Development of a Cost Effective River Water Quality Index: A Case Study of West Java Province, Indonesia

By
Arief Dhany Sutadian, (BSc, M.Eng)

Thesis submitted in fulfilment of the requirement for the degree of

Doctor of Philosophy

College of Engineering and Science, Victoria University, Australia

March 2017

Abstract

Having good water quality is important for a healthy river. However, it is difficult to quantify the state of river water quality due to the large choice of possible water quality parameters used to describe it. On the other hand, insufficient funding, particularly in developing countries, is one of the most common constraints towards monitoring all water quality parameters of a river as it is laborious and expensive. Given these facts, Water Quality Indices (WQIs) have been one of the most commonly used approaches across the world in evaluating river water quality effectively. A WQI is a useful tool to define the state of water quality in a body of water which can be used for decision making and operational management by the water authorities. It can also be used to compare the water quality of rivers spatially and temporarily, and to provide water quality status reports to policy makers and the public in a simple and an understandable manner.

Several WQIs have been developed by different agencies and researchers with the aim to establish their own indices or improve the existing indices. However, no single WQI has been globally accepted. In West Java and other provinces in Indonesia, the use of WQIs were introduced in the early 1990s.

The Ministry of Environment (MoE) of Indonesia adopted the Storet Index and the Water Pollution Index (WPI) for use in Indonesian rivers. However both these indices had been developed based on the information on specific regions and areas without considering the local conditions of West Java, such as appropriate parameters in the index which suit West Java conditions and parameter weights that consider West Java stakeholder opinion. Therefore, at a particular monitoring station, many parameters have been monitored, which has led to increased monitoring cost in the field and increased cost in the use of WQIs. Therefore, this study aims at developing a new WQI for use in the rivers in the West Java Province, called the West Java Water Quality Index (WJWQI), that is specifically developed to address the limitations of the currently used indices, namely the inability to make accurate comparisons of the general status of water quality in West Java rivers, the inability to make these comparisons in a cost effective manner, and the lack of credibility and acceptability of the currently used indices by relevant authorities in West Java (since the local conditions and local expert opinion have not been considered in the development of the currently used indices). The development of the WJWQI involved four steps, which are selection of parameters, obtaining sub-index values

(transformation to a common scale), establishing weights, and aggregation of sub-indices to produce the final index.

The following issues associated with the development of WJWQI were addressed in this study:

1) A new methodology for the selection of parameters based on the statistical assessment for parameter redundancy and the inclusion of three factors that represented criticality for cost effective water quality monitoring. This reduced the number of water quality parameters to be measured, which in turn reduced the cost of monitoring and the cost of using WJWQI.
2) The involvement of local experts' opinion in identifying parameter weights, and
3) Uncertainty and sensitivity analysis to determine the robustness of WJWQI. Accordingly, these improvements increased the credibility and acceptability of WJWQI to be used by relevant authorities in West Java.

The results of the application of WJWQI in West Java rivers provided information on the current conditions of water quality in these rivers in a more cost effective way, and provided a comparison of the general status of water quality in these rivers. The latter was possible, since WJWQI considered a common set of parameters (which is representative of all aspects of water quality in the rivers), and hence these common parameters are able to be monitored for all West Java rivers. This information obtained from WJWQI can be used by relevant authorities to design appropriate programs to improve their management of water quality for rivers in West Java.

The WJWQI can be used to replace the currently used WQIs in West Java, since it has addressed the limitations of the currently used WQIs in West Java. This index with some modifications, can also be applied to rivers in other provinces of Indonesia and worldwide.

Declaration

"I, Arief Dhany Sutadian, declare that the PhD thesis entitled 'Development of a Cost-Effective River Water Quality Index: A Case Study of West Java Province, Indonesia is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature: [redacted]

Date : 31 March 2017

Details of included papers

Chapter No.	Paper Title Publication	Status Publication	Year	Volume	Pages	Publication title	Impact Factor	ERA Rank 2010	Scimago Rank/H Index
2	Development of river water quality indices—a review	Published	2016	188:58	1-29	Environmental Monitoring and Assessment	1.633	B	Q2/66
3	Use of exploratory data analysis for cost effective monitoring of water quality data.	Published	2015	N/A	1147-1154	36th Hydrology and Water Resources Symposium (HWRS), Hobart, Tasmania	NA	B	N/A
	Parameter Selection for Cost Effective Water Quality Monitoring – Part I: Developing the Methodology	Submitted	N/A	N/A	N/A	Journal of Environmental Management	3.131	N/A	Q1/104
	Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java, Indonesia”	Submitted	N/A	N/A	N/A	Journal of Environmental Management	3.131	N/A	Q1/104

Chapter No.	Paper Title Publication	Status Publication	Year	Volume	Pages	Publication title	Impact Factor	ERA Rank 2010	Scimago Rank/H Index
4	Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index	Published	2016	75	220-233	Ecological Indicators	3.190	NA	Q1/63
5	Development of Water Quality Index for rivers in West Java Province, Indonesia	Submitted	2017	N/A	N/A	Ecological Indicators	3.190	NA	Q1/63

Declaration by Arief Dhany Sutadian Signature : [redacted] Date: 31 March 2017

Acknowledgments

In the Name of Allah, the Most Compassionate, the Most Merciful.

I would like to take this opportunity to thank the many outstanding people who contributed to the completion of this long journey. First and utmost, I am highly grateful to my principal supervisor, Dr. Nitin Muttil for his patience and thoughtful guidance during my PhD journey. All the valuable comments and suggestions provided by him have been of great worth for me. Without his help, it would have been impossible for me to write successfully all journal articles on which this thesis is based. Also I am highly grateful to the associate supervisors of mine, Professor Chris Perera for all his valuable inputs, advice, and guidance during my PhD journey, and Dr. Abdullah G. Yilmaz for his constructive comments and suggestions, particularly in the beginning of this PhD journey.

I am grateful to all my colleagues in my home country for kind assistances in obtaining all the data used in this research project. I am also grateful to the water group's PhD students and my Indonesia fellows for their warm friendship during my study at Victoria University. Special credit should be given to Dr. Iwan Juwana who has shared his experiences and provided useful helps during the completion this study.

I would like acknowledge and thank the Government of Australia for providing me Australia Awards Scholarships (AAS) to study at Victoria University, Australia. The completion this study is possible as the generosity of support provided by AAS during my stay in Australia.

I am deeply indebted to my mum, dad in heaven, parents in law, my siblings, sister and brother in law, all my relatives for all their prayers and supported me in many different ways. I believe for my dad in heaven, who always trusted me even when I failed, if you were still alive, you would say: "I am very proud of you my son".

Last but certainly not least, I am deeply gratitude to my precious gifts: my lovely wife, Diana Pramanik, for her sacrifice, love, patience, and always being beside me passing through this memorable journey, and my sons, Kemal Sutadian and Athar Sutadian for being sources of joy and happiness for the entire of my life. Without you all this journey would not be the same and this piece of achievement is for the four of us.

Table of Contents

Chapter 1
Introduction

1.1. Background

"By polluting clear water with slime, you will never find good drinking water". (Aeschylus)

Water is one of the basic needs for all living organisms on earth. For example, all plants and humans cannot survive without water. Thus, it is of utmost importance to maintain this valued resource so that it can be utilised by humans and others in a sustainable way (Juwana et al., 2014). However, the increased human population and anthropogenic activities have resulted in pressure on both quantity and quality of water resources (Ciavola et al., 2014; Goonetilleke and Thomas, 2003; Gray, 2005). Thus, nowadays there is not only a lack of water availability but water quality degradation is also a big challenge across the world. In terms of water quality, Biswas et al. (1997) highlighted that in many countries water quality considerations are receiving an increasing attention because of their adverse impacts on the health of people as well as on ecosystems. Therefore, to maintain and improve water quality, an adequate understanding of water quality management is required.

Water quality management is a term used for all aspects of water quality problems relating to the suitability of various water uses (Krenkel, 2012). One of the important elements of water quality management is monitoring the quality of water resources. This monitoring is undertaken by collecting relevant information on the physical, chemical and biological categories of water quality (Asadollahfardi, 2014; Sanders et al., 1983). Each category has a number of parameters (Swamee and Tyagi, 2007). The collected information obtained from these categories of water quality is then used to perform a complete assessment in evaluating quality of water bodies (Chapman, 1996). This assessment provides basic data for detecting trends, for providing water quality information to water authorities, and for making necessary decisions or recommendations for future actions (Sutadian et al., 2016). However, as discussed in Biswas et al. (2014), monitoring all water quality parameters with different sources of pollution (e.g. those entering a river basin) is a difficult task since it is laborious and expensive. Somlyódy (1995) has indicated that insufficient funding, particularly in developing countries, is one of the most common barriers to conduct regular monitoring programs. Considering the above facts, the water authorities should establish priorities for resource allocation and develop monitoring programs effectively for future development of sustainable water quality management.

There are a few approaches to assess water quality. In river water, traditionally it is done through assessing its compliance with the permissible limit values as defined in the water quality guidelines or objectives (de Rosemond et al., 2009). This approach is carried out on a parameter by parameter basis (CCME, 2001). However, this traditional assessment cannot provide sufficient amount of information on the general status of water quality spatially and temporally (Kannel et al., 2007). Another approach, which is commonly used is the use of multivariate statistical techniques. These techniques include cluster analysis and principal component/factor analysis (PCA/PFA), which can also be used to assess river water quality. This approach aims to identify dominant sources of river pollution spatially and temporally using the similarity of water quality characteristics (Juahir et al., 2011; Kowalkowski et al., 2006; Petersen et al., 2001; Shrestha et al., 2008; Wang et al., 2013). These techniques are suitable to be used with large and complex water quality data obtained from different monitoring stations. But the results of this approach are not always easy to interpret. Moreover, the interpretation of the results tends to be based on assumptions or priori knowledge that may be difficult to obtain.

One of the very important approaches considered in water quality assessments is the use of time series analysis. It is commonly used for forecasting the future value of the investigated parameters, based on time series data of other water quality parameters (Asadollahfardi, 2014; Georgakarakos et al., 2006; Huck and Farquhar, 1974). Nevertheless, this approach needs high observation frequency and long periods of monitoring data (Chapman, 1996). Another approach used to assess river water quality is through the use of water quality simulation models in order to predict impacts of water management policies and practices on the water quality (Loucks et al., 2005). Nevertheless, using water quality simulation models is not easily applicable as it requires significant efforts (Koçer and Sevgili, 2014). This difficulty is caused mainly due to the need for a large amount of data, significant financial resources, and expertise for model development and application. Moreover, this type of assessment is only used for specific parameters, for example, eutrophication models or oxygen balance models (Chapman, 1996). Some other approaches have also been used for river water quality assessment, but the most commonly used approach is the use of a water quality index (WQI). A WQI is a single dimensionless number expressing the state of water quality in a simple form by aggregating the measurements of selected water quality parameters. The objective of such a method is to simplify water quality data by aggregating the measurement of selected parameters so that the general status of river water quality can be identified.

A WQI has been proposed as early as in 1965 and since then this approach has been one of the most effective ways to provide and communicate information about water quality (Soliman and Ward, 1994; Walsh and Wheeler, 2012). Even though there are a few limitations in the use of a WQI, e.g. it cannot define the quality of water for all uses and all hazards nor can it provide complete information on water quality (Cude et al., 1997), the WQI can be a useful tool with the following benefits:

- It is able to express the general state of water quality spatially and temporally; therefore, it can be used as a basis for improvement in water quality programs (Cude et al., 1997).
- It can be used to compare the water quality of different sources and sites without making highly technical assessment of the water quality data. Thus, this approach can be used for reporting to policy makers and the public in a simple and an understandable manner (CCME, 2001; Sarkar and Abbasi, 2006).
- It can be used as a tool for decision making and operational management by water authorities (Gitau et al., 2016; House, 1989; Ocampo-Duque et al., 2006).

In the recent past, in order to improve the existing indices, a number of water quality indices (WQIs) have been developed and their applications have been reported by different agencies and researchers (CCME, 2001; Gitau et al., 2016; Sargaonkar et al., 2008; Sutadian et al., 2016). However, as highlighted by Lumb et al. (2011) and Srebotnjak et al. (2012), no single WQI can be generally accepted as applicable worldwide and hence, there is a continuing interest to develop accurate WQIs that suit a local or regional area.

In West Java, similar to other provinces in Indonesia, the use of WQIs has been introduced since the early 1990s. The Ministry of Environment (MoE) uses two indices, wherein they have fully adopted the Storet Index and Water Pollution Index (MoE, 2003). Although these WQIs have been used with some success, they both had been developed based on other specific case study areas without considering local knowledge or local conditions of the West Java, e.g. no guideline on parameters selection or the involvement of stakeholder's opinion on parameter weights. Moreover, in calculating the final value for each monitoring station, these indices require more than one measurement of parameters sampled during the desired period. This requirement led to increasing of the monitoring cost in the field. Therefore, there is a need for a new index that is developed to not only address the aforementioned limitations of the currently indices, but also to provide a more accurate comparison of the general status of water quality between the rivers in West Java in more cost-effective manners.

This study was aimed to develop a cost-effective water quality index for West Java Province, called the West Java Water Quality Index (WJWQI). This WJWQI will be specifically developed by taking into account the above notions of undertaking efficient water quality assessments.

