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Uncertainty and Sensitivity Analysis of West Java Water Sustainability Index– A Case Study on Citarum Catchment in Indonesia

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Abstract: Water sustainability indices have been recently used to measure the sustainability of water resources within a catchment. Developing a sustainability index involves various steps, some of which have uncertainties associated with them. For the recently developed West Java Water Sustainability Index (WJWSI), three sources of uncertainties were identified, namely uncertainties in the thresholds of non-categorical indicators and sub-indicators, in the weighting schemes, and in the aggregation methods. This paper presents the uncertainty and sensitivity analysis of WJWSI, based on the application of WJWSI to Citarum catchment in West Java, Indonesia. The results of the uncertainty analysis, measured by the coefficient of variation of the thresholds and the sub-indices, indicates that minimum thresholds of *Land Use Changes, Coverage, Education, Poverty, Health Impact* and *Sanitation*, and the maximum threshold of *Water Quality* have higher variation when compared to variation of the other thresholds. The results of the sensitivity analysis, measured by the correlation coefficients between the final index and the thresholds, indicate that changes in the thresholds of WJWSI indicators have not significantly affected the sub-index values of most indicators and sub-indicators. The sensitivity analysis also concluded that either the equal or non-equal weighting scheme can be used for future use of the aggregation of WJWSI indicators and sub-indicators, as changes from equal to non-equal weighting scheme did not significantly affect the final index. However, it was found that the final index values were most sensitive to the aggregation method used (i.e. arithmetic and geometric methods), shown by the significant changes in the final index value when the aggregation method was changed from arithmetic to geometric. The uncertainty and sensitivity analysis presented in this study will not just assist in the efficient use of the WJWSI, but will also help undertake similar analysis for other indices.

Keywords: *Uncertainty analysis, sensitivity analysis, West Java Water Sustainability Index (WJWSI), Citarum catchment*

1. Introduction

In one of the most densely populated provinces of Indonesia, West Java, the conditions of water resources are poor. The increase in population in the province has resulted in increased demand for clean water. To fulfil this demand, both surface and groundwater resources in West Java are utilised. The availability of these water resources is abundant, due to high rainfall in most areas of West Java. However, this abundance of water is not properly managed, and has resulted in water shortages in some areas of the province (Rahmat & Wangsaatmadja, 2007). In terms of their quality, most surface and groundwater resources in West Java are polluted by domestic, agricultural and industrial activities, and thus threaten its sustainability.

Sustainability of water resources is essential to ensure that available water can be used by both present and future generations. In the last decade, the provincial government of West Java has implemented various programs to improve the conditions of water resources and their sustainability. However, these programs have not been successful, due to the lack of awareness of the people of West Java on the importance of water resources. In general, people in West Java are not aware that valuable water resources are deteriorating and need to be sustained (Rahmat & Wangsaatmadja, 2007). It is therefore important to obtain a comprehensive understanding on the current status of water resource conditions in West Java. Once this information has been obtained, relevant programs can be designed to improve the quality of water resources. A water sustainability index is a useful tool to address this situation.

A water resource sustainability index offers the following benefits:

- (i) It can be used to identify all factors contributing to the improvement of water resources (Chaves & Alipaz, 2007; Policy Research Initiative, 2007; Sullivan, 2002), so that the resources can be used to fulfil present and future needs.
- (ii) It can be used to assist decision makers to prioritise issues and programs related to water resource management.
- (iii) It can be used to communicate the current status of existing water resources to the wider community (Policy Research Initiative, 2007).

A new water sustainability index, called the West Java Water Sustainability Index (WJWSI), was developed with the involvement of local water stakeholders and based on West Java natural and socio-economic characteristics (Juwana et al., 2010a, 2010b). In the development of WJWSI, uncertainties existed in the following steps: selection of components and indicators, threshold values, weighting scheme and aggregation method. The Delphi method was used to finalise the WJWSI components and indicators, which was expected to remove uncertainties in the selection of components and indicators by having water experts in West Java provide answers to rounds of Delphi questionnaires to finalise the WJWSI components and indicators (Juwana et al., 2010b). The other uncertainties are addressed through uncertainty and sensitivity analysis, which are presented in this paper.

The uncertainty analysis of an index focuses on how the variation in the thresholds might affect respective sub-index and final index values (Ayyub, 2011; Esty et al., 2005; Leach et al., 2013). It also attempts to analyse the uncertainties caused by the

possibilities of applying different weighting schemes and aggregation methods. The sensitivity analysis evaluates the importance of thresholds of indicators and sub-indicators, weighting schemes, and aggregation methods in determining the sub-index and final index values (Clemen & Reilly, 2001; Esty et al., 2005). Together, the uncertainty and sensitivity analysis determine the robustness of the index that has been developed.

The two methods commonly used for uncertainty and sensitivity analysis are the analytical methods and the probabilistic methods. The Delta method is the widely used analytical method (Hayes, 2011). The other analytical methods, such as Rosenblueth's Point Estimation Method (RPEM) and Harr's Point Estimation Method (HPEM), are not widely used as the Delta method (Hayes, 2011). The probabilistic methods aim at analysing uncertainty based on probabilistic occurrences of given input ranges. One of the most popular probabilistic methods is the Monte Carlo simulation, which generates outputs from the ranges of input variables of a model, and then combines these outputs to show the effect of the input variability on the output (Hayes, 2011).

Currently, there is little information available on the uncertainty and sensitivity analysis undertaken on water sustainability indices. Based on a survey of sustainability indices, it was found that there was only one study which had conducted uncertainty and sensitivity analysis, and it was on an Environmental Sustainability Index – ESI (Esty et al., 2005). This index was developed to measure the overall environmental sustainability achievement of countries worldwide (Esty et al., 2005). The ESI aims at providing a logical, systematic and empirical framework to assess environmental sustainability performance within and among countries. It also attempts to identify which environmental issues need higher priority. Uncertainty and sensitivity analysis of ESI was done through Monte Carlo simulations.

This paper discusses the uncertainty and sensitivity analysis of WJWSI, which includes obtaining the distribution functions for the thresholds of each indicator or sub-indicator, conducting the Monte Carlo simulations, aggregating sub-index values using different combinations of weighting schemes and aggregation methods and computing the two measures of uncertainty and sensitivity (coefficient of variation and correlation coefficient, respectively). The Citarum catchment in Indonesia was used as the case study catchment for conducting the uncertainty and sensitivity analysis of WJWSI. The data used for the analysis was from the year 2008.

