameters and two *response* parameters. For the other three indicators, each has one parameter representing *pressure, state* and *response*. In total, 15 parameters were identified. WSI indicators and parameters are shown in Table 3.

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Table 3 Indicators of Watershed Sustainability Index

Indicator	Parameter
Hydrology	Variation in basin water availability (P)
	Variation in basin BOD (P)
	Per capita water availability (S)
	Basin BOD (S)
	Improvement in water-use efficiency (R)
	Improvement in adequate sewage treatment (R)
Environment	Basin Environmental Pressure Index - EPI (P)
	Natural vegetation (S)
	Evolution in basin conservation (R)
Life	Variation in income (P)
	Human Development Index - HDI (S)
	Evolution in HDI (R)
Policy	Variation in HDI-Education (P)
	Institutional capacity (S)
	Evolution in expenditures (R)

P = Pressure, S = State, R = Response

The components and indicators of WJWSI were identified, based on the literature review on sustainability criteria, water resource sustainability guidelines, and existing water sustainability indices of WPI, CWSI and WSI. The relevancy of these components and indicators to water resources, environmental, social and economic characteristics of West Java, and the availability of data for use in the index applications were also considered.

Once the components and indicators were identified, thresholds for the indicators were obtained from relevant policies, regulations and guidelines, which defined the conceptual framework. This conceptual framework was then refined using the Delphi technique (Linstone & Turoff, 1975) and in-depth interview with key stakeholders. This process produced the final framework (Juwana et al., 2010a), as shown in Table 4.

Table 4 Components, Indicators and Thresholds of West Java Water Sustainability Index

Component	***Indicator***	***Sub-indicator***	***Thresholds***		
			Unit	***Max***	***Min***
Conservation	*Water Availability*		m^3/cap/y	1700 [a]	500 [b]
	Land Use Changes		-	1 [b]	0 [a]
	Water Quality		-	0 [a]	-31 [b]
Water Use	*Water Demand*		%	40 [b]	10 [a]
	Water Service Provision	*Coverage*	%	80 [a]	0 [b]
		Water Loss	%	15 [b]	0 [a]
Policy and Governance	*Information Disclosure*		0, 25, 75 and 100 (categorical scale was used)		
	Governance Structure				
	Public Participation	*Education*	%	100 [a]	0 [b]
		Poverty	%	20 [b]	0 [a]
		Health	*cases/1000*	100 [b]	0 [a]
		Sanitation	%	100 [a]	0 [b]
	Law Enforcement		0, 25, 75 and 100 (categorical scale was used)		

a: preferable; b: not preferable

5.2. Obtaining sub-index values

To obtain sub-index values of WPI indicators, the *continuous rescaling* technique (Eq. (2a) and Eq. (2b)) was used. The maximum and minimum values used in Eq. (2a) and Eq (2b) for each WPI indicator were the highest and lowest actual values among the participating countries (Lawrence et al., 2003). The sub-index values of WPI indicators ranged from 0 – 1.

Similar to WPI, to obtain sub-index values of the indicators, CWSI adopted the *continuous rescaling* technique. Maximum and minimum threshold values for each indicator were

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determined based on specific targets or benchmarks. These targets or benchmarks were obtained from literature reviews. The maximum and minimum threshold values of the *Availability* indicator, for example, were taken from the Falkenmark Water Stress Indicator as 1700 m^3/cap/yr and 500 m^3/cap/yr respectively (Falkenmark et al., 1989b).

To obtain the sub-index values of the parameters, WSI uses the *categorical scale* technique (Eq. (5)), with the minimum value of 0, and the maximum value of 1. For each parameter, criteria describing five different categories were determined. Actual values of each parameter were compared to obtain the sub-index values. For example, for the *Environmental Pressure Index* (EPI) parameter of a particular basin, its EPI value is compared against the criteria shown in Table 5.

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Table 5 Obtaining sub-index values for EPI parameter of WSI

Criteria	**Sub-index value**
EPI ≥ 20%	0.00
20% > EPI ≥ 10%	0.25
10% > EPI ≥ 5%	0.50
5% > EPI ≥ 0%	0.75
EPI < 0%	1.00

The *continuous rescaling* and the *categorical scale* methods were used to obtain the sub-index values of WJWSI indicators and sub-indicators. Based on the characteristics of available data, three groups of indicators and sub-indicators were identified to compute their sub-index values (Juwana et al., 2011).