1.2. Aims of the Research

The overall aim of this research was to develop the West Java Water Quality Index (WJWQI) in a cost-effective manner, which can be used as an affordable tool to assess water quality in rivers across the West Java Province. This research consisted of two parts, which have been linked to develop a cost-effective WQI. In the first part, this project aimed to develop a novel and systematic approach to identify an optimal number of selected water quality parameters along the main rivers. The developed methodology was then be applied to the major selected rivers in the West Java Province as the case study. This is expected to reduce the costs associated with the monitoring program. The second part aimed to develop the WQI by using the optimal number of water quality parameters obtained from the previous part. The second part of the project also considered local knowledge or local conditions of the West Java Province. Thus, the developed WQI will be a valuable tool to assess the river water quality in a cost-effective manner and also overcome the deficiencies of the currently used indices. The following specific aims were also considered towards fulfilling the overall aim of the project:

- Develop a new methodology for water quality parameter selection for cost-effective monitoring of the parameters, wherein this specific aim will reduce the associated costs of monitoring in the field significantly through optimal selection of water quality parameters. This was undertaken by identifying parameters to be continuously monitored and those that are to be discontinued at the monitoring stations in West Java.
- Apply the developed methodology to the major rivers in West Java province to identify a uniform set of selected parameters to be used in the development of the WJWQI.
- Establish the weights of the water quality parameters to be used in the further steps of the development of WJWQI. This specific aim was needed to justify weights for each selected parameter based on the opinion of local experts.
- Develop the WJWQI based on the basis four steps, which are selection of parameters, obtaining sub-index values (transformation to a common scale), establishing weights, and aggregation of sub-indices to produce the final index. This was followed by applying the newly proposed WJWQI to evaluate the general status of water quality spatially and temporally at monitoring networks in the case study area.

- Undertake assessment of uncertainty and sensitivity analysis to determine the robustness of the index that has been developed. The uncertainty analysis of WJWQI focused on an investigation on how the variation in the thresholds and weights might affect the variation of the final index value. On the other hand, the sensitivity analysis studied the importance of the input uncertainties (thresholds and weights of parameters) in determining the final index value.

1.3. Study Area

The aims of this study stated under Section 1.2 were demonstrated through a case study in the West Java Province.

1.3.1. The West Java Province

The West Java Province is one out of thirty three provinces in Indonesia. It is situated in the western part of Java Island and it lies between latitudes 50°50' and 70°50' South and longitudes 104°048' – 108°048' East. The West Java occupies an area of 37,095 km^2, which includes 9 cities and 18 regencies (as presented in Figure 1). It has a total coastline length of 842.66 km. The landscape of the province can be divided into three main regions, namely steep terrain in the south (altitude more than 1,500 meters above sea level (MASL), low plateaus in the middle (altitude between 10 and 1,500 MASL), and plain region in the north (altitude between 0 and 10 MASL). As shown in Figure 1, the West Java shares borders with the capital of Indonesia (Jakarta Province) and Banten Province to the west, Central Java Province to the east, the Java Sea to the north, and the Indian Ocean to the south.

Figure 1 The West Java Province

The West Java is the highest densely populated province in the country (18.17% of the national population). According to BPS (2015), the population in West Java has increased progressively from 40.74 million in 2009 to 46.71 million inhabitants in 2015 with the population growth of around 1.71% per year in 2015 (the highest among others). The northern part of the West Java, which is particularly adjacent to the Jakarta (the capital of Indonesia) and in the middle part of the West Java, especially Bandung and its vicinity, are the most populous areas in the West Java, and also are well known as “home for industry” as most of industries in Indonesia are located in these areas. The West Java Environmental Protection Agency (WJEPA) estimated that there were 3,592 big industries and 199,723 small and medium industries across the province (WJEPA, 2015). Most of these industries are textile, foods and beverages that consume a large amount of water for their productions. The increased population, along with economic growth from industrial sector has led to high demand on foods, housings, energy, daily households, and raw materials for industries. Furthermore, the increased population also has made significant impact on the existing land use. According to WJEPA (2015), between 1994 and 2012, forest areas have significantly changed to settlements, industry or agricultural, and it only accounted for one tenth of total area of West Java Province.

The West Java has tropical climate with yearly average temperature of 22.9 – 27.4^{o}C. Since the West Java is influenced by Monsoon, it has two seasons, namely wet season (Oct – April) and the remaining months are the so-called transition or dry season. In general, the West Java receives high annual rainfall ranging from 500 – 4,000 mm (BMKG, 2017). As reported by the West Java Water Resources Agency (WJWRA), across the West Java, there are 40 catchments (WJWRA, 2017). The rivers of these catchments flow from the springs mostly in the upstream mountainous regions, towards either the estuary in the Northern (22 rivers) or Southern Coast (18 rivers) of Java Island. However, due to data availability that also was considered as a limitation of this study, only seven rivers across the province as can be seen in Figure 2, namely Cisadane, Ciliwung, Cileungsi, Citarum, Cimanuk, Citanduy, Cisadane, Cilamaya River were considered as the study area. Figure 2 also shows monitoring network across the study area managed by the WJEPA. Even though there were 54 available monitoring stations, again due to lack of data availability, 6 new stations of the Citarum River, which started operating in 2009 such as Jembatan Koyod, Citarik, Cisirung, Daraulin, Outlet Jatihulur, and Cikawao, were not used in this study. Thus, only 48 stations were used to develop and apply the WJWQI, wherein 8, 9, 9, 10, 5, 3, and 4 monitoring stations were located in Cisadane, Ciliwung, Cileungsi, Citarum, Cimanuk, Citanduy, Cisadane and Cilamaya Rivers, respectively. These rivers have several tributaries and pass through cities or regencies within the province.

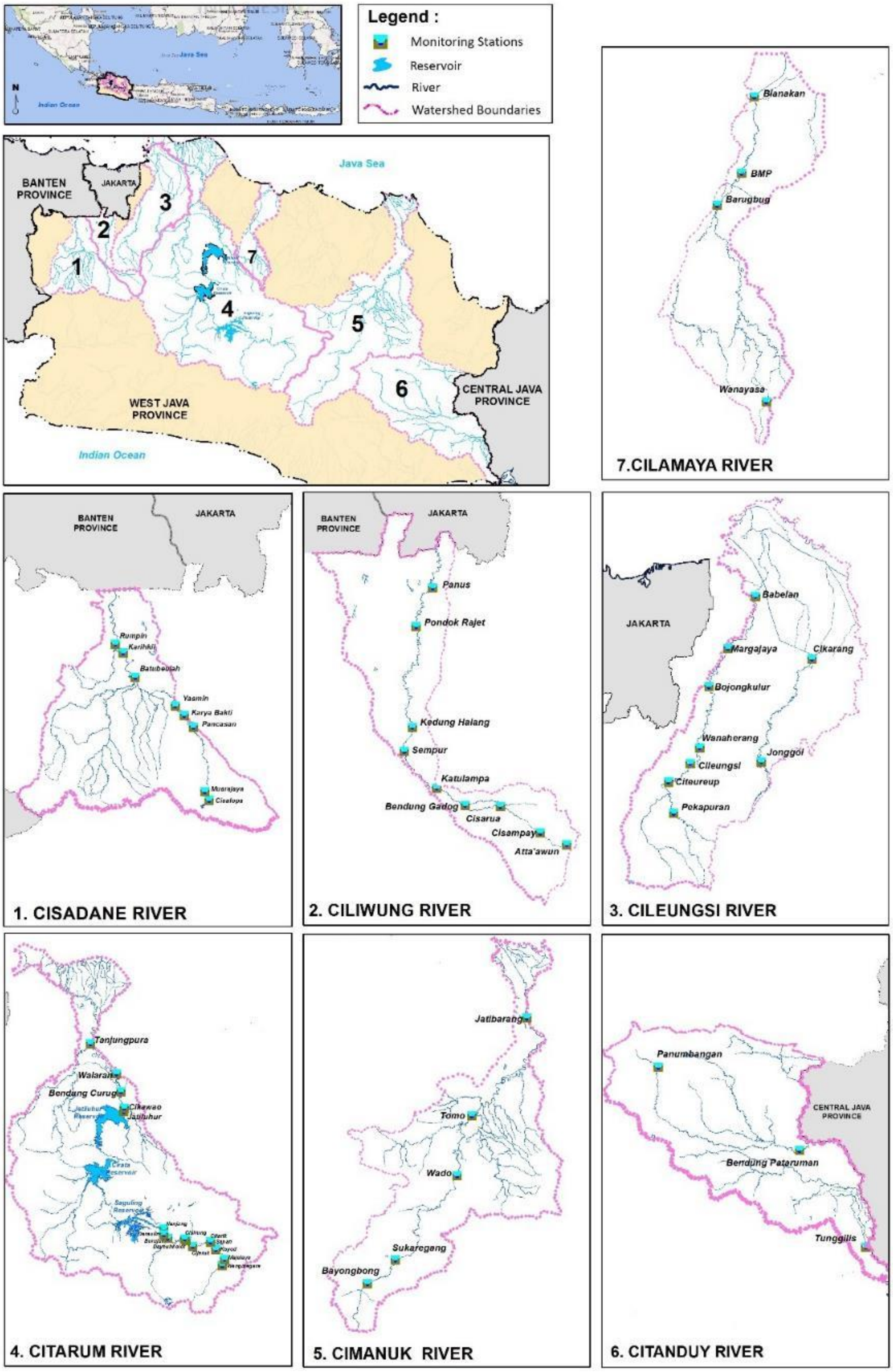


Figure 2 Water quality network across the West Java Province managed by the WJEPA

These rivers play an important role in the country as they are valuable sources of water for various needs such as agriculture and industry. They also provide bulk water supply for many cities across the region, including the capital of Indonesia (Jakarta). However, most of these rivers are vulnerable to pollution and have poor water quality, particularly those rivers that are near or are passing through urban and industrial areas. Pollutants entering the catchment and its rivers come from various activities, mostly domestic and industrial within the catchment. In addition to those two sources of pollutants, agriculture and livestock have also contributed to river pollution in the rivers (Juwana et al., 2014; WJEPA, 2015). As a result, water quality of the rivers has deteriorated significantly.

The following sub-sections describe a brief description of seven main rivers used as the study area is as follows:

1. Cisadane

The main river in the Cisadane catchment is the Cisadane River. The Cisadane River across two provinces wherein only upper stream of this river located in the West Java. The total river length is 126 km (only 76 km in length within the study area). The river originates from springs of Mount of Pangrango and Mount of Salak, and passes through Bogor city and regency towards the Banten Province. The river is used for bathing, washing, irrigation, and industries. It is also used by water companies of Bogor city and regencies as the source of raw water for their water treatment plants.

The catchment occupies an area of a 1,372 km^2. As reported in Junaidi (2013), the most dominant land use in the Cisadane catchment was shrub land of 53.82%. The second dominant, as much as 22.94%, was forested land. Settlements accounted for 15.61% of the total catchment. This was followed by cropland and paddy field of 6.16% of the total catchment. In 2010, the total population of the Cisadane catchment was approximately 3.5 million people where one third live in the upper area of the Cisadane catchment (Trimarmanti, 2014). According to Alberto and Dasanto (2010), the Cisadane catchment was taken into account as one of the most important catchments in the West Java, as it has rich natural resources (forest), provides various daily needs, and is vulnerable to land use change.

According to historical data of the Cisadane River using the flow gauge at Serpong Station, river flows vary during rainy and dry seasons with a 70 m^3/s of average flow, while the minimum and maximum flow were recorded at 2.93 m^3/s in 1991 and at 973.53 m3/s in 1997, respectively (Junaidi, 2013). Meanwhile, in terms of water quality, various activities within the catchment contributed to deterioration of the water quality of Cisadane River. As reported MoE (2012), the river suffers from three types of sources of untreated wastewater such as domestic, industrial, and agriculture waste.

2. Ciliwung

The catchment occupies an area of approximately 347 km^2, and the river length is 117 km. Average annual rainfall of the Ciliwung catchment is between 3,500– 4,000 mm (Soewandita and Sudiana, 2010). The river flows vary during rainy and dry seasons. It was observed that during flood event in 2002 and 2007, flow gauge at the outlet of the catchment, Katulampa Station was 247 m^3/s and 247.6 m^3/s, respectively (Ruspendi et al., 2013). In the upper part of the Ciliwung catchment, the dominant land is used for forestry of 34.13% of the total catchment (Soewandita and Sudiana, 2010). The Ministry of Environment and Forestry (MoEF) reported that the catchment is taken account as one of the priority catchments nationwide in terms of water quality and water scarcity (MoEF, 2015).

The Ciliwung River had been used as transportation until the early 1900s (INFID, 2010). Currently, the Ciliwung River is used for different users including domestic, industries and farmers. The river is also used by water companies in the catchment as the source of raw water for their water treatment plants of Bogor and Depok City, Bogor Regency, and the Jakarta Province.

As highlighted in Juwana et al. (2016), various activities by 5.17 million people living in the Ciliwung catchment contribute to river pollution as approximately 40% of the total population discharge their untreated wastewater, both directly and indirectly into the river. Juwana et al. (2016) also highlighted that the river also suffers from industrial and agricultural waste, wherein some of 101 industries in the Ciliwung catchment constantly discharge their untreated waste into the river. Other potential pollutants come from agricultural (the use of fertilisers and pesticides) and poultry (in the forms of biochemical oxygen demand, suspended particles, and nitrogen) (Juwana et al., 2016).

3. Cileungsi

The Cileungsi catchment covers an area of approximately 266.15 km^2, which includes Bogor Regency and Bekasi City (Permatasari, 2015). The main river in the catchment is the Cileungsi River, and its length is 39.11 km long. The dominant land use in the Cileungsi catchment is plantation and settlement. WJEPA (2015) reported that as much as 41.61% of the Cileungsi catchment was used for paddy field in 2015. This was followed by settlement as the second dominant land use in this catchment. Similar to other rivers in the study area, the main sources of pollutants are discharge of domestic and industry disposed into the river without proper treatment. WJEPA (2015) indicated that suspended solids, biochemical oxygen demand, chemical oxygen demand. In addition, a few heavy metal parameters often exceeded their permissible limits.