2. Citarum Catchment in West Java, Indonesia

The Citarum catchment occupies an area of approximately 7,400 km², which can be divided into three parts; upper (1,771 km²), middle (4,242 km²) and lower (1,387 km²). As illustrated in Figure 1, three reservoirs have been built in the catchment, which are used to supply water for various purposes, such as domestic, agriculture, power plant and fishery. Average rainfall over the catchment is 2,300 mm/year, and the flow of the Citarum River, gauged at the inlet of Saguling dam is approximately 5.7 billion m³/year.

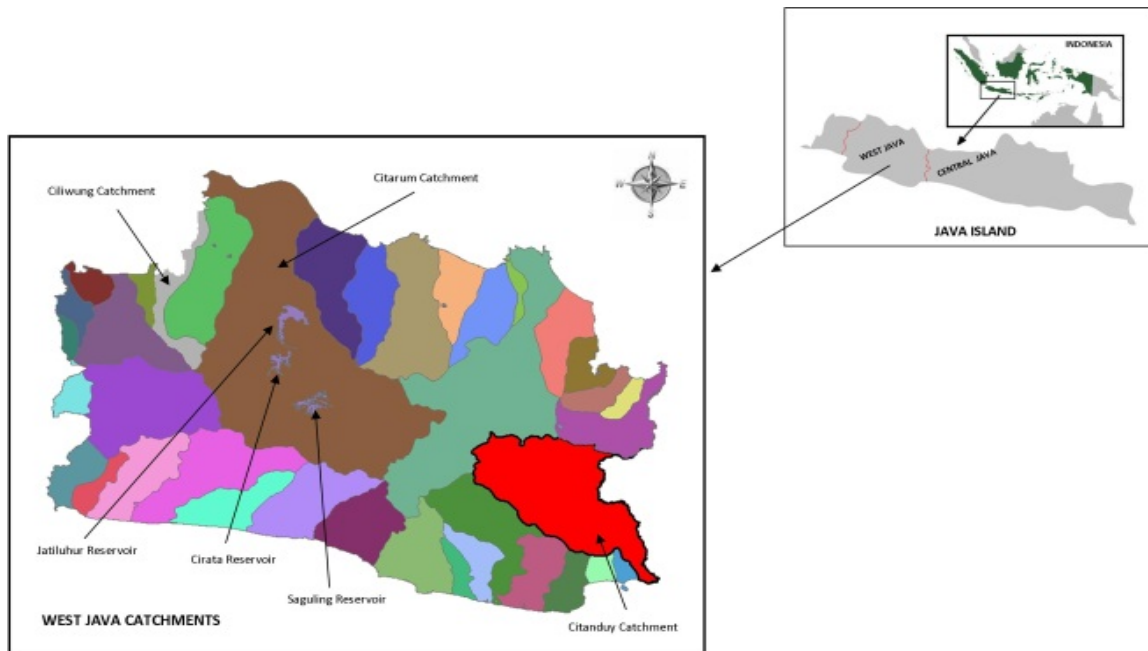


Figure 1.Citarum catchment in West Java

In 2008, the total population within the catchment was just over 11 million. The majority live along the river banks, and have directly used the river for various domestic uses, including drinking water. Pressures on the catchment and its rivers come from pollutants from various activities within the catchment. Pollutants from the domestic sector originate from both direct and indirect discharge of *black water* and *grey water* of households. Hundreds of industries located along the river also pollute the river due to lack of awareness, as well as lack of law enforcement from relevant authorities. In addition, agriculture and livestock have also contributed to river pollution in the catchment.

3. Applying WJWSI to Citarum Catchment

3.1. Framework of WJWSI

The conceptual framework of WJWSI was developed through an extensive literature review on available sustainability criteria, water resource guidelines and existing water sustainability indices, which then was refined through the application of the Delphi technique and an in-depth interview with key stakeholders (Juwana et al., 2010b). The final framework of the WJWSI is shown in Table 1.

Table 1 Final Framework of the West Java Water Sustainability Index

Component	Indicator	Sub-indicator	Thresholds		
			Unit	Max	Min
Conservation	Water Availability		m ³ /cap/yr	1700 ^a	500 ^b
	Land Use Changes		%	100 ^a	0 ^b
	Water Quality		-	0 ^a	-31 ^b
Water Use	Water Demand		%	40 ^b	10 ^a
	Water Service Provision	Coverage	%	80 ^a	0 ^b
		Water Loss	%	30 ^b	15 ^a
Policy and Governance	Information Disclosure		-	100 ^a	0 ^b
	Governance Structure		-	100 ^a	0 ^b
	Public Participation	Education	%	100 ^a	0 ^b
		Poverty	%	20 ^b	0 ^a
		Health Impact	(cases/1000 people)	2 ^b	0 ^a
		Sanitation	%	100 ^a	0 ^b
Law Enforcement		-	100 ^a	0 ^b	

a: preferable; b: not preferable

3.2. Steps in Applying WJWSI

The steps followed in the application of WJWSI to the Citarum catchment are as follows:

(a) Obtaining Sub-indices

The sub-index values were obtained using either the *continuous rescaling* method or the *categorical scale* method. The suitable method was chosen based on the nature of the WJWSI indicators and sub-indicators. Based on the characteristics of the indicators and sub-indicators, three groups were considered (Juwana et al., 2012). The first two groups of indicators and sub-indicators are known as non-categorical indicators and sub-indicators, while the third group is called categorical indicators.

The first group of indicators and sub-indicators are *Water Availability*, *Land Use Changes*, *Water Quality*, *Coverage*, *Education* and *Sanitation*. For this group, the higher the value of the indicator and sub-indicator, the more preferable it is for water sustainability and vice versa.

Indicators and sub-indicators of the second group are *Water Demand*, *Water Loss*, *Poverty* and *Health Impact*. For this group, the smaller the value of the indicator and sub-indicator, the more preferable it is and vice versa.

The third group consists of three indicators, namely *Information Disclosure*, *Governance Structure* and *Law Enforcement*. For these indicators, the categorical scale was used to obtain their sub-indices (Juwana et al., 2012).

(b) Aggregation of Sub-index Values

In the WJWSI, the final index value was obtained by aggregation of sub-index values of indicators and sub-indicators listed in Table 1. The sub-index values at the component level was not computed, as water sustainability issues and measures to improve them are addressed at the level of indicators and sub-indicators. This approach was also used in ESI (Esty et al., 2005).