The first group of indicators and sub-indicators are *Water Availability, Land Use Changes, Coverage, Education* and *Sanitation*. For these indicators and sub-indicators, the sub-indices increase as the actual values increase. The sub-index values for this group were obtained using the continuous rescaling method (Eq. (2b)). Indicators and sub-indicators of the second group are *Water Quality, Water Demand, Water Loss, Poverty* and *Health Impact*. For these indicators and sub-indicators, the sub-indices decrease as the actual values increase. The sub-index values for this group were obtained using the modified continuous rescaling method (Eq. (3b)) (Juwana et al., 2011). The third group consists of three indicators: *Information Disclosure, Governance Structure* and *Law Enforcement*. For these indicators, the categorical scale was used to obtain their sub-indices, as shown in Eq. (5), but with a quartile scale.

5.3. Weighting

In the original WPI framework, no specific weighting scheme was suggested. Sullivan et al. (2006) believe that the responsibility in determining indicator weights should be given to decision makers, not to the researchers. In using WPI, the users are allowed to define their own weights to be assigned to WPI indicators. However, Sullivan et al. (2006) emphasised the importance of transparent consultation with relevant stakeholders in defining weights. During the first WPI application, equal weights among all indicators and components were applied (Lawrence et al., 2003).

In the CWSI, an equal weighting scheme was used to aggregate the indicators. This means that each indicator has the same weight during the aggregation process. The decision to apply the equal weighting scheme (along with the finalisation of components and indicators) was made by selected experts during their two-day workshop. However, each catchment or community is also allowed to make changes for the weighting scheme, if justifications can be provided.

In the WSI, the equal weighting scheme was used to aggregate the indicators. Chaves & Alipaz (2007) believe there is no clear and significant evidence to assign different weights on WSI indicators. However, if non-equal weights are needed during the application of WSI in particular basin(s), Chaves & Alipaz (2007) suggest a consensus among relevant stakeholders to assign appropriate and reliable weights for indicators.

During the development of WJWSI, both equal and non-equal weighting schemes were considered to aggregate the sub-index values. Non-equal weights were obtained using the Revised Simos procedure (Figueira & Roy, 2002). With this procedure, WJWSI indicators and sub-indicators were assigned different weights based on the input from water-related stakeholders in West Java. After the robustness analysis of WJWSI, it was concluded that either the equal or non-equal weighting scheme can be used, as it will not significantly affect the final index (Juwana et al., 2011).

5.4. Aggregation

Two aggregation processes were used in WPI. The first aggregation was used to combine the sub-index values of different indicators into components using the arithmetic aggregation method. As the indicators are equally weighted, the index value for each component was the average of the sub-index values. Once these values for the five WPI components were obtained, they are aggregated using the arithmetic method with equal weights to obtain the final index value, ranging from 0 – 100 (Lawrence et al., 2003).

To aggregate CWSI indicators, the arithmetic method was used (Eq. (7)). In CWSI, aggregation occurs both at the component and indicator levels as in WPI. The three indicators in each component are aggregated to obtain the sub-index value of the component. The five sub-index values of components are then aggregated to obtain the final index value. As CWSI has equal numbers of indicators in each component and all indicators have equal weights, the final aggregated index value is also the average of sub-index values. The equal weights applied to all indicators also imply that each component value is the average value of its respective indicator values (Policy Research Initiative, 2007).

In WSI, the arithmetic method (Eq. (7)) was used. There were two levels of aggregation, similar to WPI and CWSI. First, the parameters of an indicator were aggregated using the following equation:

$$I = \frac{(P + S + R)}{3} \quad \textbf{(9)}$$

where *I* is the sub-index value of the indicator, *P* is the average sub-index value for *pressure* parameters, *S* is the average sub-index value for *state* parameters, and R is the average sub-index value for *response* parameters. As indicated earlier, it is to be noted that the terminology used in WSI for components and indicators were different to the other indices (Section 5.1). The components and indicators (of other indices) are referred to as indicators and parameters respectively in WSI.