4. Citarum

The Citarum catchment occupies an area of approximately 7400 km^2, which consist of three sub-catchment, namely upper, middle and lower catchment. The main river in the Citarum catchment is Citarum River, which is the longest river in West Java (297 km in length). It flows across two main provinces, West Java and Jakarta, and stretching across 4 cities and 6 regencies. The Citarum River originates from Mount of Wayang in the Bandung Regency and it ends to its estuary in the Java Sea. The Citarum catchment receives average annual precipitation of 2,300 mm, or when gauged at the inlet of Saguling reservoir, it is equivalent to annual discharge at around 5.7 billion m^3 (Juwana et al., 2016).

As illustrated in Figure 2, the Citarum River feeds three multi-purpose cascade reservoir systems (Saguling, Cirata, and Jatiluhur), generating approximately 1,400 MW of hydropower that supports both Java and Bali Islands. These three reservoirs are also used to supply up to 80% of raw water for the regional water company in Jakarta, raw water for industry, irrigation, fishery, flood control, and recreational (MoE, 2012). This catchment is referred as a ‘high priority’ catchment across the country, as the catchment has made a significant impact on the national development of Indonesia, particularly on the economic sector (Juwana et al., 2014; Tarigan, 2009).

Total population within the catchment increased from 6.2 million in 2000 to 7.86 million inhabitants in 2010. It is expected to keep growing, and it will have reached 11.4 million by 2025 (MoE, 2012). Pressures on the catchment and its rivers come mainly from untreated domestic wastewater since its centralized domestic wastewater system only covers a small portion of population living in urbanized area of the upper Citarum (Prihandrijanti and Firdayati, 2011). In addition, industry, agriculture and livestock have also contributed to river pollution in the catchment. Juwana et al. (2016) highlighted that hundreds of industries located along the river also pollute the river due to lack of awareness on the importance of healthy rivers and lack of law enforcement from the relevant authorities.

5. Cimanuk

The Cimanuk catchment covers an area of approximately 3,409 km^2, which includes upper, middle and lower catchment. The catchment has annual precipitation of 2,800 mm. The main river of this catchment is Cimanuk River. The Cimanuk River rises in the Mount of Papandayan and flows from the southern into northern of the West Java, reaching its estuary in Java Sea (258 km in length). This river flows through four regencies, which includes Garut, Sumedang, Majalengka, and Indramayu.

As reported in Caya et al. (2014), the dominant land use in the catchment is mixed used among open land, shrub land or even swamp (43.13%). This is followed as much 32.69% of the catchment area, which is used for agriculture. As much as 14.73% and 5.88% of the catchment area are used for forest and settlements, respectively.

Various activities by 3.3 million people living in the Cimanuk catchment contribute to river pollution. As reported in Caya et al. (2014), industries might pollute the river as hundreds of industries constantly discharge their waste into the river. Most of these industries are small industries related to leather production processes, wherein they neither operate nor own a waste water treatment plant (Caya et al., 2014). Agriculture and livestock also contribute to the pollution of the river as phosphate and chloride often exceeded their permissible limits. The Ministry of Public Works (MoPW) indicated that the Cimanuk catchment is one of the critical catchments in terms of erosion, sedimentation, and flood risk. High erosion and sedimentation rate are contributed to the pollution, particularly physical aspects of the river (turbidity and colour) (MoPW, 2010).

6. Citanduy

The Citanduy catchment occupies two provinces, namely the West Java and Central Java. It covers an area of approximately 4,472 km^2, wherein only 2,214 km^2 is located in the West Java (MoPW, 2013). The catchment encompasses several cities and regencies. These cities are Banjar and Tasikmalaya, and the regencies are Ciamis, Tasikmalaya, Kuningan, Majalengka, Cilacap and Banyumas. According to WJEPA (2015), in the Citanduy catchment, as much as 69.50% of the catchment area is used for cropland. MoPW (2013) reported that estimated of total population living in the Citanduy catchment was around 3.2 million in 2010. Thus, compared to the other catchments described in this study, the Citanduy catchment is the least densely populous. As reported Prasetyo (2004) in Juwana et al. (2016), the catchment is also one of the critical catchments in terms of erosion, sedimentation and flood risk.

The main river of this catchment is Cilamaya River. The origin of the Cilamaya River are from Mount of Cakrabuana 1,720 m ASL) in Tasikmalaya Regency, which flows eastward to its estuary in Indian Ocean. The length of the river is 175 Km. However, only 60 km flows thorough within the West Java, while the rest flows through within the Central West Java Province (MoPW, 2013).

7. Cilamaya

The Cilamaya catchment is relatively smaller than other catchments in the study area as it covers an area of approximately 335.91 km^2. It occupies three regencies in the West Java Province, which are Karawang, Purwakarta, and Subang. The main river of this catchment is Cilamaya River. The Cilamaya River originates from mountainous areas in Purwakarta and flows towards its estuary in Java Sea. Average annual discharge, which were recorded in 2012 at Cipeundeuy Station was at 189 million m^3 (WJEPA, 2014). This river is used for bathing, washing, irrigation, raw water of local water supply companies, and as well as for freshwater shrimp. As reported in WJEPA (2014), total population within the catchment was over 1.1 million people in 2008. It was expected that due to lack of domestic wastewater treatment and the decreased carrying capacity of the catchment, and hence the downstream of the river is not be able to provide ‘self-purification’. As much as 53.6 ton/day of biochemical oxygen demand and 2.1 ton/day were disposed into the river (WJEPA, 2014). Other sources polluting the river are from industry, agriculture, and livestock waste.

1.3.2. Data Used

The water quality data from the WJEPA’s monitoring network were used in this study. The study period was considered as 2001-2011. However, due to budgetary constraints and change of institutional settings and laws in monitoring the water quality data, not all 54 stations as illustrated in Figure 2 had data for the above study period, as the WJEPA did not monitor the water quality data regularly for each station. The WJEPA also conducted irregular sampling frequencies, ranging from zero to five measurements per year. As a consequence, in the development and application of the WJWQI, not all monitoring stations even within the same river had either the same period of monitoring or number of water samples. For example, in the application of WJWQI, the final index was computed at the station CTM1 in the Citarum River for the period between 2001 and 2010, while in the CTM3 in the same river, it was computed for the period 2003 – 2010. In addition, as to the number water samples used in the application of WJWQI, since the general status of water quality refers to a specific time and location where a water sample was taken, in this study the application of WJWQI was computed based on individual samples rather than one average yearly value.

It is important to mention here (as discussed earlier in Section 1.3.1), 6 monitoring stations were not used either in the development or application of WJWQI. They are Jembatan Koyod, Citarik, Cisirung, Daraulin, Outlet Jatihulur, and Cikawao, which are indicated by superscript of (*) in column 2 of Table 1 as presented below. Furthermore, only water quality parameters obtained from 30 out of the 54 monitoring stations were used for the application of parameter selection for cost-effective water quality monitoring. Apart from the six monitoring stations aforementioned, some of the monitoring stations were also excluded since they did not have a minimum number of consecutive years of monitored water quality data that were considered for the statistical assessment of the parameter selection. The monitoring stations used for parameter selection for cost-effective water quality monitoring are provided in Table 1 and they are indicated by superscript of ([1]) in column 2 of Table 1. Meanwhile, the spatial locations of these 30 monitoring stations can be seen in the Chapter 3 of the thesis, under Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java, Indonesia.

Similar to the above reason, in the application of the WJWQI, only 48 out of the 54 stations were used in this study since these 48 monitoring stations had the selected parameters used in the development of the WJWQI. The monitoring stations used for application of the newly proposed WJWQI are provided in column 2 of Table 1 and they are indicated by superscript of ([2]). In addition, the relative spatial locations of these 48 monitoring stations can be seen in Chapter 5 of the thesis, under discussion of Development of the River West Java Water Quality Index.

Table 1 Monitoring network station used in the development and application of WJWQI

River	Monitoring Stations		Code	Data availability											
				2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
(1)	(2)		(3)	(4)											
Cisadane	1	Cisalopa[1,2]	CSN1	x	x	x	x	x	x	x	x	x	x	NA	NA
	2	Muarajaya[2]	CSN2	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	3	Pancasan[2]	CSN3	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	4	Karya Bakti[2]	CSN4	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	5	Yasmin[2]	CSN5	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	6	Batubeulah[2]	CSN6	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	7	Karihkil[2]	CSN7	NA	NA	NA	NA	NA	x	x	x	x	NA	NA	NA
	8	Rumpin[1,2]	CSN8	x	x	x	x	x	x	x	x	x	NA	NA	NA
Ciliwung	1	Atta'awun[1,2]	CLW1	NA	NA	x	x	x	x	x	x	x	x	([3])	([3])
	2	Cisarua[1,2]	CLW2	x	NA	x	x	x	x	x	x	x	x	NA	NA
	3	Katulampa	CLW3	NA	NA	x	x	x	x	x	x	x	x	([3])	([3])
	4	Kedung Halang	CLW4	NA	NA	x	x	x	x	x	x	x	x	([3])	([3])
	5	Pondok Rajet	CLW5	NA	NA	x	x	x	x	x	x	x	x	([3])	([3])
	6	Panus[1,2]	CLW6	x	NA	x	x	x	x	x	x	x	x	([3])	([3])
	7	Cisampay[2]	CSP	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	8	Bendung Gadog[2]	BDG	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
	9	Sempur[2]	SEM	NA	NA	NA	NA	NA	x	x	x	x	x	NA	NA
Cileungsi	1	Cileungsi-Pekapuran[1,2]	CL1	x	x	x	x	x	x	x	x	x	x	x	([3])
	2	Cileungsi-Cileungsi[2]	CL1A	x	x	x	x	x	NA	NA	NA	NA	NA	NA	NA
	3	Cileungsi-Wanaherang[2]	CL2	NA	NA	NA	NA	NA	NA	x	x	x	x	x	([3])
	4	Cikeas-Citeureup[1,2]	CL3	NA	NA	x	x	x	x	x	x	x	x	x	([3])
	5	Cikeas-Bojongkulur[2]	CL4	NA	NA	NA	NA	NA	NA	x	x	x	x	x	([3])
	6	Cikarang-Jonggol[1,2]	CL5	x	x	x	x	x	x	x	x	x	x	x	([3])
	7	Cikarang-Cikarang[1,2]	CL6	x	x	x	x	x	x	x	x	x	x	x	([3])
	8	Bekasi-Margajaya[2]	CL7	NA	NA	NA	NA	NA	NA	x	x	x	x	x	([3])
	9	Bekasi-Babelan[1,2]	CL8	NA	NA	x	x	x	x	x	x	x	x	x	([3])
Citarum	1	Wangiasagara[1,2]	CTM1	x	x	x	x	x	x	x	x	x	x	([3])	([3])
	2	Majalaya[1,2]	CTM2	x	x	x	x	x	x	x	x	x	x	NA	NA
	3	Sapan[1,2]	CTM3	NA	x	x	x	x	x	x	x	x	x	NA	NA
	4	Cijeruk[1,2]	CTM4	x	x	x	x	x	x	x	x	x	x	NA	NA
	5	Dayeuh Kolot[1,2]	CTM5	NA	x	x	x	x	x	x	x	x	x	NA	NA
	6	Burujul[1,2]	CTM6	x	x	x	x	x	x	x	x	x	x	NA	NA
	7	Nanjung[1,2]	CTM7	x	x	x	x	x	x	x	x	x	x	([3])	([3])
	8	Bendung Curug[1,2]	CTM8	x	x	x	x	x	x	x	x	X	x	NA	NA
	9	Walahar[1,2]	CTM9	x	x	x	x	x	x	x	x	x	x	([3])	([3])
	10	Tanjungpura[1,2]	CTM10	x	x	x	x	x	x	x	x	x	x	NA	NA

River	Monitoring Stations		Code	Data availability											
				2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
(1)	(2)		(3)	(4)											
	11	Jembatan Koyod*	JK	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	(*)	(*)
	12	Citarik*	Cit	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	NA	NA
	13	Cisirung*	Cis	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	(*)	(*)
	14	Daraulin*	Dar	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	NA	NA
	15	Outlet Jatiluhur*	Out	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	(*)	(*)
	16	Cikawao*	Cik	NA	NA	NA	NA	NA	NA	NA	NA	(*)	(*)	NA	NA
Cimanuk	1	Bayongbong[1,2]	CMN1	x	x	x	x	x	x	x	x	x	x	x	([3])
	2	Sukaregang[1,2]	CMN2	x	x	x	x	x	x	x	x	x	x	x	([3])
	3	Wado[2]	CMN3	NA	NA	NA	NA	NA	NA	NA	NA	x	x	x	([3])
	4	Tomo[1,2]	CMN4	x	x	x	x	x	x	x	x	x	x	x	([3])
	5	Jatibarang[1,2]	CMN5	x	x	x	x	x	x	x	x	x	x	x	([3])
Citanduy	1	Panumbangan[1,2]	CTD1	NA	NA	x	x	x	x	x	x	x	x	NA	NA
	2	Bendung Paturaman[1,2]	CTD2	NA	NA	x	x	x	x	x	x	x	x	NA	NA
	3	Tunggilis[1,2]	CTD3	NA	NA	x	x	x	x	x	x	x	x	NA	NA
Cilamaya	1	Wanayasa[2]	CLM1	NA	NA	NA	x	x	x	NA	x	x	x	x	NA
	2	Barugbug[2]	CLM2	NA	NA	NA	x	x	x	NA	x	x	x	x	NA
	3	BMP[2]	CLM3	NA	NA	NA	NA	NA	NA	x	x	x	x	x	NA
	4	Blanakan[2]	CLM4	NA	NA	NA	NA	NA	NA	NA	NA	x	x	x	NA

* Neither for parameter selection nor application of WQI used these stations
[1] Water quality data in these stations were used for parameter selection in the development of WJWQI
[2] Water quality data in these stations were used for application of WJWQI
[3] Water quality data in the respective years were used only for parameter selection in the development of WJWQI
NA: Not available
X : Water quality data is available

1.4. Significance of the research

To assess the general status of river water quality, the WJEPA uses two indices, namely the Storet Index and the Water Pollution Index (MoE, 2003). Although these WQIs have been used with some success, they both had been developed based on other specific case study areas without considering local knowledge or local conditions of the West Java, e.g. no guidelines of the selected parameters to be used in the currently indices. As a result, applications of such WQIs might vary from one place to another because the selected parameters could be different, both spatially as well as temporally. Thus, comparison the final values at monitoring sites across rivers in the West Java using the two currently used indices were not possible.