The two most common methods for aggregation of sub-indices are the arithmetic and geometric methods. The former method has been widely used to aggregate sub-indices of various indices including the existing water sustainability indices of CWSI, WPI and WSI (Chaves & Alipaz, 2007; Policy Research Initiative, 2007; Sullivan, 2002). A survey conducted by Bohringer and Jochem (Böhringer & Jochem, 2007) informs that the arithmetic method is also used by the Ecological Footprint, City Development Index, Human Development Index, Environmental Sustainability Index, Environmental Performance Index, Environmental Vulnerability Index, Index of Sustainable Economic Welfare, Well Being Index, Genuine Savings Index and Environmentally Adjusted Domestic Product. As for the latter method, the geometric method, it is only being used to aggregate sub-indices for Living Planet Index.

In WJWSI, both arithmetic and geometric methods were considered. The preference on which method is more suitable for future use of WJWSI will be determined based on the results of the uncertainty and sensitivity analysis of WJWSI.

(c) Weights for aggregation

Both aggregation methods available in WJWSI (i.e. arithmetic and geometric methods) use weights to aggregate the sub-index values to the final index. Their weights can have either equal or non-equal values. The non-equal weightings for WJWSI were obtained using the Revised Simons procedure (Figueira & Roy, 2002). The detailed implementation of this procedure can be found in Juwana (2012).

(d) Index Interpretation

Index interpretation is important to understand the meaning of the sub-index and aggregated index values. For the WJWSI, the interpretation for sub-indices and their aggregated index will be based on a quartile scale with four levels of *Performance*: Good ($75 \leq \text{value} \leq 100$), Medium-Good ($50 \leq \text{value} < 75$), Poor-Medium ($25 \leq \text{value} < 50$) and Poor ($\text{value} < 25$). The *Performance* reflects the condition of the issue(s) related to an indicator, a sub-indicator, or the overall aggregated index at a particular time of assessment and would be used as the basis for relevant *Priority of Action* to improve the water resource management at the catchment scale. The *Priority of Action* reflects the priority of action to improve the *Performance* of indicators or sub-indicators, which is the opposite of its respective *Performance* (Juwana et al., 2012). If *Performance* of an indicator/sub-indicator is Poor, the *Priority of Action* of the indicator/sub-indicator is High. Conversely, if *Performance* is Good, the *Priority of Action* is low.

3.3. Data Used and Sub-index Values

The main data used for the application of WJWSI are taken from official and reliable sources of Indonesian databases for the year 2008, namely Bureau of Meteorology of Indonesia, West Java Environmental Protection Agency (EPA), Health Department of Indonesia, Regional Forestry Service of West Java, Bureau of Statistics of Indonesia and Association of Water Companies of Indonesia.

After all required data were collected, the sub-index for each indicator and sub-indicator was calculated. The threshold values in Table 1 were used for the calculation of sub-index values for non-categorical indicators and sub-indicators. Then, all sub-indices were aggregated to obtain the final index. The sub-index values of the indicators and sub-indicators, and their respective *Performance* and *Priority of Action* values are presented in Table 2.

. The details for calculating the sub-indices for the 13 indicators and sub-indicators used in the WJWSI can be found in Juwana et al. (2014).

Table 2 WJWSI sub-index values for the Citarum catchment using 2008 data

<i>Indicator/sub-indicator</i>	<i>Unit</i>	<i>Actual Value</i>	<i>Sub-index</i>	<i>Performance</i>	<i>Priority of Action</i>
<i>Water Availability</i>	m ³ /cap/yr	587.32	7.28 ^a	Poor	High
<i>Land Use Changes</i>	%	84.68	84.68 ^a	Good	Low
<i>Water Quality</i>	-	-96.1	0.00 ^a	Poor	High
<i>Water Demand</i>	%	23.04	56.54 ^b	Medium-Good	Medium-Low
<i>Coverage</i>	%	34.96	43.70 ^a	Poor-Medium	High-Medium
<i>Water Loss</i>	%	40.10	0.00 ^b	Poor	High
<i>Information Disclosure</i>	-	-	37.27 ^c	Poor-Medium	High-Medium
<i>Governance Structure</i>	-	-	35.00 ^c	Poor-Medium	High-Medium
<i>Education</i>	%	14.19	14.19 ^a	Poor	High
<i>Poverty</i>	%	15.23	23.87 ^b	Poor	High
<i>Health Impact</i>	(cases/1000 pop)	0.99	50.60 ^b	Medium-Good	Medium-Low
<i>Sanitation</i>	%	61.86	61.86 ^a	Medium-Good	Medium-Low
<i>Law Enforcement</i>	-	-	40.00 ^c	Poor-Medium	High-Medium
Final Index			20.04	Poor	High

a = obtained using Eq. (1); *b* = obtained using Eq. (2); *c* = obtained using Eq. (3)

4. Uncertainty and Sensitivity Analysis for WJWSI

The WJWSI was developed to assist the water authorities in West Java to address the problems of managing their water resources (Juwana et al., 2010a). This water sustainability index, as other indices, cannot capture all conditions for the sustainability of water resources in West Java with full certainty. During its development, uncertainties existed (Juwana et al., 2010b). Thus, it is essential to analyse these uncertainties through uncertainty and sensitivity analysis.

In this paper, the analysis focuses on the non-categorical indicators and sub-indicators. The values of categorical indicators and sub-indicators are kept constant because during this study, there was no uncertainty identified for these indicators and sub-indicators. For the non-categorical indicators and sub-indicators, three sources of uncertainties were identified, namely thresholds values, weighting schemes, and the aggregation methods. The uncertainty of thresholds is due to the range of possibilities for each threshold in WJWSI. The review of existing policies and guidelines has identified different values for thresholds of the majority of non-categorical indicators and sub-indicators (Juwana et al., 2010a). Based on these values, the upper and lower values of respective minimum and maximum thresholds were identified for use in the uncertainty analysis, and are shown in Table 3. For the remaining non-categorical indicators and sub-indicators, $\pm 10\%$ of the base value was used as the upper and lower values for respective minimum and maximum thresholds. The base values are the maximum or minimum threshold for each indicator or sub-indicator, used to obtain the sub-index values of WJWSI indicators and sub-indicators. They were listed in Table 1 and are again presented in Table 3 as ‘Max’ and ‘Min’.

As far as the weighting schemes and aggregation methods are concerned, currently different methods are available for use in WJWSI applications (which become sources of uncertainties as each method might result in different final index values). As discussed earlier, the two weighting schemes available for WJWSI are the equal and non-equal weight schemes, whereas the two aggregation methods available are the arithmetic and geometric methods.