Once the sub-index values for all indicators were obtained, they were aggregated using the following equation:

$$WSI = \frac{(H + E + L + P)}{4} \tag{10}$$

where *WSI* is the final index, *H* is the sub-index value for the *Hydrology* indicator, *E* is the sub-index value for the *Environment* indicator, *L* is the sub-index value for the *Life* indicator, and *P* is the sub-index value for the *Policy* indicator. The values of H, E, L and P are obtained from Eq. (9).

In WJWSI, the final index is obtained through the aggregation of sub-index values of all 13 indicators and sub-indicators. The aggregation method recommended for the WJWSI was the geometric method (Eq. (8)). This method is more appropriate for the WJWSI as the differences of sub-index values among indicators are important and these differences are reflected better in the final index obtained through the geometric aggregation method than through the arithmetic method (Juwana et al., 2011). Poor indicator performances, shown by low sub-index values, will be reflected in the aggregated index value. In contrast, when using the arithmetic aggregation method, poor indicator performances will not be reflected in the aggregated index value if other indicators perform well.

5.5. Final index value interpretation

In general, higher values of WPI are preferred. However, in its first application, the performance of a country was interpreted by comparing its final WPI value, as well as the sub-index values of the components, with those of other countries. During the application, it was found that most of the rich or developed countries performed better, compared to the less-developed countries (Lawrence et al., 2003). To better interpret these results, the correlation of final WPI values and the values of other existing indices at the time such as the Falkenmark Water Stress Indicator and Human Development Index (HDI) in different countries was analysed (Lawrence et al., 2003). The analysis showed moderate to strong positive correlation between WPI and HDI (correlation coefficient = 0.81), explained by the fact that some of WPI indicators were taken from HDI components and/or indicators. The correlation coefficient of WPI and the Falkenmark Water Stress Indicator was 0.35, which indicated low to moderate correlation.

Similar to WPI, higher values of the final index of CWSI show higher water sustainability. If CWSI application was among various communities, it was found that the index was more useful when applied to communities in the same region, or communities which shared similar water resource conditions (Policy Research Initiative, 2007). Based on these results, the communities were able to work together to formulate relevant water policies at the regional scale.

For the interpretation of the final index, WSI adopted the Human Development Index (HDI). According to HDI interpretation, the performance of a basin is considered low if the final index of WSI is < 0.5; intermediate if WSI is between 0.5 and 0.8; and high if WSI is > 0.8. This HDI interpretation, adopted by WSI, was based on the 2000 HDI Report (Chaves & Alipaz, 2007).

For the WJWSI, the interpretation for sub-indices and their aggregated index was based on a quartile scale, as shown in Table 6 (Juwana et al., 2011).

Table 6 Interpretations of sub-indices and aggregated Index in WJWSI

Aggregated index and Sub-indices	***Performance***	***Priority of Action***
0 – <25	Poor	High
25 – <50	Poor – Medium	High – Medium
50 – <75	Medium – Good	Medium – Low
75 – 100	Good	Low

This scheme provides four levels of index performance, compared to three HDI groups. This performance classification is used as the basis for relevant priority action to improve the water resource management at the catchment scale. In Table 6, *Performance* reflects the condition of issue(s) related to an indicator, a sub-indicator, or aggregated index (i.e. the overall water resource condition) at a particular time of assessment. The *Priority of Action* reflects the priority of action(s) required to address the issue(s).

5.6. Summary of Comparative Analysis of Water Sustainability Indices

Table 7 summarises similarities and differences of these four indices: WPI, CWSI, WSI and WJWSI. As seen in Table 7, the components and indicators of these four indices (in WSI, they are referred to as indicators and parameters) were initially identified, based on literature reviews. The literature review in CWSI, WPI and WJWSI was undertaken to produce the initial set of components and indicators. This set was then brought into stakeholder consultations or expert meetings to finalize the index development (Lawrence et al., 2003; Policy Research Initiative, 2007; Juwana et al., 2010b).