In applying the currently used indices, many parameters need to be monitored at numerous monitoring stations along the river. Such monitoring of water quality parameters requires massive resources in terms of equipment, expertise and so on. However, due to the limited budget available to the monitoring agencies, it is difficult to monitor all water quality parameters at all the established monitoring stations. Moreover, in calculating the final index value for each monitoring station, the two currently used indices require more than one measurement of parameters sampled during the desired period. This requirement lead to increasing of the monitoring cost in the field. Therefore, this study attempted to address the limitations of the currently used indices by considering parameters selection in more cost effective manner, which is expected to result in significant reductions in the costs for monitoring of the water quality parameters.

This study proposed a new methodology for the selection of parameters in a cost effective way, which can be applied in any case worldwide (not only for West Java case). The proposed methodology was based on a statistical assessment for parameter redundancy and also incorporated the use of three important factors (i.e. the cost of parameters' monitoring, the magnitude and frequency of the parameter exceeding its permissible limits). According to the knowledge of the author, there are no records in the published literature on the development of a water quality index taking account of cost-effective monitoring in selecting the WQIs' parameters. Therefore, this provides international significance and it contribute to the existing knowledge on water quality assessment, particularly to the previous research of parameter selection since the approach has not been used in the selection of parameters of previous WQIs.

The development of the WJWQI was also specifically developed through the involvement of water stakeholders in West Java for identifying parameter weights of the selected parameters.

This not only addresses one of the limitations of the currently used indices in West Java, but also at some level is important for the acceptability of a WQI as a useful tool in water resources management. The WJWQI in the future may be an important part of water quality management in West Java as it provides a better WQI for rivers across the West Java. Once this tool is available, appropriate programmes can be designed more accurately and effectively to improve the water quality of rivers throughout the province.

1.5. Outline of the thesis

This thesis consists of 6 chapters as presented in Figure 3, which indicates the interconnection between chapters described in the thesis. The first chapter provides an introduction of the research presented in the thesis and it has been discussed in the previous sub-sections of this chapter.

The second chapter provides details on the literature on WQIs, their applications and significant contribution to the development of future river WQIs. In the second chapter, a review of 30 existing WQIs based on the four steps needed to develop a WQI is presented. These steps are the selection of parameters, the generation of parameter weights, the generation of sub-indices, and the aggregation process to compute the final index value. Also challenges along with some recommendations, for example, using statistical methods to select a fixed set of water quality parameters in a WQI are discussed. In the second chapter, to improve acceptability of an index, it was also observed that the involvement of the opinion of local water quality experts was recommended to be undertaken in the first three steps. Moreover, since robustness analysis (i.e. uncertainty and sensitivity analysis) is rarely investigated to identify and reduce sources of uncertainty, hence such an analysis was also recommended for future studies in the second chapter.

The third chapter presents a novel contribution of the thesis by proposing a generic methodology for parameters selection in a more cost-effective manner, which was through an enhancement of the statistical assessment based methodology used for hydrometric network rationalization, and later adopted for parameter redundancy. The method comprised three sequential steps, namely screening, statistical assessment for parameter redundancy to identify redundant parameters, and identification of common parameters (i.e. a uniform set of parameters) for use in a particular river basin or a region/country. The effectiveness of screening step to eliminate some parameters based on “data availability” and “being within the permissible limits” was presented in a paper entitled “Use of exploratory data analysis for cost effective monitoring of water quality data". Then, the statistical assessment based methodology in general involved two sequential tasks, namely (i) identifying highly correlated clusters to assess redundancy information among the studied parameters using correlation analysis and hierarchal cluster analysis and (ii) identifying the optimal combinations of continued and discontinued water quality parameters using an consolidated performance index (which was an aggregated information based on the variance of the mean value estimator among the studied parameters).

In Chapter 3, three critical factors were introduced to address limitations of the consolidated performance index. These critical factors was proposed to be included since they reflect the criticality of water quality parameters for cost effective monitoring. The first factor represents the cost of monitoring of parameters, and the other two factors represent the magnitude and frequency of the parameter exceeding its permissible limits. Through this enhancement, the index developers or related water authorities are able to accurately select a fixed set of parameters across the monitoring network. As a result, it will lead to a significant reduction in the number of parameters to be used in the development of a WQI without losing a substantial amount of information in representing the water quality. The application of this proposed methodology is also presented in the same chapter, wherein results obtained in this chapter were used in further steps of the development of the West Java WQI (described in the fourth and the fifth chapter of the thesis).

In the fourth chapter, one of the most important steps in the development of a WQI, which is that of establishing the weights of the water quality parameters, is presented. Taking in account an important recommendation in the first chapter (i.e. in the literature review), stakeholder's opinion was involved in establishing the parameter weights. Two analytical hierarchal procedure (AHP) models based on results of the third chapter, namely individual and parameter groupings form were employed in this study. Later, a pool of respondents from related stakeholders in West Java with different backgrounds was surveyed to obtain their judgement independently. In the fourth chapter, results of both AHP models on parameters weights were compared and investigated. Of the two AHP models, only the results of the best AHP model was used for the remaining steps of this study, which is that of aggregations of sub-indices to obtain the final index value.

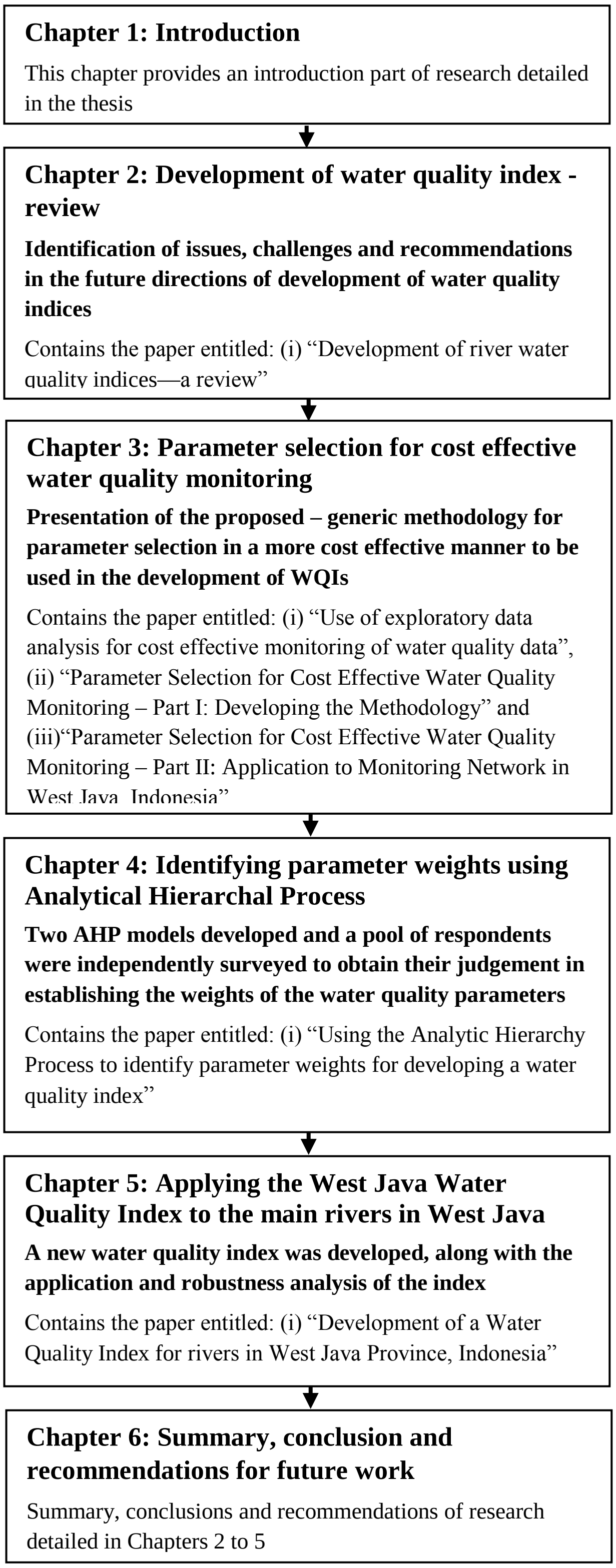


Figure 3 Interconnection between chapters presented in this thesis

In the fifth chapter, the application of the WJWQI is presented. This index was developed based on the basis four steps as described in the literature review chapter. The results obtained from a novel approach for parameters selection in cost effective manner (as presented earlier in the third chapter of the thesis) and the results of the parameters weights (as presented earlier in the fourth chapter of the thesis) were used in the development of the WJWQI. Also for the first time at monitoring networks of study area, application of the newly proposed index for rivers in West Java was undertaken using monitoring data taken between 2001 and 2011, to evaluate the general status of water quality spatially and temporally. Moreover, as recommended in the second chapter, uncertainty and sensitivity analysis was undertaken to determine the robustness of the index which have been developed. This analysis was used to finalize the outcomes of the case studies, so water quality index calculations can be conveyed confidently. This will increase credibility and validity of this WQI to be used by the index users such as the related authorities in West Java.

Finally, in the sixth chapter, a summary and the conclusions drawn from the study are presented along with some recommendations for future work.

References

Alberto, A., Dasanto, B.D., 2010. Model Perubahan Penggunaan Lahan dan Pendugaan Cadangan Karbon di Daerah Aliran Sungai Cisadane, Jawa Barat. Jurnal Agromet 24, 18-26

Asadollahfardi, G., 2014. Water quality management : assessment and interpretation. Heidelberg : Springer

Biswas, A.K., Ordoñez, E.B., Cabrera, J.G., 1997. Development of a Framework for Water Quality Monitoring in Mexico. Water International 22, 179-186.10.1080/02508069708686699

Biswas, A.K., Tortajada, C., Izquierdo, R., 2014. Water Quality Management. Present Situations, Challenges and Future Perspectives. Hoboken : Taylor and Francis

BMKG, 2017. Peta Curah Hujan Jawa Barat (Rainfall of West Java) 1980-2010. Indonesia Buerau of Meteorological, Climatological and Geophysics

BPS, 2015. Jawa Barat in Figures 2015.

Caya, Gunawan, T., Suprodjo, S.W., Muta'ali, L., 2014. Optimalisasi penggunaan lahan untuk agroforestri di Daerah Aliran Sungai Cimanuk Propinsi Jawa Barat. Jurnal TeknoSains 4

CCME, 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. Canadian Council of Ministers of the Environment Winnipeg.http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf (accessed 20.01.2015)

Chapman, D., 1996. Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring - Second Edition. E&FN Spon, an imprint of Chapman & Hall, Great Britain at the University Press, Cambridge

Ciavola, S.J., Jantz, C.A., Reillya, J., Moglen, G.E., 2014. Forecast Changes in Runoff Quality and Quantity from Urbanization in the DelMarVa Peninsula. Journal of Hydrologic Engineering 19, 1-9.10.1061/(ASCE)HE.1943-5584.0000773

Cude, C., Dunnette, D., Avent, C., Frankin, A., Gross, G., Hartman, J., Hayteas, D., Jenkins, T., Leben, K., Lyngdal, J., Marks, D., Morganti, C., Quin, T., 1997. Exploring Possibilities for An International Water Quality Index Applied to River System, in: Best, G., Bogacka, T., Niemirycz, E. (Eds.), International River Water Quality: Pollution and restoration. E & FN Spoon, London

de Rosemond, S., Duro, D.C., Dubé, M., 2009. Comparative analysis of regional water quality in Canada using the Water Quality Index. Environmental Monitoring And Assessment 156, 223-240.10.1007/s10661-008-0480-6

Georgakarakos, S., Koutsoubas, D., Valavanis, V., 2006. Time series analysis and forecasting techniques applied on loliginid and ommastrephid landings in Greek waters. Fisheries Research 78, 55-71.http://dx.doi.org/10.1016/j.fishres.2005.12.003

Gitau, M.W., Chen, J., Ma, Z., 2016. Water Quality Indices as Tools for Decision Making and Management. Water Resour Manage 30, 2591-2610.10.1007/s11269-016-1311-0

Goonetilleke, A., Thomas, E.C., 2003. Water quality impacts of urbanisation: Evaluation of current research. Energy & Resource Management Research Program. Centre for Built Environment and Engineering Research. Queensland University of Technology.http://eprints.qut.edu.au/4209/1/4209.pdf

Gray, N.F., 2005. Water technology : an introduction for environmental scientists and engineers. Elsevier, Oxford

House, M.A., 1989. A Water Quality Index for River Management. Water and Environment Journal 3, 336-344.DOI:10.1111/j.1747-6593.1989.tb01538.x

Huck, P.M., Farquhar, G.J., 1974. Water Quality Models Using the Box-Jenkins Method. Journal of the Environmental Engineering Division 100, 733-753

INFID, 2010. Studi Sungai Ciliwung pengabaian pemerintah terhadap eksistensi penduduk pinggir sungai: Wajah Pengelolaan Sungai di Indonesia, in: Nikmah, S.K. (Ed.). INFID, Jakarta

Juahir, H., Zain, S., Yusoff, M., Hanidza, T.I.T., Armi, A.S.M., Toriman, M., Mokhtar, M., 2011. Spatial water quality assessment of Langat River Basin (Malaysia) using environmetric techniques. Environmental Monitoring and Assessment 173, 625-641.10.1007/s10661-010-1411-x