Table 3 Upper and lower values of thresholds of non-categorical indicators and sub-indicators

Indicator/Sub-indicator	Unit	Thresholds of Indicators and Sub-indicators			
		Max	Upper/Lower Values	Min	Upper/Lower Values
Water Availability	m ³ /cap/yr	1700 ^a	1300 - 1800	500 ^b	500 - 600
Land Use Changes	%	100 ^a	80 - 100	0 ^b	+10%
Water Quality	-	0 ^a	- 10%	-31 ^b	+ 10%
Water Demand	%	40 ^b	$\pm 10\%$	10 ^a	0 – 10%
Coverage	%	80 ^a	$\pm 10\%$	0 ^b	+10%
Water Loss	%	30 ^b	25 – 30	15 ^a	0 - 15
Education	%	100 ^a	-10%	0 ^b	0 – 20%
Poverty	%	20 ^b	15 - 25	0 ^a	+10%
Health Impact	(cases/1000 population)	2 ^b	$\pm 10\%$	0 ^a	+10%
Sanitation	%	100 ^a	- 10%	0 ^b	0 – 20%

a: preferable; b: not preferable

These uncertainties were then analysed based on the MC simulations. The simulation was performed using @Risk software from Palisade Corporation (Clemen & Reilly, 2001). The MC simulation sampled various values of the maximum and minimum thresholds of WJWSI indicators and sub-indicators, and calculated their respective sub-index values. These sub-index values were then computed to obtain the final index values using different combination of weighting schemes and aggregation methods to produce the final index values.

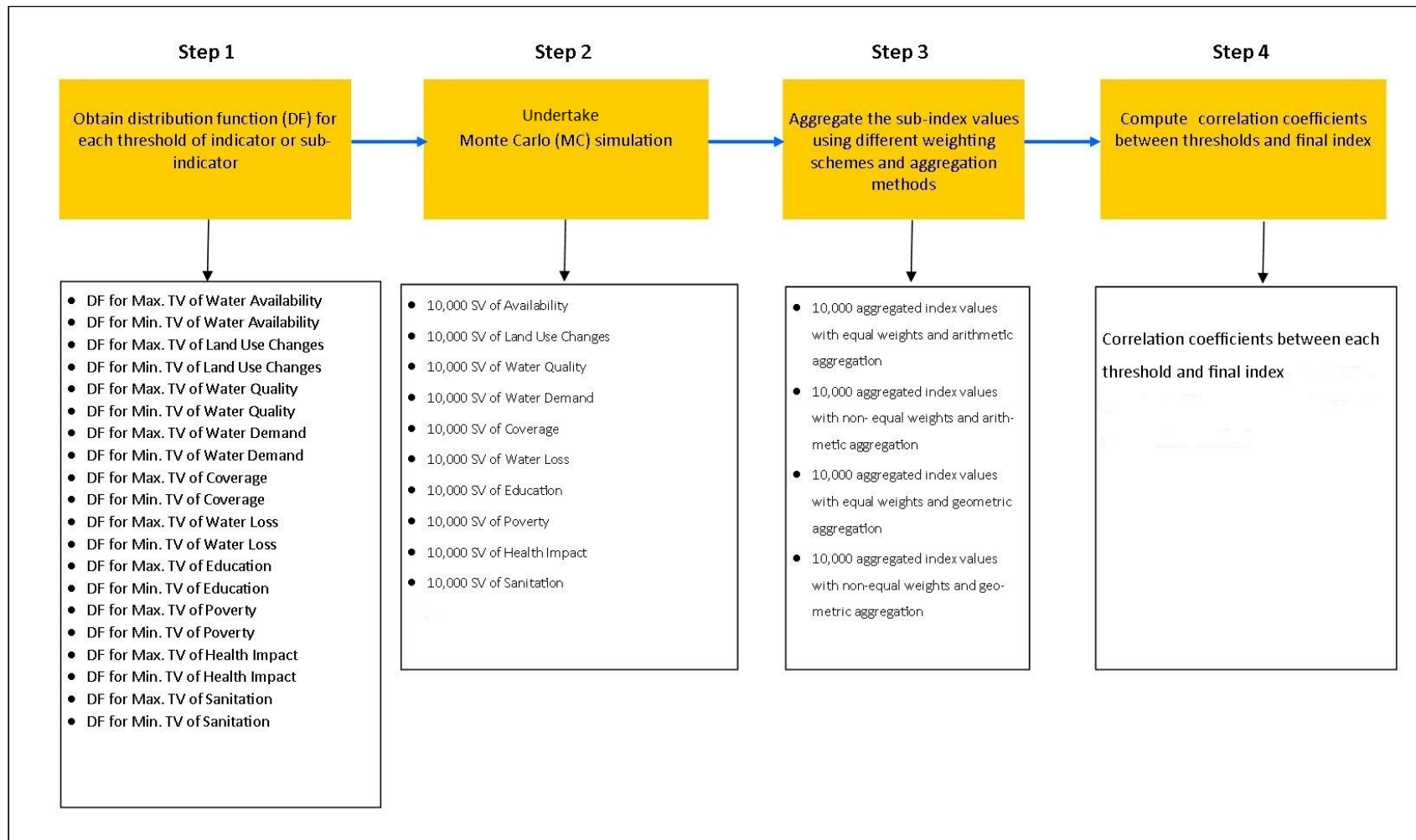
The sensitivity analysis of the WJWSI was undertaken to answer the following questions:

- Which indicators were the most sensitive to the changes in their threshold values?
- Which indicators were the most important in determining the final index value?
- Which of the weighting schemes or aggregation methods was the most important in determining the final index value?

4.1. Steps of Uncertainty and Sensitivity Analysis of WJWSI

As indicated earlier, the uncertainty and sensitivity analysis was conducted using four steps. Figure 2 presents the four major steps undertaken in this study for conducting the uncertainty and sensitivity analysis of WJWSI.

The first step (Step 1 in Figure 2) is to obtain the distribution functions for the thresholds of each indicator or sub-indicator. For each of WJWSI indicators and sub-indicators, only the upper, base and lower values for category boundaries are available, because of which a triangular distribution function was considered to be the most suitable distribution function. The triangular distribution has been used by Schuhmacher (2001), Kawai & Teixeira (2011), Dawood et al.(2012), Kim et al. (2012), Sinija& Mishra (2011), Schien et al. (2015), Mauelshagen et al.(2014), Rojas-Rueda et al. (2011), Tait et al. (2012) and Lee et al. (2013)for conducting uncertainty and sensitivity analysis in their respective studies.



DF - Distribution Function; TV – Threshold Value; SV – Sub-index Value

Figure 2 Steps for uncertainty and sensitivity analysis of WJWSI

The triangular distribution function requires three input values, i.e. minimum, most likely and maximum values (Kroese et al., 2011). As an example, the triangular distribution that was used for defining the maximum threshold of *Water Availability* is shown in Figure 3, using the upper, base and lower values of 1800, 1700 and 1300 m³/cap/year respectively (which are extracted from Table 4). This figure also shows the statistics of 10,000 samplings from the distribution, which were used in the MC simulation. Using 95% confidence intervals, Figure 3 shows that the mean, lower and upper confidence limits of this threshold are 1,600, 1370.7 and 1,764.6 m³/cap/year respectively.