Table 7 Comparisons of WPI, CWSI, WSI and WJWSI

Index	**Component Selection**	**Obtaining Sub-index Values Method**	**Weighting Scheme**	**Aggregation Method**	**Final Index Value Interpretation**
WPI (Water Poverty Index)	Literature review, then consensus opinion of experts and other stakeholders	Continuous rescaling	Equal weights	Arithmetic	**0 – 100**
CWSI (Canadian Water Sustainability Index)	Literature review, then expert workshop	Continuous rescaling	Equal weights	Arithmetic	**0 – 100**
WSI (Watershed Sustainability Index)	Literature review by authors	Categorical scaling	Equal weights	Arithmetic	**0 – 1** ≤ 0.5: Low 0.5 – 0.8: Intermediate ≥ 0.8: High
WJWSI (West Java Water Sustainability Index)	Literature review, then Delphi application and in-depth interview with stakeholders	Continuous and categorical rescaling	Equal and non-equal weights (both were considered)	Geometric	0 – <25 : Poor 25 – <50 : Poor-Medium 50 – <75 : Medium-Good 75 – 100 : Good

The continuous rescaling method was used in both WPI and CWSI to obtain the sub-index values of the indicators. Typically, the WPI and CWSI used local, regional, national or internationally recognised policies, regulations or standards to determine maximum and minimum threshold values, which were then used to compute sub-index values (Nardo et al., 2005). The categorical scale method was used by WSI to obtain sub-index values. Criteria for each indicator were identified to obtain sub-index values using the categorical method. These criteria were divided into different groups, representing the categories of the sub-index values. For WJWSI, the sub-index values of 10 indicators and sub-indicators were obtained using the continuous rescaling method, while the remaining 3 indicators were obtained using the categorical method. See Table 4 for indicators and sub-indicators of WJWSI.

The interpretation of the final index value for CWSI and WPI is based on the 0 - 100 range. The final index value for these indices are preferred if it is closer to 100, and less preferred if it is closer to 0. The interpretation of WSI value is based on the 0 - 1 range, with 1 being the most preferred and 0 the least preferred. In WSI, further interpretation was given based on the 2000 HDI Report. The performance of a basin is considered low, intermediate or high if the WSI value is $\leq$ 0.5, between 0.5 and 0.8, or > 0.8 respectively. For WJWSI, the performance of a catchment is considered Poor, Poor-Medium, Medium-Good or Good if the WJWSI value is < 25, between 25 and 50, between 50 and 75, or between 75 and 100 respectively.

6. OTHER INDICES

The indicator-based approach has been widely used in fields other than water resources, such as economics or human development. The applications of indices in these fields were considerably useful for decision makers in their respective fields. The following sub-sections discuss the development and applications of two indices, namely the Human Development Index (HDI) and Environmental Sustainability Index (ESI), since these two indices were thought to be useful for development and use of water sustainability indices.

6.1. Human Development Index

The Human Development Index (HDI) was proposed by the Pakistani economist, Mahbub ul Haq (Haq, 1989) and was published by the United Nations Development Program - UNDP (Rodríguez, 2010) in 1990. Since then, its applications have been widely used to assess performances of various countries considering three dimensions: health, knowledge and income (Rodríguez, 2010). These dimensions are similar to components in other indices. The index was proposed as the alternative to previous human development measurements, which focused solely on economic issues (Haq, 1989).

Selection of dimensions and indicators

Originally, the selection of dimensions and indicators of HDI, including threshold values to assess the indicators, was published by the index founder (Haq, 1989). When this paper was published, it received enormous response from various stakeholders, including public officials, policy makers, media and others (Rodríguez, 2010). Having global and positive attention from various stakeholders, the HDI was then adopted by UNDP to assess the performance on human development among countries. This assessment is updated regularly and still reported today. The dimensions, indicators and threshold values of HDI are regularly reviewed by a panel of experts, and necessary changes made during the review. The latest HDI framework of 2010 has four indicators. Each of the health and income dimensions has one indicator, while knowledge has two indicators: literacy and children in schools.

Obtaining sub-index values

In HDI, the sub-index values of health, knowledge and income dimensions are obtained using the *continuous rescaling method* (Eq. 2a). In HDI, the minimum and maximum threshold values are known as target values. To obtain the sub-index value of the health dimension, for example, the target values used for the maximum value is a life expectancy of 85 and the minimum value is a life expectancy of 25.