Junaidi, E., 2013. Peranan penerapan agroforestry terhadap hasilair Daerah Aliran Sungai (DAS) Cisadane (The role of agroforestry implementation to water yield in Cisadane Watershed). Jurnal Penelitian Agroforestry 1, 41-53

Juwana, I., Muttil, N., Perera, B.J.C., 2014. Application of West Java water sustainability index to Citarum catchment in West Java, Indonesia. Water Science and Technology: Water Supply 14, 1150-1159.10.2166/ws.2014.075

Juwana, I., Muttil, N., Perera, B.J.C., 2016. Application of west java water sustainability index to three water catchments in west java, Indonesia. Ecological Indicators 70, 401-408.http://dx.doi.org/10.1016/j.ecolind.2016.06.017

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R., Khan, S.P., 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environmental Monitoring and Assessment 132, 93-110

Koçer, M.A.T., Sevgili, H., 2014. Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. Ecological Indicators 36, 672-681.http://dx.doi.org/10.1016/j.ecolind.2013.09.034

Kowalkowski, T., Zbytniewski, R., Szpejna, J., Buszewski, B., 2006. Application of chemometrics in river water classification. Water Research 40, 744-752.http://dx.doi.org/10.1016/j.watres.2005.11.042

Krenkel, P., 2012. Water Quality Management. Elsevier Science, Saint Louis, United States

Loucks, D.P., Beek, E.V., Stedinger, J.R., Dijkman, J.P., Villars, M.T., 2005. Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Paris: UNESCO

Lumb, A., Sharma, T.C., Bibeault, J.F., Klawunn, P., 2011. A Comparative Study of USA and Canadian Water Quality Index Models. Water Qual Expo Health 3, 203-216.10.1007/s12403-011-0056-5

MoE, 2003. Keputusan Menteri Negara Lingkungan Hidup Nomor : 115 Tahun 2003 Tentang Pedoman Penentuan Status Mutu Air (Ministrial's Decree No. 115 on Technical guidance for water class determination), in: MoE (Ed.), Jakarta

MoE, 2012. State of the Environment Report Indonesia 2012: Pillars of the Environment of Indonesia. Ministry of Environment of the Republic of Indonesia, Jakarta

MoEF, 2015. Rencana Strategis Direktorat Jenderal Pengendalian Daerah Aliran Sungai dan Hutan Lindung Tahun 2015- 2019, P. /PDASHL-SET/2015 Kementrian Lingkungan Hidup dan Kehutana (MoEF), Jakarta

MoPW, 2010. Pola Pengelolaan SUmber Daya Air Wilayah Sungai Cimanuk-Cisanggarung, in: Works, M.o.P. (Ed.). Ministry of Public Works, Jakarta

MoPW, 2013. Pola Pengelolaan Sumber Daya Air Wilayah Sungai Citanduy, in: Works, M.o.P. (Ed.). Ministry of Public Works, Jakarta

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M., 2006. Assessing water quality in rivers with fuzzy inference systems: A case study. Environment International 32, 733-742.http://dx.doi.org/10.1016/j.envint.2006.03.009

Permatasari, A., 2015. Studi perencanaan tanggul dan dinding penahan untuk pengendalian banjir di Sungai Cileungsi Kabupaten Bogor Jawa Barat, Fakultas Teknik. Universitas Brawijaya, Malang

Petersen, W., Bertino, L., Callies, U., Zorita, E., 2001. Process identification by principal component analysis of river water-quality data. Ecological Modelling 138, 193-213.http://dx.doi.org/10.1016/S0304-3800(00)00402-6

Prasetyo, L.B., 2004. Deforestasi dan Degradasi Lahan DAS Citanduy (Deforestation and Land Degradation in Citanduy Catchment),

Prihandrijanti, M., Firdayati, M., 2011. Current Situation and Considerations of Domestic Wastewater Treatment Systems for Big Cities in Indonesia (Case Study: Surabaya and Bandung) Journal of Water Sustainability 1, 97-104

Ruspendi, D., Hadi, S., Rusdiana, O., 2013. Kajian perubahan penutupan lahan pada DAS Ciliwung Hulu dengan pendekatan spasial dinamik (Study of land cover changing in Ciliwung upper stream with spatial dynamic approach). Jurnal Landscape Indonesia 5

Sanders, T.G., Ward, R.C., Loftis, J.C., Steele, T.D., Adrian, D.D., Yevjevich, V., 1983. Design of networks for monitoring water quality. Water Resources Publication, LLC, Highland Ranch, Colorado, USA

Sargaonkar, A.P., Gupta, A., Devotta, S., 2008. Dynamic weighting system for water quality index. Water Science and Technology 58, 1261-1271.10.2166/wst.2008.468

Sarkar, C., Abbasi, S.A., 2006. Qualidex – A New Software for Generating Water Quality Indice. Environmental Monitoring and Assessment 119, 201-231.10.1007/s10661-005-9023-6

Shrestha, S., Kazama, F., Nakamura, T., 2008. Use of principal component analysis, factor analysis and discriminant analysis to evaluate spatial and temporal variations in water quality of the Mekong River. Journal of Hydroinformatics 8, 43–56

Soewandita, H., Sudiana, N., 2010. Studi dinamika kualitas air DAS Ciliwung. JAI 6, 24-33

Soliman, W.R., Ward, R.C., 1994. The Evolving Interface between Water Quality Management and Monitoring. Water International 19, 138-144.10.1080/02508069408686217

Somlyódy, L., 1995. Water quality management: Can we improve integration to face future problems? Water Science and Technology 31, 249-259.http://dx.doi.org/10.1016/0273-1223(95)00378-Z

Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016. Development of river water quality indices—a review. Environmental Monitoring and Assessment 188:58.10.1007/s10661-015-5050-0

Swamee, P., Tyagi, A., 2007. Improved Method for Aggregation of Water Quality Subindices. Journal of Environmental Engineering 133, 220-225.doi:10.1061/(ASCE)0733-9372(2007)133:2(220)

Tarigan, S.D., 2009. Pengembangan Sistem Informasi Spasial Berbasis Web (Web GIS) untuk Sinergi Rehabilitasi DAS Kritis Nasional 2009.

Trimarmanti, T.K.E., 2014. Evaluasi perubahan penggunaan lahan kecamatan di Daerah Aliran Sungai Cisadane Kabupaten Bogor. Jurnal Wilayah dan Lingkungan 2, 55-72

Walsh, P., Wheeler, W., 2012. Water Quality Index Aggregation and Cost Benefit Analysis. Working Papers # 12-05. United States Environmental Protection Agency, Washington DC

Wang, Y., Wang, P., Bai, Y., Tian, Z., Li, J., Shao, X., Mustavich, L.F., Li, B.-L., 2013. Assessment of surface water quality via multivariate statistical techniques: A case study of the Songhua River Harbin region, China. Journal of Hydro-environment Research 7, 30-40.http://dx.doi.org/10.1016/j.jher.2012.10.003

WJEPA, 2014. Laporan Akhir Penyusunan Kajian Hingkungan Hidup Strategies untuk Evaluasi RTRW Jawa Barat (Study on environmental strategic for land use planning of West Java). The West Java Environmental Protection Agency, Bandung, Indonesia

WJEPA, 2015. Status Lingkungan Hidup Daerah Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia

WJWRA, 2017. Buku Saku Sumber Daya Air Jawa Barat (Annual Book of West Java Water Resources) West Java Water Resources Agency, Bandung

Chapter 2
Development of a Water Quality Index for Rivers – A Review

2.1. Introduction

This chapter reviews the literature of Water Quality Index (WQI) for rivers worldwide to meet the aim of this research, as outlined in Section 1.2. In this review, there are four steps used in developing a Water Quality Index (WQI), which are selection of parameters, obtaining sub-index values (transformation to a common scale), establishing weights, and aggregation of sub-indices to produce the final index. A thorough review of 30 existing WQIs based on the four aforementioned steps to develop a WQI is presented and 7 were identified as most important based on their wider use. These 30 WQIs are discussed in greater detail in this chapter. It was concluded that the index developers may consider all the four steps or they could consider some of the steps. Neither of the available WQIs have been universally accepted, since 100 % objectivity or accuracy cannot be achieved in applying a WQI as there is a lot of subjectivity and uncertainty involved in the steps for developing and applying a WQI. Therefore, minimizing subjectivity and uncertainty in each step should also be taken in the development of a WQI. Some of the uncertainties and challenges in WQIs studies can be addressed in several ways, such as through the use of statistical-based methods, which include correlation analysis or multivariate analysis, involvement of the opinion of local water quality experts, and uncertainty and sensitivity analysis. Taking into account the need for accurate comparisons of water quality between monitoring stations/river basins, common WQI parameters (i.e. having a fixed set of parameters) for river basins within a province or region was recommended. This chapter also discussed the uncertainties and the challenges associated with development of river water quality indices along with some potential recommendations for future directions.

This chapter contains the following journal paper:

1. Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016. Development of river water quality indices—a review. Environmental Monitoring and Assessment 188:58.10.1007/s10661-015-5050-0.

2.2

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

GRADUATE RESEARCH CENTRE

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Development of river water quality indices—a review

Surname: Sutadian | First name: Arief Dhany

College: College of Engineering & Science | Candidate's Contribution (%): 85

Status:

Accepted and in press: ☐ Date:

Published: ☑ Date: 28 Dec 2015

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted] | 30/03/2017

Signature | Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. There are no other authors of the publication according to these criteria;
4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing	[redacted]	30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing	[redacted]	30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing	[redacted]	30/03/2017

Updated: June 2015

Environ Monit Assess (2016) 188:58
DOI 10.1007/s10661-015-5050-0

2.3
Development of river water quality indices—a review

**Arief Dhany Sutadian · Nitin Muttil ·
Abdullah Gokhan Yilmaz · B. J. C. Perera**

Received: 13 April 2015 / Accepted: 10 December 2015

Abstract The use of water quality indices (WQIs) as a tool to evaluate the status of water quality in rivers has been introduced since the 1960s. The WQI transforms selected water quality parameters into a dimensionless number so that changes in river water quality at any particular location and time could be presented in a simple and easily understandable manner. Although many WQIs have been developed, there is no world-wide accepted method for implementing the steps used for developing a WQI. Thus, there is a continuing interest to develop accurate WQIs that suit a local or regional area. This paper aimed to provide significant contribution to the development of future river WQIs through a review of 30 existing WQIs based on the four steps needed to develop a WQI. These steps are the selection of parameters, the generation of sub-indices, the generation of parameter weights and the aggregation process to compute the final index value. From the 30 reviewed WQIs, 7 were identified as most important based on their wider use and they were discussed in detail. It was observed that a major factor that influences wider use of a WQI is the support provided by the government and authorities to implement a WQI as the main tool to evaluate the status of rivers. Since there is a lot of subjectivity and uncertainty involved in the steps for developing and applying a WQI, it is recommended that the opinion of local water quality experts is taken, especially in the first three steps (through techniques like Delphi method). It was also observed that uncertainty and sensitivity analysis was rarely undertaken to reduce uncertainty, and hence such an analysis is recommended for future studies.

Keywords Water quality indices · Water quality status · Water quality parameters · River · Review

A. D. Sutadian (✉) · N. Muttil · A. Yilmaz · B. J. C. Perera
College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
e-mail: arief.sutadian@live.vu.edu.au

N. Muttil · A. Yilmaz · B. J. C. Perera
Institute for Sustainability and Innovation, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia

Introduction

Water quality is one of the important issues in water resources management. In broad terms, water quality can be classified into three broad categories, namely physical, chemical and biological and each category has a number of parameters (Swamee and Tyagee 2007). The assessment of these three categories by field monitoring of rivers provides basic data for detecting trends, for providing water quality information to water authorities, and for making recommendations for future actions. This assessment is usually conducted by referring to natural water quality, human health and intended uses (Pesce and Wunderlin 2000; Gazzaz et al. 2012). In fact, monitoring all parameters with different sources of pollution entering a river basin is laborious and expensive. Moreover, many scientists and researchers have difficulty in defining water quality and presenting it in a simple and consolidated way. This difficulty exists due

Published online: 28 December 2015

to the complexity of factors or parameters affecting water quality, and the large variability of parameters used to describe the water quality status of water bodies (Chapman 1992). This has led to many extensive attempts to present the state of water quality in simply ways without losing its scientific basis.

A water quality index (WQI) is a single dimensionless number expressing the water quality in a simple form by aggregating the measurements of selected parameters. A WQI has been proposed as early as in 1965, to define the state of water quality in a river (Horton 1965). Considering the easiness of their use and the scientific basis, WQIs have become important and popular tools in assessing the water quality of water bodies worldwide, particularly of rivers. Since the birth of the concept of WQI, various indices have been formulated and developed by many researchers. WQIs have also been considered as a pivotal component of the wider environmental or natural resource indices such as the Environmental Performance Index (EPI 2010) and the Stream Index (Ladson et al. 1999).

The general structure of a WQI is presented in Fig. 1. As can be seen in the figure, a WQI consists of a number of water quality parameters, which are transformed to a common scale. Such transformations are carried out since the monitored water quality data have different units. These values of the parameters transformed to a common scale are known as sub-indices. After all the sub-indices are obtained, they are aggregated to form the final index value. As indicated in Fig. 1, the aggregation process may occur in two sequential stages, from the sub-indices to the aggregated sub-indices (if aggregated sub-indices exist) and then from the aggregated sub-indices to the final index. The final index will be interpreted to evaluate or assess the status of the water quality.