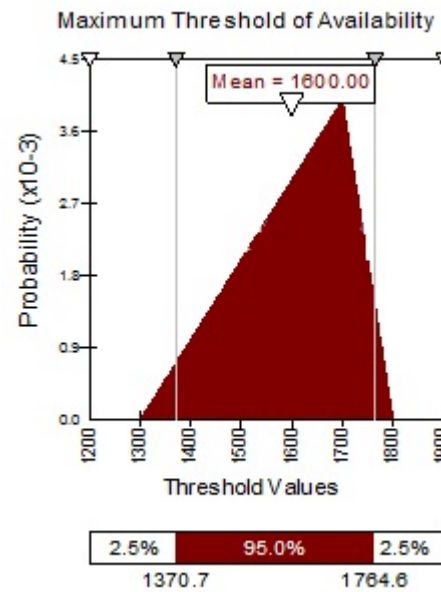


Figure 3 Distribution function for *Water Availability*

After the distribution functions of all the indicators and sub-indicators were obtained, they were used in Step 2 (of conducting MC simulations). In this step, 10,000 sampling points were used for each indicator and sub-indicator. Each sampling point consists of minimum and maximum thresholds of the indicators and sub-indicators. The 10,000 sub-index values of indicators and sub-indicators thus obtained were used to identify their *Performance*, and to evaluate the changes of the *Performances* against their original (or base) *Performances* (based on the base values of these thresholds).

In Step 3, the 10,000 sub-index values of indicators and sub-indicators (from the MC simulations in Step 2) were aggregated using different combinations of weighting schemes and aggregation methods. Thus, the final index values were calculated based on the following combinations:

1. Equal weighting – arithmetic aggregation
2. Equal weighting – geometric aggregation
3. Non-equal weighting - arithmetic aggregation
4. Non-equal weighting - geometric aggregation

Each combination was calculated using the 10,000 sub-index values of indicators/sub-indicators obtained from the MC simulation.

Finally, Step 4 calculates correlation coefficients between thresholds of each indicator or sub-indicator and the final index value, using the SPSS software. To calculate correlation coefficients, 10,000 data of each threshold from the MC simulation, and the corresponding 10,000 final index values from Step 3 were used. These correlation coefficients were also used to evaluate which thresholds were more sensitive to the final

index value. The use of correlation coefficient in the uncertainty and sensitivity analysis has been done previously, such as by Schoups & Vrugt (2010) and Briggs et al. (2012).

4.2. Results

As described earlier, the uncertainty and sensitivity analysis of the WJWSI was conducted based on data from 2008. The results of the uncertainty and sensitivity analysis of the Citarum catchment are presented in Tables 5, 6 and 7.

To analyse the uncertainties, the coefficient of variation (CV) of the thresholds of indicators/sub-indicators and percentage of unchanged performance of the 10,000 sub-index values were used. The CV is the ratio of the standard deviation to the mean value. It indicates the variability of the data compared to the mean of the population (Field, 2005). In this study, the CV is used to analyse the variability of thresholds of the indicators with respect to their mean values. Higher variability of the threshold indicates higher uncertainty for the respective threshold. Data in columns 4, 5 and 6 in Table 4 were obtained from the results of MC simulation on thresholds. For each threshold, the mean, standard deviation and CV of 10,000 data generated from its distribution function were computed. This table shows that higher CV values belong to the minimum thresholds of *Land Use Changes, Coverage, Education, Poverty, Health Impact and Sanitation*, and the maximum threshold of *Water Quality* (which are shaded grey in Table 4). This implies that the upper and lower values of these thresholds have resulted in their higher variation as compared to the other thresholds, which indicates higher uncertainties.

The results of the MC simulation, presented in Table 4, are also used to analyse the sensitivity of the sub-index and final index values to the changes in the thresholds. The sensitivity of the sub-index values of the indicators is analysed by comparing the CV of the sub-index values (column 8 of Table 4) with their respective CV of threshold values (column 6 of Table 4). The sensitivity of the sub-index values of the indicators was also done by analysing the changes in their *Performances*.

For most indicators and sub-indicators, the differences in CV of their maximum and minimum thresholds compensate each other in producing the sub-index values, as reflected in their coefficients of variation (e.g. *Poverty, Education and Land Use Change*). For example, the coefficients of variation for maximum and minimum thresholds for the *Poverty* indicator (0.10 and 0.70 respectively) compensate each other to produce the coefficient variation of 0.35 for *Poverty*.

The above pattern does not apply to *Water Availability, Water Quality and Water Loss*. Low values of coefficients of variation of maximum and minimum thresholds for *Water Availability* (0.07 and 0.05 respectively) have resulted in a higher sub-index CV (0.44). This indicates that changes in the thresholds of *Water Availability* will have higher effects on their sub-index value, compared to changes in the thresholds of other indicators. The CV values for sub-indices of *Water Quality* and *Water Loss* cannot be computed because their sub-index values were 0 (zero) throughout the analysis.

Table 4 Results of uncertainty and sensitivity analysis of WJWSI for the Citarum catchment