Weighting of dimensions and indicators

The HDI uses equal weights for all three dimensions. Under the knowledge dimension, the literacy indicator, a higher weight (two-thirds) is assigned than for the children in schools indicator (one-third), as the former indicator is deemed more important than the latter (Rodríguez, 2011). Once the index values for all dimensions are obtained, the aggregated index is computed with equal weights for all dimensions.

Aggregation of dimensions and indicators

As each of the health and income components has only one indicator, the sub-index values of these indicators are also the sub-indices of respective dimensions. The sub-index values of indicators for the knowledge dimension were aggregated using the geometric method (Eq. (8)) to obtain the sub-index value of the knowledge dimension. Once the sub-index values for all three dimensions were obtained, they were aggregated again using the geometric method to produce the final HDI value. With this method, a country with considerably high and low sub-index values for three dimensions will have a lower HDI value, compared to another country with the same sub-index values for all three dimensions.

Final index value interpretation

In the 2010 HDI Report (Rodríguez, 2010), changes were made to the interpretation of the final HDI value compared to the previous reports. In previous HDI reports, absolute HDI values were used to interpret country performance. In the 2010 HDI Report however, the interpretation of the final HDI values were based on relative HDI values (i.e. in terms of percentiles) among participating countries. The changes of classification and interpretation of the HDI are shown in Table 8. Based on performance, it is intended that each country will develop relevant policies for improving low performance. Different countries with similar HDI values or dimension values can also work together in designing appropriate policy actions.

Table 8 Interpretation of final HDI values

Year	**Final HDI Value**	**Performance**
Pre 2010	HDI <0.5	Low
	0.5 < HDI < 0.8	Intermediate
	HDI > 0.8	High
2010	HDI: 0-25 percentiles	Low
	HDI: 26-50 percentiles	Medium
	HDI: 51-75 percentiles	High
	HDI: 76-100 percentiles	Very High

6.2. Environmental Sustainability Index

The Environmental Sustainability Index (ESI) was developed to measure the overall environmental sustainability achievement of countries worldwide (Esty et al., 2005). Since its first application in 2001, the ESI has been regularly applied until now. Even though the index was previously used to compare environmental sustainability performances of countries worldwide, it is emphasized that the rankings were not the main concern. Rather, the information on the underlying indicators and variables (or sub-indicators), and how the information is used to formulate relevant policies, were the most essential (Esty et al., 2005).

Selection of indicators and variables

The ESI comprises 21 indicators, with each indicator having 2 to 13 variables (known as sub-indicators in other indices). In total, there are 76 variables used in the ESI. The 21 indicators are classified under 5 environmental themes, namely (1) Environmental systems, (2) Reducing environmental stresses, (3) Reducing human vulnerability to environmental stresses, (4) Societal and institutional capacity to respond to environmental challenges, and (5) Global stewardship.

The indicators and variables of ESI were selected by experts and based on existing analytical frameworks. As the index was meant to be applied globally, availability of data sources across these countries was considered during the selection of ESI indicators and variables. The indicators and variables of ESI were selected using the improved PSR method known as Driving force Pressure State Impact Response (DPSIR) of Smeets et al., (1999).

Obtaining sub-index values

The sub-index values of ESI are obtained using the *continuous rescaling* method (Eq. (2b)). The maximum and minimum threshold values used in the equation were based on the actual values of variables of participating countries.

Weighting of variables and indicators

An analysis of the non-equal weighting schemes was conducted during the development of the ESI. Two non-equal weighting schemes were studied: one based on Principal Component Analysis (PCA) and the other was based on the Budget Allocation scheme (Esty et al., 2005). Based on the analysis, it was found that the weights of the indicators differed insignificantly from the equal weighting results, and therefore equal weights were used in the ESI to aggregate its indicators and variables.

Aggregation of indicators and variables

To aggregate the ESI indicators and variables, the arithmetic method was used at both levels (Eq. (7)).