In general, the information gained from the WQIs can be used for the following purposes:

a) To provide an overall status of water quality to the water authorities and the wider community (Ocampo-Duque et al. 2006)\
b) To study impacts of regulatory policies and environmental programs on environmental quality (Swamee and Tyagi 2007)
c) To compare the water quality of different sources and sites, without making highly technical assessment of the water quality data (Sarkar and Abbasi 2006)
d) To assist policy makers and the public to avoid subjective assessments and subsequent biased opinions (Stambuk-Giljanovic 1999; 2003)

The use of river water quality indices as a tool to evaluate water quality status has been adopted by many organizations and agencies, but there is no worldwide accepted methodology in developing a WQI. On the basis of literature reviewed, all indices have their own strengths and weaknesses. There are a few studies that have reviewed the existing WQIs. Lumb et al. (2011a) reviewed the conceptual frameworks of various WQI models developed from the 1960s till 2010 and presented the importance of various WQIs, the steps used in their formulation and their current uses. They also presented future directions and noted a need to develop a universally applicable WQI model that is flexible enough to cut across the available data for assessing the water quality for different uses. Tyagi et al. (2013) reviewed four popular WQIs and presented their merits and demerits. However, there is no systematic and thorough review of existing WQIs in the literature to explore and assess the steps used in their development and bring out the advantages and disadvantages of different methods used in each step.

This paper reviews 30 WQIs developed and used in different countries across the world. The reviewed WQIs, the country or region where they were applied and the reports or papers that presented their application are listed in Table 2 in the Appendix. The indices are reviewed on the basis of the following four steps that have been used in the past to develop a WQI (Abbasi and Abbasi 2012):

1. Selection of parameters
2. Obtaining sub-index values (transformation to a common scale)
3. Establishing weights
4. Aggregation of sub-indices to produce the final index

This paper presents the different methods employed in the reviewed indices for each of the above steps needed to develop a WQI. The advantages and disadvantages of the different methods used in each step are also discussed. Although 30 WQIs were reviewed, seven WQIs were identified as most important based on the popularity of their use. For these seven WQIs, the different steps used in their development and application are presented in detail.

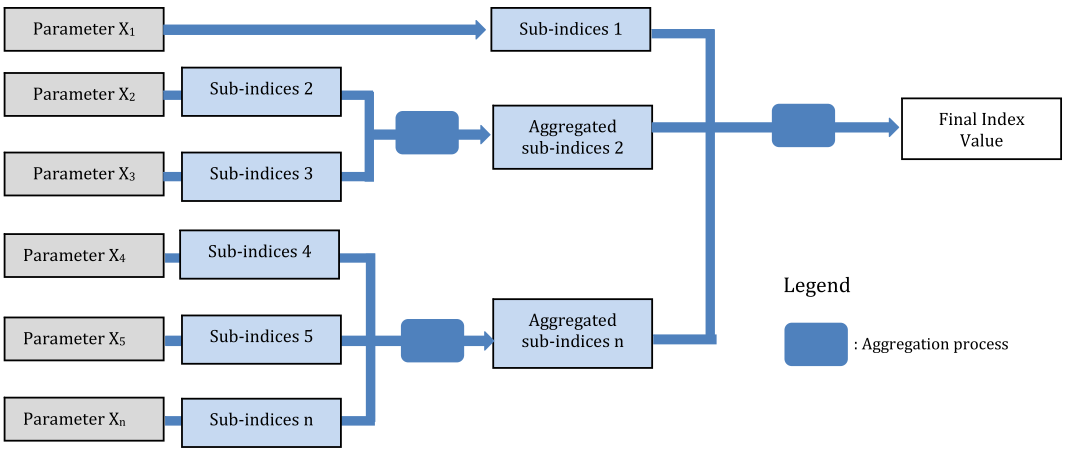


Fig 1 General structure of an index

The structure of this paper is as follows. Firstly, an overview of the 30 WQIs reviewed in this study is presented. Based on the 30 WQIs, details of the different methods used in each of the above-mentioned four steps needed to develop an index are then presented. This is followed by a detailed discussion on how the seven selected popular WQIs were developed and applied. Finally, recommendations for future research and conclusions are presented.

Overview of the reviewed WQIs

The 30 WQIs reviewed in this study (which are listed in the Appendix) are based on their applications in 66 journal articles, 30 reports from various government agencies and 4 conference papers. The applications for each of the 30 WQIs are also presented in the Appendix. The journals that contributed the maximum to this review are *Environmental Monitoring and Assessment* (19 papers), *Water Research* (8 papers), *Journal of Environmental Engineering* (4 papers), *Environmental Management* (4 papers), *Ecological Indicators* (4 papers) and *Water Science and Technology* (2 papers). The other journals had contributions of less than two papers each. The reviewed applications were published during the period 1987–2014, but it should be noted that the WQI may have been originally developed prior to 1987. In Table 2, the report or paper that presented the originally developed index is in italics.

Although all WQIs have a common overall structure, there were two main purposes in developing an index. These purposes can be either for general assessment of the water quality or for some specific uses. For all the reviewed WQIs, the purpose for which it was developed or has been applied is also provided in Table 2 (column 5). A general assessment aims to provide a glimpse of the water quality status, whereas specific uses are intended to fulfil "suitability" for certain uses (Smith 1990). As can be seen in Table 2, most of the WQIs aim to provide a general assessment of the river water quality status, whereas a few WQIs also consider specific uses such as suitability for drinking water supply, irrigation, bathing, aquaculture, forestry related activities and recreational uses.

It is worth mentioning here that the reviewed WQIs are based predominantly on physical and chemical parameters, and only a few WQIs have faecal coliform as an indicator for assessing the suitability of the river for recreational use. A state-of-the-art review of WQIs based on bioassessment has been presented in Abbasi and Abbasi (2011). It should also be noted that some of the WQI applications have adopted an originally developed WQI as it is or have modified a previous WQI so as to make it more suitable for a particular region or for a particular purpose. These modifications were typically made by using different water quality parameters or by applying different types of aggregation methods.

Steps in developing a water quality index

As mentioned earlier, there are in general four steps undertaken for the development of a WQI. Table 1 presents specific details about each of these four steps for all 30 WQIs reviewed in this study. Some studies had considered all steps to establish their indices, while a few others considered only certain steps in the development of the WQI. Of the four steps, 1, 2 and 4 are essential for all WQIs, whereas step 3 (which is the establishing of weights) was not used in some indices (i.e. they used equal weights). Details of these steps, including the different methods used under each step are discussed in this section.

Selection of parameters

Parameter selection is an essential step in the development of an index as the selected parameters are the main constituents of a WQI. The indices have different number of selected parameters, ranging from four (in Ross 1977; The River Ganga Index of Ved Prakash et al. as cited in Abbasi and Abbasi 2012) to 26 (in Diljido et al. 1994). With regard to the type of system used for the selection of parameters, they can be divided into three categories, viz. fixed, open and mixed systems. These three systems are discussed below:

1. Fixed system: The majority of WQIs reviewed have used a fixed set of parameters (e.g. Brown et al. 1970; Prati et al. 1971; Scottish Research Development Department (SRDD) 1976; Ross 1977; Dunnette 1979; House 1986; Cude 2001, Department of the Environment (DoE) Malaysia 2002; Hallock 2002; Liou et al. 2004; Said et al. 2004; Almeida et al. 2012). Consequently, the user can only utilize the selected parameters for final index calculation. Although using the same set of parameters will allow the user to have a better comparison of water quality status among sites or among rivers, this will create a common problem in index application called “rigidity”. Rigidity is manifested when necessity arises for additional important variables to be included in an index to address specific water quality concerns, but the user cannot add the new parameters needed for the future index application (Swamee and Tyagi 2007).
2. Open system: Some WQIs recommend the use of a minimum number of so-called basic parameters based on their characteristics [Ministry of the Environment of Indonesia (MoEI) 2003; CCME 2001] and also based on their impacts on the environment (Oudin et al. 1999). The basic parameters are a fixed set of parameters that should always be in the final index calculation as they are the most significant parameters for water quality evaluation in that site or region (Dojlido et al. 1994). On the other hand, some WQIs (e.g. Harkins 1974) do not provide any guidelines at all for the selection of parameters. Application of such WQIs might vary from one place to another because not only are the parameters not specified, but the maximum number of selected parameters in the final index calculation is also not specified. Thus, in the application of such WQIs, the users are able to incorporate as many parameters from the list of potential parameters. Such flexibility has the advantage that it will avoid rigidity (Swamee and Tyagi 2007). However, not having a fixed set of parameters poses critical issues such as difficulty in making comparisons among monitored sites and among river basins (Terrado et al. 2010).
3. Mixed system: The mixed system consists of the basic as well as additional parameters. Additional parameters are used in the final index calculation only if one of the additional parameters has a greater sub-index value than the aggregated index value based on the basic parameters. In this case, the final aggregated index value should be recalculated by adding or considering those additional parameters having greater sub-index values (Dojlido et al. 1994). These additional parameters are usually less monitored, particularly toxic parameters (Hanh et al. 2011).

The selection of parameters, in particular for the fixed and mixed systems, aim to select the parameters which have the greatest influence on water quality of the river. However, Abbasi and Abbasi (2012) accentuate that there is no method by which 100 % objectivity or accuracy can be achieved in the selection of parameters. In general, in the design of a WQI, an initial set of the water quality parameters is decided through the following:

a) A literature review (Said et al. 2004; Pesce and Wunderlin 2000; Kannel et al. 2007)
b) Data availability (Cude 2001)
c) Redundancy of parameters (parameters that have similar properties need not be considered) (Dunnette 1979)
d) Parameters should represent the overall water quality status (Dunnette 1979; Hanh et al. 2011)

Table 1 Specific details regarding the four steps needed to develop a WQI for all the reviewed WQIs

Name of WQI (1)	Selected parameters (2)	Sub-indices used (3)	Weights used (4)	Aggregation method used (5)
Canadian Council of Ministers of the Environment (CCME) Water Quality Index	• At least 4 parameters • Maximum number of parameters is not specified	• No sub-indices used	• No weights used	• Specific equation (as presented later in Eq. 21) by considering three factors namely, scope, frequency and amplitude
National Sanitation Foundation (NSF) Index	• 11 parameters: dissolved oxygen (DO), faecal coliform (FC), pH, biochemical oxygen demand—5 days (BOD_5), temperature, total phosphorus (TP), nitrates (NO_3), turbidity, total solids (TS), pesticides and toxic compounds	• Parameters directly taken as sub-indices using rating curves developed by expert's opinions	• Unequal weights • Sum of weights is 1	• Additive aggregation (first version) • Multiplicative aggregation (second version)
Oregon Index	• 6 parameters (first version): DO, pH, FC, BOD_5, TS, NO_3 + ammonia • 8 parameters (second version): TP, temperature (in addition to the 6 parameters in the first version)	• Parameters directly taken as sub-indices	• Unequal weights with the sum of weights equal to 1 (first version) • Equal weights (second version)	• Additive (first version) • Unweighted. Harmonic mean of squares of the sub-indices (second version)
Bascarón index	• 26 parameters: pH, BOD_5, DO, temperature, total coliform (TC), colour, turbidity, permanganate reduction, detergents, hardness, DO, pesticides, oil and grease, sulphates (SO_4), NO_3, cyanides, sodium, free CO_2, ammonia nitrogen (ammonia-N), chloride (Cl), conductivity, magnesium (Mg), phosphorus (P), nitrites (NO_2), calcium (Ca) and apparent aspect	• Parameters directly taken as sub-indices through piecewise (segmented) linear transformation	• Unequal weights • Sum of weights is 54	• Modified additive
House's Index	• 9 parameters for general water quality: DO, ammoniacal nitrogen, BOD_5, suspended solids (SS), NO_3, pH, temperature, Chlorides (Cl), and Total Coliform (TC) • 13 parameters for potable water supply: DO, ammoniacal nitrogen, BOD_5, SS, NO_3, pH, temperature, Cl, TC, sulphates, fluorides, colour and dissolved iron • 12 parameters for aquatic toxicity: dissolved copper, total zinc, dissolved cadmium, dissolved lead, dissolved chromium, total arsenic, total mercury, total cyanide, phenols, total hydrocarbons, PAHs, total pesticides • 12 parameters for potable sapidity: total copper, total zinc, total cadmium, total lead, total chromium, total arsenic, total mercury, total cyanide, phenols, total hydrocarbons, PAHs, total pesticides	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Additive
Scottish Research Development Department (SRDD) index	• 10 parameters: DO, BOD_5, free and saline ammonia, pH, total oxidized (TO), N, phosphate, (SS), temperature, conductivity and *Escherichia coli* (EC)	• Parameters directly taken as sub-indices using rating curves developed by expert's opinions	• Unequal weights • Sum of weights is 1	• Additive

Table 1 (continued)