1	2	3	4	5	6	7	8			9
Thresholds/Boundary Values	Unit	Base Value	Mean	Std. Deviation	Coefficient of Variation	Indicators/Sub-Indicators	Sub-index values			Change in Performance (%)
							Mean (Original Values)	Standard Deviation	Coefficient of Variation	
<i>Water Availability – Maximum</i>	m ³ /cap/yr	1,700	1,599.8	108.50	0.07	<i>Water Availability</i>	5.09 (7.28)	2.24	0.44	0
<i>Water Availability – Minimum</i>	m ³ /cap/yr	500	533.2	23.80	0.05					
<i>Land Use Changes – Maximum</i>	%	100	93.3	4.69	0.05	<i>Land Use Change</i>	90.53 (84.68)	4.66	0.05	0
<i>Land Use Changes – Minimum</i>	%	0	3.4	2.36	0.70					
<i>Water Quality – Maximum</i>	-	0	-1.0	0.72	0.71	<i>Water Quality</i>	0.00 (0.00)	0.00	-	0
<i>Water Quality – Minimum</i>	-	-31	-30.0	0.73	0.02					
<i>Water Demand – Maximum</i>	%	40	40.0	1.64	0.04	<i>Water Demand</i>	50.94 (56.54)	4.29	0.08	40.03
<i>Water Demand – Minimum</i>	%	10	6.6	2.39	0.36					
<i>Coverage – Maximum</i>	%	80	80.0	3.23	0.04	<i>Coverage</i>	41.81 (43.70)	2.26	0.05	0
<i>Coverage – Minimum</i>	%	0	2.6	1.87	0.71					
<i>Water Loss – Maximum</i>	%	30	28.3	1.18	0.04	<i>Water Loss</i>	0.00 (0.00)	0.00	-	0
<i>Water Loss – Minimum</i>	%	15	10.0	3.52	0.35					
<i>Education – Maximum</i>	%	100	96.7	2.35	0.02	<i>Education</i>	8.41 (14.19)	4.52	0.54	0
<i>Education – Minimum</i>	%	0	6.6	4.66	0.71					
<i>Poverty – Maximum</i>	%	20	20.0	2.04	0.10	<i>Poverty</i>	23.85 (23.87)	8.23	0.35	0
<i>Poverty – Minimum</i>	%	0	0.7	0.47	0.70					
<i>Health Impact – Maximum</i>	(cases/1000 pop)	2	2.0	0.08	0.04	<i>Health Impact</i>	52.29 (50.60)	2.39	0.05	17.26
<i>Health Impact – Minimum</i>	(cases/1000 pop)	0	0.1	0.05	0.70					
<i>Sanitation – Maximum</i>	%	100	96.7	2.37	0.02	<i>Sanitation</i>	61.23 (61.86)	2.68	0.04	0
<i>Sanitation – Minimum</i>	%	0	6.7	4.74	0.71					

The sensitivity of the sub-index of the indicators can also be analysed through their *Performance*. The *Performance* reflects the condition of issue(s) related to an indicator or sub-indicator, which was obtained based on the sub-index value of an indicator or sub-indicator. This *Performance* will be used by water authorities to analyse the condition of water-related issues in West Java. If the MC simulation results in a change in the *Performance* of the indicator when compared to its original *Performance*, it indicates presence of uncertainty in the respective indicator. The percentage of unchanged performance was obtained by comparing 10,000 *Performances* obtained from outputs of the MC simulation with the original *Performances* of indicators and sub-indicators shown in Table 2. The original *Performance* was calculated based on the most likely values for respective indicators (shown in Table 3 under ‘Max’ and ‘Min’ values).

Table 4 (column 9) presents the change in performance of 10,000 *Performances* of each indicator or sub-indicator obtained from the MC simulation with respect to its original performance. According to Esty (2005), if the changes in performance is less than 10%, then the uncertainties are considered insignificant. From Table 4 (column 9), it can be seen that performances has not changed for most of the indicators and sub-indicators, except for *Water Demand* and *Health Impact*. The performances of *Water Demand* and *Health Impact* indicators have changed 4,003 times (40.03%) and 1,726 times (17.26%) during the MC simulation from Medium-Good to Medium-Poor respectively, as their original sub-index values were close to the *Performance* boundary. Thus, even though the performances of these two indicators have changed significantly during the simulation, it cannot be used to conclude that these two indicators are sensitive.

The sensitivity analysis of the WJWSI was also undertaken, based on the correlation coefficients of the thresholds of the indicators and the final index value. The correlation was based on the Spearman correlation method(Field, 2005), with the two-tailed probability value for its significance. These correlation coefficients between the thresholds and the final index value are presented in Table 5. This table shows that the maximum threshold of *Poverty* has produced the highest correlation coefficient (0.520), while the minimum threshold of *Water Quality* produced the lowest correlation (0.004). The correlation coefficient should lie between the values of -1 and 1. A perfect negative or positive correlation is indicated by a value of -1 or 1, respectively. A correlation coefficient value of 0 represents no correlation between the variables (Caldwell, 2010; Lind et al., 2000). Further interpretations of correlation coefficients are provided by different authors. Lind et al. (2000) consider correlation coefficients as strong (>0.67), moderate (between 0.33 and 0.67) and weak (<0.33). Caldwell (2010) interprets correlation coefficients as no correlation (0 - 0.2), weak (0.2 - 0.4), moderate (0.4 - 0.6), strong (0.6 - 0.8) and very strong (0.8 - 1).

According to the above interpretations, only the maximum threshold of *Poverty* has a significant effect on the final index (or is the most sensitive), compared to changes in the other thresholds. The positive correlation of the *Poverty* indicator implies that the increase in its maximum threshold will produce an increase in the value of the final index.

Table 5 Correlation coefficients between the final index and the thresholds

No	Thresholds of Indicators and Sub-indicators	Correlation Coefficient
1	Water Availability / Maximum Threshold	-0.049*
2	Water Availability / Minimum Threshold	-0.111*
3	Land Use Changes / Maximum Threshold	-0.254*
4	Land Use Changes / Minimum Threshold	-0.015
5	Water Quality / Maximum Threshold	0.004
6	Water Quality / Minimum Threshold	-0.014
7	Water Demand / Maximum Threshold	0.132*
8	Water Demand / Minimum Threshold	0.199*
9	Coverage / Maximum Threshold	-0.101*
10	Coverage / Minimum Threshold	-0.074*
11	Water Loss / Maximum Threshold	0.023
12	Water Loss / Minimum Threshold	-0.011
13	Education / Maximum Threshold	-0.005
14	Education / Minimum Threshold	-0.265*
15	Poverty / Maximum Threshold	0.520*
16	Poverty / Minimum Threshold	0.043*
17	Health / Maximum Threshold	0.107*
18	Health / Minimum Threshold	0.069*
19	Sanitation / Maximum Threshold	-0.082*
20	Sanitation / Minimum Threshold	-0.136*

* Significant, based on the two-tailed probability value (p value < 0.05)

As mentioned earlier, the sensitivity analysis in this study also aims to answer the question regarding which of the weighting schemes and aggregation methods was the most important in determining the final index value. To answer this question, different combinations of weighting schemes and aggregation methods were considered. As mentioned earlier, 10,000 sub-index values corresponding to each indicator/sub-indicator obtained from the MC simulation were used to compute final index values. The mean of the 10,000 final index values obtained from these computations are presented in Table 6.

Table 6 Final index values based on combination of different weighting schemes and aggregation methods

Combination	Arithmetic	Geometric	Changes
Equal weights	34.67	19.00	15.67
Non-equal weights	30.97	20.52	10.45
Changes	3.7	1.52	

From Table 6, it can be seen that a change from equal to non-equal weights resulted in a change in the final index value of 3.7 and 1.52 for arithmetic and geometric aggregation methods respectively. On the other hand, a change from arithmetic to geometric aggregation methods resulted in a change in the final index value of 15.67 and 10.45 for equal and non-equal weighting schemes respectively. Based on these

results, it can be concluded that the final index value of WJWSI is more sensitive to changes in the aggregation method, rather than to the changes in the weighting scheme. Hence, for future uses of the WJWSI, either equal or non-equal weighting scheme can be used, as it will not have a significant impact on the final index.