Robustness analysis

Robustness analysis of ESI was done by undertaking an uncertainty and sensitivity analysis of the index, using the Monte Carlo simulation, based on the 2005 data of countries. During the Monte Carlo (MC) simulation, different scenarios were performed, based on identified uncertainties. The scenarios performed in the MC simulation were the combinations of the following uncertainties (Esty et al., 2005):

(i) Data imputation methods

(ii) Equal weighting scheme or expert opinion weighting scheme

(iii) Aggregation at the component level or aggregation at the indicator level

(iv) Linear (arithmetic) aggregation method or multi-criteria aggregation method

The uncertainty and sensitivity analysis of ESI were undertaken to answer the questions below (Esty et al., 2005):

1. How can the ESI values in a particular year change under different scenarios?
2. What is the most preferable scenario for each country?
3. Which countries are vulnerable to changes in uncertainties?
4. Which of the uncertainty factors affect the countries' rankings at the most?

Final index value interpretation

The interpretation of the final ESI value was not purely based on its absolute value. The absolute value of ESI is preferred if it is closer to 100, and less preferred if it is closer to 0. Further interpretation is undertaken by comparing the results of one country with other countries. One of the comparisons were based on the cluster analysis (Esty et al., 2005) of sub-index values of ESI themes. In the cluster analysis, countries with similar sub-index values of themes were grouped together.

7. SUMMARY AND CONCLUSIONS

The review presented in this paper on indicator-based water sustainability assessment aims to provide significant inputs to water stakeholders worldwide for using existing indices, for customising existing indices for their applications, and for developing new water sustainability indices. To apply the indicator-based sustainability assessment, this study has identified six elements that need to be considered. These six elements are:

i) The selection of components and indicators

ii) Obtaining sub-index values

iii) Obtaining weights for components and indicators

iv) Aggregation of components and indicators

v) Robustness analysis of the index

vi) Interpretation of the final index value

In general, it can be concluded that the selection of components and indicators for developing an index was undertaken through extensive literature review on available relevant frameworks and existing indices, as shown in the selection of components and indicators of all reviewed indices presented in this paper (namely, WPI, CWSI, WSI, WJWSI, ESI and HDI). Different methods were used to finalise the initial components and indicators for each of the indices. In the development of CWSI, for example, the initial components and indicators were finalised through an expert workshop, as these experts were able to meet at the agreed time and place. Meanwhile, for WJWSI, the experts were unable to set an agreed time and place for finalising the initial components and indicators. Therefore, the Delphi method was used to finalise the components and indicators for the WJWSI.

It can also be concluded that the methods to obtain the sub-index values of components and indicators (and sub-indicators) are dependant on the potential users of the indices. These methods include the *continuous rescaling* and *categorical* methods. The *continuous rescaling* method was used by WPI, CWSI, WJWSI, HDI and ESI, whereas the *categorical* method was used by WSI and WJWSI. Other available methods were not chosen as either they are not as simple as these two methods or the data to use the methods are not available.

With regards to the weights for components and indicators of an index, it was found in all indices that the weights for components and indicators should be obtained through consultation, and if possible through consensus among relevant stakeholders. Then, the results of the consultation should be widely disseminated to other potential index users. The process of aggregating the components and indicators is dependant on the purpose of developing the index. For some indices, such as WPI, CWSI and WSI, two levels of aggregation were undertaken. The first level was done at the indicator level (to obtain the sub-index value of the components), and the other level was done at the component level (to obtain the final index). The index developer of these indices (and their relevant stakeholders) considered the sub-index value of the components for these indices to be important for further water resource management policy formulation. On the other hand, in WJWSI the aggregation was undertaken only at the indicator level to obtain the final index value, as the developer of the index (and their relevant stakeholders) only considered the final index value to be important for further policy formulation.

In this review paper, it is also shown that the robustness analysis of some indices (i.e. ESI and WJWSI) were able to demonstrate how uncertainties of different factors (such as weighting schemes, aggregation methods) have resulted in different values of the final index. In ESI, for example, through robustness analysis, the index developer has provided justification of using the equal weight scheme instead of non-equal weight scheme for ESI indicators, as both methods have resulted in insignificant difference of final ESI values.

It can also be concluded from this paper that the purpose of developing the index affects which method to use for interpreting the sub-index and final index values. For some indices (i.e. WPI, CWSI and ESI), the general interpretation of 0-100 scale was adequate to explain the sub-index and final index values. For other indices (i.e. HDI, WSI and WJWSI), further interpretation were provided to explain their sub-index and final index values. For example, in WJWSI, the interpretation of the sub-index and final index values has been linked with the level of priority of action.

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