Name of WQI (1)	Selected parameters (2)	Sub-indices used (3)	Weights used (4)	Aggregation method used (5)
Fuzzy-based indices	• No guidelines	• Using fuzzy logic	• Unequal weights	• Using fuzzy logic
Bhargava's Index	• 4 different groups: coliform organisms, heavy metals, physical parameters and organic and inorganic parameters	• Parameters in the same group are aggregated to obtain 4 different group sub-indices	• Unequal weights • Sum of weights is 1	• Modified multiplicative
Malaysian index	• 6 parameters: COD, ammonia-N, nitrate, phosphate and sulphates and pH	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Additive
Status and Sustainability index	• 15 alteration classes based on their similar nature and its impact on environment: nitrates, phosphorus matter, suspended particles, colour, temperature, mineralization, acidification, microorganisms, phytoplankton, mineral micro pollutants, metals in bryophytes, pesticides, organic micro-pollutants and non-pesticides	• 3 alteration classes, NO_3^-, colour, temperature: directly taken as sub-indices • Other alteration classes: only 1 parameter, which has the worst value in the same alteration class, is considered as sub-indices (minimum operator)	• Equal weights	• Minimum operator
Dalmatian index	• 9 parameters: temperature, mineralization, corrosion coefficient, $K = (Cl + SO4)/HCO_3$, DO, BOD_5, TN, protein N, TP and TC	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 100	• Additive or multiplicative
Dinius' index	• 12 parameters: DO, BOD_5, EC, alkalinity, hardness, fluoride, specific conductance, pH, NO_3, temperature and colour	• Parameters directly taken as sub- indices	• Unequal weights • Sum of weights is 10	• Multiplicative means
Diljido's index	• 7 basic parameters: BOD_5, SS, phosphate, ammonia, DO, COD-Mn, dissolved solids • 19 additional parameters: Fe, phenols, organic nitrogen, hardness, manganese (Mn), sulphates, Cl, COD-Cr, nitrate, lead (Pb), mercury (Hg), copper (Cu), chromium (IV), total chromium, zinc (Zn), cadmium (Ca), nickel and free cyanides	• Parameters directly taken as sub-indices	• Equal weights	• The square root of the harmonic mean
The River Ganga Index of Ved Prakash et al.	• 4 parameters: DO, FC, pH and BOD	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Additive
Water pollution index	• Recommended at least 15 parameters include the following: temperature, colour, turbidity, pH, FC, total dissolved solids (TDS), SS, total nitrogen (TN), alkalinity, hardness, Cl, iron (Fe), manganese (Mn), SO_4 and DO	• Parameters directly taken as sub-indices using average and maximum values of ratio between concentration of the respective parameter over the permissible limits	• Equal weights	• The root mean square
Almeida's Index	• 9 parameters: pH, COD, NO_3, phosphate, detergents, enterococci, TC, FC and *Escherichia coli*	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Multiplicative
Boyacioglu's index	• 12 parameters: TC, cadmium, cyanide, mercury, selenium, arsenic, fluoride (F), nitrate-nitrogen, DO, pH, BOD_5, TP	• Parameters directly taken as sub-indices using the permissible limits of water standards	• Unequal weights • Total weight is 1	• Additive
Contact recreation index	• 8 parameters: pH, colour, visual clarity, turbidity, dissolved reactive phosphorus, dissolved inorganic nitrogen, BOD_5	• Parameters directly taken as sub-indices	• Equal weights	• Minimum operator

Table 1 (continued)

Name of WQI (1)	Selected parameters (2)	Sub-indices used (3)	Weights used (4)	Aggregation method used (5)
Hallock's index	• 8 parameters: temperature, DO, pH, FC, TN, TP, TSS and turbidity, FC	• Temperature, pH, FC, pH directly taken as sub-indices using continues scaling developed from the permissible limits • Turbidity and TSS are aggregated to generate 1 sub-indices using average mean • Other parameters directly taken as sub-indices using distribution of historical data • TP and TN have lower scale compared to others sub-indices	• Equal weights	• Additive
Hanh's index	• At least 10 parameters: SS, turbidity, DO, COD, BOD5, orthophosphate, ammonium nitrogen, TC, temperature, toxicity and pH	• Parameters directly taken as sub-indices using the permissible limits of water standards • All parameters directly taken as sub-indices using TC taken as "bacteria" sub-indices • DO, COD, BOD_5, ammonia nitrogen and orthophosphate are aggregated to obtain "organics and nutrients" sub-indices • SS and turbidity are aggregated to obtain "particulates" sub-indices	• Equal weights	• Combination of additive and multiplicative means • Additive method is used to aggregate parameters in similar characteristic (organics, particulates and microorganism) • Multiplicative method is used to aggregate all sub-indices
Harkins' index	• No guidelines	• Parameters are standardized using the target value (usually the permissible limit)	• Unequal weights	• Statistical procedures through multivariate Kendall's statistic (non-parametric classification procedure)
Indian pollutant index	• 13 parameters: turbidity, pH, colour, DO, BOD_5, TDS, hardness, Cl, SO_4, NO_3, total coliform, As and F.	• Parameters directly taken as sub-indices	• Equal weights	• Additive
Liou's index	• At least following 10 parameters (the main parameters): DO, BOD_5, ammonia nitrogen, SS, turbidity, FC, temperature, toxic parameters and pH	• Parameters directly taken as sub-indices using the permissible limits of water standards • FC directly taken as "microorganism" sub-indices • DO, BOD_5, ammonia nitrogen are aggregated to obtain "organics" sub-indices • SS and turbidity are aggregated to obtain "particulates" sub-indices	• Equal weights	• Combination of additive and multiplicative means • Additive method is used to aggregate parameters in similar characteristic (organics, particulates and microorganism) • Multiplicative method is used to aggregate all sub-indices
Prati's index	• 13 parameters: pH, DO, BOD, COD (based on permanganate or Kubel test), SS, ammonia, nitrates, chlorine, Fe, Mn, alkyl benzene sulphonates and carbon chloroform extract	• Parameters directly taken as sub-indices using the permissible limits of water standards	• Unequal weights • Sum of weights is 1	• Additive
Ross' index	• 4 common parameters: SS, BOD_5, DO and ammoniacal N	• Parameters directly taken as sub-indices using rating curves developed by expert's opinions	• Unequal weights • Sum of weights is 10	• Additive

Table 1 (continued)

Name of WQI (1)	Selected parameters (2)	Sub-indices used (3)	Weights used (4)	Aggregation method used (5)
Said's index	• 5 parameters: DO, Turbidity, TP, FC and specific conductivity	• Parameters directly taken as sub- indices	• Equal weights	• Specific linear equation
Smith's index	• 4 parameters for fish spawning use: SS, turbidity, temperature, BOD_5 (unfiltered) • 6 parameters for general and bathing uses: DO, SS, turbidity, temperature, BOD_5 (unfiltered), FC • 7 parameters for water supply use : DO, SS, turbidity, temperature, BOD_5 (unfiltered), ammonia and FC	• Parameters directly taken as sub-indices using rating curves developed by expert's opinions	• Unequal weights • Sum of weights is 1	• Minimum operator
Stoner's index	• 13 parameters for water supply use: ammonia-nitrogen, Cl, colour, Cu, FC, F, Fe, MBAS, nitrite-nitrogen, pH, phenols, sulphate, Zi • 16 parameters for irrigation use: SAR, specific conductance, FC, arsenic, boron, Cd, aluminium, beryllium, chromium, cobalt, manganese, vanadium, Cu, F, nickel and Zi	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Additive
Storet index	• No specific number, but the parameters are divided into three major groups, namely physical, chemical and biological	• Having three sub-indices: physical, chemical and biological using direct comparison between values of respective parameters and the permissible limits	• Unequal weights generated based on different types of sub-indices, minimum values, mean values and maximum values	• Additive
Walski and Parker's index	• SS, turbidity, nutrients, grease, colour, threshold odor, pH, temperature, toxicity and coliform count	• Parameters directly taken as sub-indices	• Unequal weights • Sum of weights is 1	• Modified multiplicative (geometric mean)

e) The intended use of the water body (Prati et al. 1971; Stoner 1978; Smith 1990; Hurley et al. 2012)

To minimize subjectivity and uncertainty in this step, the initial set (decided based on the above criteria) is usually refined through two methods, namely expert judgement and statistical methods, which are discussed below:

Expert judgement

One of the challenges in many WQIs is the selection of significant parameters to be included in the final aggregation of the index. The initial set of selected water quality parameters involves a great deal of subjective assessment of the index developers. To deal with this, the involvement of expert judgement has been applied to reduce the uncertainty and inaccuracy in selecting the significant parameters.

In general, expert judgement can be incorporated in the selection of parameters through three approaches, namely individual interviews, interactive groups and the Delphi method (Meyer and Booker 1990). Of the three approaches, the Delphi method is the one that has been widely used for the selection of parameters (Juwana et al. 2010). This method aims to mine view or opinion from experts without having the experts to congregate at an agreed time and place (Delbecq et al. 1975). Linstone and Turoff (2002) define the Delphi method as follows:

> …a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem (Linstone and Turoff 2002, p. 3).

There is an important pre-condition for the Delphi method that should be met before its implementation. The index developers should isolate the water quality experts from one another when they give their judgements and should also make their judgements anonymous. This aims to avoid some of the biasing effects, particularly due to interactions between experts. Such interactions could lead to dominant experts causing the other experts to agree to a judgement that they do not hold (Meyer and Booker 1990).

Application of this method often needs several rounds of questionnaires until convergence of experts' opinion is achieved (Brown et al. 1970; SRDD 1976; Dunnette 1979; Dinius 1987; House 1989; Almeida et al. 2012). In the first questionnaire, the respondents are asked to rate a set of parameters for possible inclusion in the WQI. At this stage, they are also allowed to add new parameters that were not included in the questionnaire. In the second round, they are asked to review the results of the first questionnaire, including adding new parameters. The intention here is to introduce new parameters and initiate a lesser divergence of water quality experts' opinion with respect to various parameters rated. These iterations can be continued until consensus on types and number of parameters is achieved.

Statistical methods

The other approach that is commonly used in the selection of significant parameters is the use of statistical methods, which include Pearson's coefficient of correlation and principal component/factor analysis (PCA/PFA). Although this might be the most objective method for parameter selection, it is still subjective in the sense that these methods are ultimately dependent upon the data provided for the analysis (House 1986; Abbasi and Abbasi 2012).

Pearson's coefficient of correlation is, in general, used to reduce the number of water quality parameters by eliminating some parameters which are highly correlated with the others. For example, Debels et al. (2005) eliminated ammonia and orthophosphate due to their high correlation with chemical oxygen demand (COD). The other statistical method, PCA/PFA, is often employed for grouping the parameters that have similar characteristics (Liou et al. 2004; Hanh et al. 2011) and to reduce number of parameters by selecting the parameters that explain most of the variance observed. Debels et al. (2005) and Koçer and Sevgili (2014) used PCA to cluster several parameters into "certain groups" and then removed some of them to develop a WQI with a minimum number of parameters. Gazzaz et al. (2012) employed the PFA to reduce number of water quality parameters by considering only parameters that exhibit large factor loadings for subsequent analysis.

Generation of sub-indices

This step aims to transform the water quality parameters into a common scale since the actual values of the parameters have their own different units; for example, ammonia nitrogen has the unit of milligram per litre, while turbidity is presented in nephelometric turbidity units (NTU). Further, the ranges of levels to which different parameters can occur vary greatly from parameter to parameter; for example, dissolved oxygen (DO) would rarely be beyond the range 0–12 mg/L, whereas sodium can be in the range 0–1000 mg/L or beyond (Abbasi and Abbasi 2012). In most of the WQIs, the parameters can only be aggregated when they have the same common scales; therefore, rescaling or standardizing to form sub-indices is necessary. A few WQIs do not consider this step. Instead of sub-indices, the actual values of the parameters are used in the final index aggregation. For example, CCME (2001) developed multivariate statistical procedure to aggregate the actual values of the parameters without transforming them into a common scale, whereas Said et al. (2004) proposed a specific mathematic equation used for directly aggregating the index, in which there is no need to standardize the parameters.

In some WQIs, particular parameter(s) are directly taken as individual sub-indices to be aggregated to a final index value. On the other hand, the individual sub-indices can also be further aggregated to form a bigger group of sub-indices, which are then aggregated to a final index value (often called composite or aggregated sub-indices). For example, Bhargava's Index (Bhargava 1985) has four different aggregated sub-indices, viz. coliform, heavy metals, physical parameters and organic and inorganic sub-indices. The Status and Sustainability index (Oudin et al. 1999) has 12 different aggregated sub-indices, ranging from phosphorous matter to phytoplankton sub-indices.

In general, to obtain the sub-index values, the index developers establish sub-index functions or rating curves. Sub-index functions are mathematical relationships between actual values of parameters monitored and the sub-index values. The actual values of the parameters can be converted to sub-index values using the sub-index functions. A rating curve is a corresponding graph of the value of parameters (on *x*-axis) against the sub-index values (on *y*-axis). In most WQIs, different sub-index functions are used for computing the sub-index values of different parameters. These sub-index functions or rating curves can also be used interactively and thus help the index developers to define all parameters with dimensionless values within an identical range (i.e. 0–100 or 0–1). To establish the sub-index functions or rating curves of different parameters, there are three different methods that are commonly employed: (1) expert judgement, (2) use of the water quality standards and (3) statistical methods.

Expert judgement

Experts' judgement can be used to develop sub-index functions or rating curves. In this approach, "key points" of rating curves are obtained using questionnaires. Similar to the selection of parameters for the WQI, the Delphi method is employed here also to have convergence of water experts' opinion on sub-index values. Deininger (1980) explained that the experts are asked to draw (often manually) the rating curves based on their judgement to identify the level of water quality variation by the various possible measurements of the respective parameters. A set of rating curves were developed based on agreed key points from experts' opinions. In many WQIs, such rating curves are then converted into linear or non-linear sub-index functions. Then, the index users generate the sub-index values through direct calculations by using the sub-index functions. Such an approach has been widely used in the development of various WQIs, such as the National Sanitation Foundation (NSF) Index (Brown et al. 1970), the Scottish Research Development Department (SRDD) index (SRDD 1976), Ross' Index (Ross 1977), Oregon Index (Dunnette 1979), House's Index (House 1986), and Almeida's Index (Almeida et al. 2012).

Use of the water quality standards

Another approach to establish rating curves or sub-index functions is based on the permissible limits from the legislated standards, such as technical regulations, national water requirements and WHO standards or international directives. House (1986) explained that the use of water quality standards facilitates sub-division of sub-index values and provide more information for the users. In this approach, the key points defining rating curves or sub-index functions are obtained using the permissible limits for various levels of intended uses. On the basis of these, actual parameter values can be transformed into sub-index values through three methods, namely linear interpolation rescaling, categorical scaling and comparison with the permissible limits.