The aggregation method recommended for the WJWSI is the geometric method (which is used by multiplying the weighted sub-index values). With the geometric method, substitutability and compensability among the sub-index values of the indicators does not occur, which means that low values of some sub-indices are not compensated with high values of other sub-indices. For example, two cases with significant differences in their sub-indices will have different aggregated index values, even if their weighted average sub-index values are identical. Poor indicator performances, shown by the low sub-index values, will be reflected in the aggregated index value. In contrast, when the arithmetic aggregation method is used, poor performances of a few indicators will not be reflected in the aggregated index value if other indicators perform well. Hence, with this aggregation method, perfect substitutability and compensability among all sub-indices occur. Since the differences of sub-index values among WJWSI indicators are important, they are better reflected in the final index obtained with the geometric aggregation method than with the arithmetic method (Böhringer & Jochem, 2007).

5. Summary and Conclusions

Developing an index involves different steps, many of which include uncertainties. The West Java Water Sustainability Index (WJWSI) was recently developed and three sources of uncertainties were identified during that stage, namely the thresholds of non-categorical indicators and sub-indicators, the weighting schemes and the aggregation methods. To assist the water authorities in West Java (or other users of WJWSI) in their better use of the index, these uncertainties need to be taken into account when applying the index. Therefore, the uncertainty and sensitivity analysis of WJWSI conducted in this study is important towards minimising the identified uncertainties. This paper analyses the uncertainties based on its application to one of the biggest catchments in West Java, the Citarum catchment, for the year 2008.

The results of the uncertainty analysis of the thresholds of WJWSI indicators, shown by their coefficient of variation from 10,000 Monte Carlo simulations, indicate that the minimum thresholds of *Land Use Changes*, *Coverage*, *Education*, *Poverty*, *Health Impact* and *Sanitation*, and the maximum threshold of *Water Quality* have higher variation as compared to the other thresholds. Thus, it can be concluded that these thresholds have higher uncertainties associated with them.

The sensitivity analysis also showed that changes in the thresholds of WJWSI indicators have not significantly affected the sub-index values of most indicators and sub-indicators. The only exception to this is the *Water Availability* indicator, whose sub-index value changed significantly by the changes in its thresholds. As a consequence, if water authorities in the Citarum catchment preferred to use different threshold values for this indicator, they need to be aware of the possible significant changes in the sub-index value of the indicator.

The sensitivity analysis in this study also showed that only the maximum threshold of *Poverty* had statistically significant correlation with the final index. Hence, it can be concluded that for this sub-indicator, changes in its thresholds will significantly change the final index. However, for other indicators and sub-indicators, changes in their thresholds will have a low impact on the final index value as the correlation was low. Due to the significant changes either in the sub-index values or the final index value, it is recommended that the water authorities in West Java obtain more catchment-specific values for the thresholds of *Water Availability* and *Poverty* indicators. Such values for the thresholds of these indicators are expected to provide more certainty to their sub index values and to the final index.

As far as the uncertainty associated with the weighting scheme is concerned, the sensitivity analysis concluded that either equal or non-equal weighting scheme can be used for future use of WJWSI, since changes from equal to non-equal weighting scheme did not significantly affect the final index. However, it was found that the final index values were sensitive to the aggregation methods (i.e. arithmetic and geometric methods), shown by the significant changes in the value of the final index when the aggregation methods were changed from arithmetic to geometric.

The uncertainty and sensitivity analysis presented in this study will provide the water authorities and users of WJWSI with useful information on how to effectively apply the WJWSI. This includes the use of appropriate thresholds of the indicators and sub-indicators, weighting scheme and aggregation method. There is little information available in literature on the use of uncertainty and sensitivity analysis in water sustainability indices. Hence, the methods used in this study can also be used for uncertainty and sensitivity analysis of other sustainability indices.

References

- Aven, T., & Nøkland, T. E. (2010). On the use of uncertainty importance measures in reliability and risk analysis. *Reliability Engineering & System Safety*, 95(2), 127-133. doi: <http://dx.doi.org/10.1016/j.res.2009.09.002>
- Ayyub, B. M. (2011). *Vulnerability, uncertainty, and risk analysis, modeling and management : proceedings of the First International Conference on Vulnerability and Risk Analysis and Management (ICVRAM 2011) and the Fifth International Symposium on Uncertainty Modeling and Analysis (ISUMA 2011) : April 11-13, 2011, Hyattsville, Maryland*. Reston, Va. : American Society of Civil Engineers.
- Böhringer, C., & Jochem, P. E. P. (2007). Measuring the immeasurable — A survey of sustainability indices. *Ecological Economics*, 63(1), 1-8. doi: <http://dx.doi.org/10.1016/j.ecolecon.2007.03.008>
- BPS Team. (2009). Annual BPS report: poverty. Bandung: Badan Pusat Statistika Jawa Barat.
- Briggs, A. H., Weinstein, M. C., Fenwick, E. A. L., Karnon, J., Sculpher, M. J., & Paltiel, A. D. (2012). Model Parameter Estimation and Uncertainty: A Report of the ISPOR-SMDM Modeling Good Research Practices Task Force-6. *Value in Health*, 15(6), 835-842. doi: <http://dx.doi.org/10.1016/j.jval.2012.04.014>
- Caldwell, S. (2010). *Statistics unplugged* (3rd ed.). Belmont, California: Wadsworth Cengage Learning.

- Chaves, H., & Alipaz, S. (2007). An integrated indicator based on basin hydrology, environment, life, and policy: the Watershed Sustainability Index. *Water Resources Management*, 21(5), 883-895.
- Clemen, R., & Reilly, T. (2001). *Making hard decisions with decision tools*. Pacific Grove, California Duxbury Press.
- Cude, C. G. (2001). Oregon water quality index: a tool for evaluating water quality management effectiveness. *Journal of the American Water Resources Association*, 37(1), 125-138.
- Dawood, F. S., Iuliano, A. D., Reed, C., Meltzer, M. I., Shay, D. K., Cheng, P.-Y., . . . Widdowson, M.-A. (2012). Estimated global mortality associated with the first 12 months of 2009 pandemic influenza A H1N1 virus circulation: a modelling study. *The Lancet Infectious Diseases*, 12(9), 687-695. doi: [http://dx.doi.org/10.1016/S1473-3099\(12\)70121-4](http://dx.doi.org/10.1016/S1473-3099(12)70121-4)
- Esty, D. C., Levy, M., Srebotnjak, T., & de Sherbinin, A. (2005). Environmental sustainability index: benchmarking national environmental stewardship (pp. 102). New Haven, Connecticut: Yale University.
- Falkenmark, M., & Rockström, J. (2004). *Balancing water for humans and nature: the new approach in ecohydrology*. London: Earthscan.
- Field, A. (2005). *Discovering statistics using SPSS* (3rd ed., pp. 821). London: SAGE Publications.
- Figueira, J., & Roy, B. (2002). Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. *European Journal of Operational Research*, 139(2), 317-326.
- Hayes, K. (2011). Uncertainty and uncertainty analysis methods. *Australian Centre of Excellence for Risk Assessment (ACERA) project A*, 705.
- Indonesian Ministry of Environment. (2003). Guidelines for water quality assessment. Retrieved 19 March, 2014, from http://www.google.com.au/url?sa=t&source=web&cd=1&ved=0CBgQFjAA&url=http%3A%2F%2Fhelpingpeopleideas.com%2Fpublichealth%2Fsearch%2Fkputusan-menteri-lingkungan-hidup-tentang-standar-baku-mutu-air%2F&ei=gdzlTdLXE4bwrQfykYSZCA&usq=AFQjCNHsCYNyR82U5JIJ1BLIr6UKz_ftXQ
- Juwana, I. (2012). *Development of a Water Sustainability Index for West Java, Indonesia*. Victoria University, Australia.
- Juwana, I., Muttill, N., & Perera, B. (2012). Indicator-based water sustainability assessment—A review. *Science of the Total Environment*, 438, 357-371.
- Juwana, I., Muttill, N., & Perera, B. (2014). Application of West Java water sustainability index to Citarum catchment in West Java, Indonesia. *Water Science & Technology: Water Supply*, 14(6), 1150-1159.
- Juwana, I., Perera, B., & Muttill, N. (2010a). A water sustainability index for West Java - Part 1: developing the conceptual framework. *Water Science and Technology: A journal of the International Association on Water Pollution Research*, 62(7), 1629-1640.
- Juwana, I., Perera, B., & Muttill, N. (2010b). A water sustainability index for West Java - Part 2: refining the conceptual framework using Delphi technique. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, 62(7), 1641-1652.
- Kawai, H., & Teixeira, J. (2011). Probability Density Functions of Liquid Water Path and Total Water Content of Marine Boundary Layer Clouds: Implications for

- Cloud Parameterization. *Journal of Climate*, 25(6), 2162-2177. doi: 10.1175/JCLI-D-11-00117.1
- Kim, S. C., Kim, H. M., & Chien, S. I. (2012). Threshold Variation Based on Triangular Probability Density Function for Error Diffusion Halftoning. *Advanced Materials Research*, 462, 676-683.
- Kroese, D. P., Taimre, T., & Botev, Z. I. (2011). *Handbook of Monte Carlo Methods* (Vol. 706): John Wiley & Sons.
- Leach, D., Hagger-Johnson, G., Doerner, N., Wall, T., Turner, N., Dawson, J., & Grote, G. (2013). Developing a measure of work uncertainty. *Journal of Occupational & Organizational Psychology*, 86(1), 85-99. doi: 10.1111/joop.12000
- Lee, J., Kim, E.-S., Roh, B.-S., Eom, S.-W., & Zoh, K.-D. (2013). Occurrence of disinfection by-products in tap water distribution systems and their associated health risk. *Environmental Monitoring and Assessment*, 185(9), 7675-7691.
- Lind, D. A., Marchal, W. G., & Mason, R. D. (2000). *Basic statistics for business and economics* (3rd ed.). Boston, Boston: Irwin/McGraw-Hill.
- Mauelshagen, C., Pollard, S., Owen, D., Herndlhofer, S., Firth, P., McKenna, J., . . . Jensen, P. (2014). Protecting asset value and driving performance with a dynamic, risk-based contingency fund. *Environment Systems and Decisions*, 34(3), 417-424.
- MDG Indonesia Team. (2007). Achievement of Millenium Development Goals Indonesia Jakarta: National Planning and Development Board.
- Policy Research Initiative. (2007). Canadian Water Sustainability Index. Retrieved 5 July 2007, from http://policyresearch.gc.ca/doclib/SD_PR_CWSI_web_e.pdf
- Rahmat, A., & Wangsaatmadja, S. (2007). Laporan status lingkungan hidup tahun 2007 (Annual state of environmental report 2007) (pp. 60). Bandung, Indonesia: BPLHD Jawa Barat.
- Rojas-Rueda, D., de Nazelle, A., Tainio, M., & Nieuwenhuijsen, M. J. (2011). The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. *BMJ*, 343.
- Schien, D., Coroama, V. C., Hilty, L. M., & Preist, C. (2015). The energy intensity of the Internet: edge and core networks *ICT Innovations for Sustainability* (pp. 157-170): Springer.
- Schoups, G., & Vrugt, J. A. (2010). A formal likelihood function for parameter and predictive inference of hydrologic models with correlated, heteroscedastic, and non-Gaussian errors. *Water Resources Research*, 46(10), W10531. doi: 10.1029/2009WR008933
- Schuhmacher, M., Meneses, M., Xifró, A., & Domingo, J. L. (2001). The use of Monte-Carlo simulation techniques for risk assessment: study of a municipal waste incinerator. *Chemosphere*, 43(4-7), 787-799. doi: [http://dx.doi.org/10.1016/S0045-6535\(00\)00435-5](http://dx.doi.org/10.1016/S0045-6535(00)00435-5)
- Sholichin, M., Othman, F., & Limantara, L. M. (2010). Use of PI and Storet Methods to Evaluate Water Quality Status of Brantas River. *Journal of Mathematics & Technology*, 3(1), 116-124.
- Sinija, V., & Mishra, H. (2011). Fuzzy analysis of sensory data for quality evaluation and ranking of instant green tea powder and granules. *Food and bioprocess technology*, 4(3), 408-416.
- Sullivan, C. (2002). Calculating a Water Poverty Index. *World Development*, 30(7), 1195-1210.

Tait, P., Baskaran, R., Cullen, R., & Bicknell, K. (2012). Nonmarket valuation of water quality: Addressing spatially heterogeneous preferences using GIS and a random parameter logit model. *Ecological Economics*, 75(0), 15-21. doi: <http://dx.doi.org/10.1016/j.ecolecon.2011.12.009>