The linear interpolation rescaling is a method used to produce an identical range for sub-index values, usually 0–100 or 0–1 (Prati et al. 1971; House 1989; Bascarón 1979; Dojlido et al. 1994; Stambuk-Giljanovic 2003;

Liou et al. 2004). The index developers established the rating curves based on drinkable water use (class 1), domestic water supply (class 2), irrigation (class 3), navigation (class 4) and wastewater (class 5), wherein the permissible limits for each class has different sub-index values. For example, the permissible limit for BOD_5 is 4, 6, 15, 20 and 50 mg/L for class 1, 2, 3, 4 and 5, respectively. Those actual parameters are then converted into specific sub-indices, e.g. 100, 75, 50, 25 and 1, respectively. These pairs of data (i.e. 4:100, 6:75, 15:50, 20:25 and 50:1) based on the relationship between the permissible limits and the sub-index values are referred to as the key points of rating curves (Hanh et al. 2011). If actual parameters lie in between two classes, a simple linear interpolation is used to obtain their sub-index values. The permissible limits of upper and lower classes will be the maximum and minimum values. In this method, sub-index functions used to calculate the sub-index values use the following general equations:

$$S_i = S_1 - \left[(S_1 - S_2) \left(\frac{x_i - x_1}{x_2 - x_1} \right) \right] \tag{1}$$

$$S_i = S_1 - \left[(S_1 - S_2) \left(\frac{x_1 - x_i}{x_1 - x_2} \right) \right] \tag{2}$$

where S_i is ith sub-index value, S_1 and S_2 are the sub-index values for upper and lower class, respectively, and X_1 and X_2 are values of the permissible limits for upper and lower class. Equation (1) is used to generate sub-indices when a parameter has a decreasing level of water quality with an increase in actual parameter values (e.g. BOD_5). On the other hand, Eq. (2) is used if a parameter has an increasing level of water quality with an increase in actual parameter values (e.g. DO).

The second method that transforms actual parameter values to sub-indices is the categorical scaling method. It is a method typically used for parameters assigned as constants wherein the values must be 0 or 1. If the concentration of a parameter is well above or exceeding the permissible limit, then the sub-index value will fall to 0. In contrast, the sub-index value will be 1 if the concentration is below the permissible limits (MoEI 2003; Liou et al. 2004). The general equation to generate sub-index values using this method is as follows:

$$S_i = 0, \text{ if } X_i \text{ is well above the permissible limits} \tag{3}$$

$$S_i = 1, \text{ if } X_i \text{ is well below the permissible limits} \tag{4}$$

where S_i is the ith sub-index value and x_i is the ith actual parameter value.

The last method to generate sub-indices is based on comparison of the actual value of the parameters with their permissible limits. The sub-index values range from 0 to 1, in accordance with the degree of water quality from worst to highest. Liou et al. (2004) defined the sub-index value in this approach as follows:

$$S_i = \frac{x_i}{x_{\max}} \tag{5}$$

where S_i is ith sub-index value, X_i is the actual parameter value (mg/L) and $X_{\max}$ is the maximum value of the permissible limit (mg/L).

Statistical analysis

This approach utilizes statistical characteristics (like the mean or various quantiles) of the historical data to obtain the key points for generating the rating curves. For example, Dunnette (1979) used arithmetic mean of actual parameter values of six monitoring stations during the years 1973–1975 in Willamette River in Oregon to correspond to sub-index values of 80 for BOD_5, total solids, oxygen and nitrogen and 70 for faecal coliform (FC). Hallock (2002) developed rating curves of total phosphorous, total nutrients, turbidity and total suspended solids based on fitting sub-index values of 100, 80, 40 and 20 to actual parameter values of those parameters at the 10th, 80th, 95th and 99th percentiles, respectively.

Establishing weights

The weights are assigned to the parameters with regard to their relative importance and their influence on the final index value. In general, the weights of all parameters can be either equal or unequal. Equal weights are assigned if the parameters of an index are equally important, whereas if some parameters have greater or lesser importance than others, then unequal weights are assigned.

A few of the index developers used equal weights in the development of WQIs (e.g. Nemerow and Sumitomo 1970; Harkins 1974; Dojlido et al. 1994; Oudin et al. 1999; Cude 2001; CCME 2001; Hallock 2002; Hanh et al. 2011). These studies preferred equal weights to unequal weights since there were doubts related to subjectivity over experts' opinion in reaching a convergence (as expert panel often give different weights to the same parameters) (Harkins 1974). Moreover, different weights could lead to sensitivity of the final index to the most heavily weighted parameter. For instance, in an index heavily weighted towards DO, high concentrations of faecal coliform may not be reflected in the final index value if DO concentration is near ideal. This characteristic (of high faecal coliforms not being reflected in the final index) may be desirable in water quality indices specific to the protection of aquatic life. However, for WQIs that are designed to communicate general status of water quality rather than the quality of water for any specific use, sensitivity to changes in each variable is more desirable than sensitivity to the most heavily weighted variable (Cude 2001).

In unequal weights, to avoid subjectivity of the index developers, parameter weights are given based on participatory-based approaches, which may involve the key stakeholders like water quality experts, policy makers or practitioners from environmental protection agencies of a certain region. Even though there are a few participatory-based approaches that are available to generate weights, only two methods have been widely used. These two methods are the Delphi method and the analytical hierarchy process (AHP). The other available participatory-based approaches such as budget allocation procedure (BAP) and the revised Simos' procedure have been used to determine weights of indicators for indices other than WQIs (Kodikara et al. 2010).

The Delphi method has been commonly used for summing up individual expert opinions to establish parameter weights for various WQIs. Horton (1965) proposed weights for parameters as follows: one for four parameters (special conductivity, chlorides, alkalinity and carbon chloroform extract), two for one parameter (coliform) and four for three parameters (DO, sewerage treatment and pH). To minimize subjectivity and enhance credibility, this procedure for parameter weighting was then improved by Brown et al. (1970) through incorporating a large panel of water quality experts from the USA. They were asked to compare relative water quality using a scale of 1 (highest) to 5 (lowest). Arithmetic mean was calculated for the ratings of all experts' opinion. Then, a temporary weight of 1.0 was assigned to the parameter which received the highest significance rating. All other temporary weights were obtained by dividing the highest rating by the individual mean rating. Each temporary weight was then divided by the sum of all the temporary weights to arrive at the final weight. Since then, the Delphi method has been used in many WQIs to generate the relative weights of the selected parameters. It should be noted that the total weight, which is the summation of weights of all the selected parameters, is 1 for most WQIs.

The AHP is the other method employed to gain expert's judgement for assigning weights to the parameters. It is a mature and easy concept, which has been widely used in many other different fields. It allows the decision-makers to incorporate both quantitative and qualitative aspects in the decision-making processes. In this method, a weight assessment is performed through pair-wise comparison matrices, in which the respondents (experts or public) are required to give their preference by comparing several choices. The AHP method is very useful to determine the weights of either individual or aggregated parameters. Ocampo-Duque et al. (2006) employed the AHP for generating weights of five groups of similar parameters. Gazzaz et al. (2012) used the AHP for establishing weights that will be used in an artificial neural network (ANN) model for computing the WQI.

Index aggregation

Index aggregation is performed after the assignment of weights to obtain the final index value. Such an aggregation may occur in sequential stages if an index has aggregated sub-indices. In such cases, the aggregated sub-indices are again aggregated to obtain the final index value. The two most common aggregation methods for the sub-indices are the additive (arithmetic) and multiplicative (geometric) methods. It should also be noted that there are other modified versions of these two basic methods. The basic equations for additive aggregation with equal and unequal weights are presented in Eqs. (6) and (7), respectively.

$$\mathrm{WQI} = \sum_{i=1}^{n} S_i \tag{6}$$

$$\mathrm{WQI} = \sum_{i=1}^{n} S_i w_i \tag{7}$$

where WQI is the aggregated index, n is the number of sub-indices, w_i is ith weight and S_i is the ith sub-index. The weights (w_i) indicate the relative importance of S_i. As can be seen in Table 1 (column 5), the additive method has been widely used to aggregate the sub-indices of various existing WQIs (e.g. Prati et al. 1971; Brown et al. 1970; SRDD 1976; Ross 1977; Bascarón 1979; Dunnette 1979; House 1989; Sargaonkar and Deshpande 2003). It offers simplicity wherein the final index value is calculated by the addition of the weighted sub-indices.

A few WQIs have also used modified additive methods that calculate the squared function of an aggregated index and then divide it by 100 (SRDD 1976; Bordalo et al. 2006; Carvalho et al. 2011), as shown by the following equations:

$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} S_i\right)^2 \tag{8}$$

$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} S_i w_i\right)^2 \tag{9}$$

where the symbols in Eqs. (8) and (9) are the same as those in Eqs. (6) and (7).

Bascarón (1979) proposed another modified version of the additive method for index aggregation, as shown in Eq. (10). In this version, the total values of final aggregation should be divided by the total weights of the selected parameters. Such an aggregation method has been adopted and modified further in some WQIs (e.g. Pesce and Wunderlin 2000; Debels et al. 2005; Abrahão et al. 2007; Sánchez et al. 2007; Koçer and Sevgili 2014).

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \tag{10}$$

where WQI is the aggregated index, n is number of parameters, C_i is the sub-index value (called normalization factor in Bascarón index) and P_i is the relative weight of each parameter. Details of the method used for calculating C_i are presented later, when the Bascarón index is discussed in detail.

Although the additive method provides a simple way of index aggregation, this method creates the problem known as "eclipsing", wherein the final index value does not represent the actual state of overall water quality as the lower values of one or some sub-indices are dominated by the higher values of other sub-indices or vice versa (Swamee and Tyagi 2000; Liou et al. 2004; Juwana et al. 2012). Smith (1990) also highlighted that this method would never produce a zero value of the final index albeit one of sub-indices is 0.

The other commonly used index aggregation method, namely the multiplicative method which is shown in Eqs. (11) and (12), was suggested by Brown (1973). Since then, this method has been adopted for final aggregation in many WQIs (e.g. Walski and Parker 1974; SRDD 1976; Bhargava 1985; Dinius 1987; Almeida et al. 2012).

$$\mathrm{WQI} = \prod_{1=1}^{n} S_i^{w_i} \tag{11}$$

$$\mathrm{WQI} = \prod_{1=1}^{n} S_i^{1/n} \tag{12}$$

where the symbols are the same as earlier and the sum of weights is equal to 1. When the weights in Eq. (11) are equal, then the equation takes the form presented in Eq. (12).

Although perfect substitutability and compensability among sub-indices do not arise in the multiplicative method (as these problems occur in the additive method), the multiplicative method still suffers from the eclipsing problem (Simth 1990; Swamee and Tyagi 2000; Juwana et al. 2012). Smith (1990) and Liou et al. (2004) showed that if one low water quality parameter exists, using the multiplicative method will lead to a low final aggregated index. As an extreme case, the final aggregated index value will be 0 if one of the parameters has a sub-index value of 0 (irrespective of other sub-index values). Furthermore, another ambiguity arises if variables' weighing is very close to zero. It will lead to the weighted sub-index value being close to 1 (even though it has a high unweighted sub-index value). Such a situation in aggregation is referred to as the dichotomous sub-index problem (Ott 1978; Liou et al. 2004). Thus, the value of the sub-index gets transformed into either 0 or 1. To deal with these limitations, Smith (1990) proposed a minimum operator to aggregate sub-indices, which is defined by Eq. (13):

$$\mathrm{WQI} = \mathrm{Min}(I_1, I_2, \ldots, I_n) \tag{13}$$

where I_i is the sub-index value for the ith parameter and n is number of sub-indices.

The minimum operator aggregation addresses eclipsing and ambiguity in the aggregation process; however, this method fails to provide a composite picture of overall water quality (Swamee and Tyagi 2000). This aggregation method has been adopted by few indices (Oudin et al. 1999; Hèbert 2005).

Dojlido et al. (1994) proposed to use the harmonic mean of squares method to aggregate sub-indices of a WQI in order to deal with the eclipsing problem. Cude (2001) explained that this method allows the parameters that have low quality to impart the greatest influence on the water quality index and acknowledges that different water quality parameters will pose different significance to overall water quality at different times and locations. Nevertheless, Swamee and Tyagi (2000) highlighted that such an aggregation method suffers from the problem called "ambiguity". Ambiguity exists where all the sub-indices are acceptable and yet the overall index is not. This may result in considering the overall water quality as unacceptable, although it actually is of acceptable quality. The equation for the square root of the harmonic mean of squares (of the sub-indices) aggregation is as follows:

$$\mathrm{WQI}-\sqrt{\frac{n}{\sum_{i=1}^{n}\frac{1}{S_i^2}}} \tag{14}$$

where the symbols are the same as those used earlier. In this aggregation method, it is assumed that all S_i values are non-zero and if any S_i value is zero, the WQI will be taken as zero.

To avoid the problems of eclipsing and ambiguity, another aggregation approach was proposed by Liou et al. (2004) through the use of a mixed-aggregation method (combination of additive and geometric methods). According to Liou et al. (2004), parameters that have a very strong correlation are first clustered into three groups, namely organics, particulates and faecal coliform. In order to generate the aggregated sub-index values for each group, parameters in the same group are aggregated through the equal additive method. Then, the three sub-indices are aggregated to have the final index value by using geometric mean. The overall water quality index is generated by multiplying the aggregated index by three scaling coefficients, as shown in Eq. (15):

$$\mathrm{WQI} = C_{\mathrm{temp}}C_{\mathrm{pH}}C_{\mathrm{Tox}}\left[\left(\sum_{i=1}^{n} I_i w_i\right)\left(\sum_{j=1}^{n} I_j w_j\right)\left(\sum_{k=1}^{n} I_k w_k\right)\right]^{1/3} \tag{15}$$

where I_i denotes the sub-index value for the organics parameters, I_j represents the sub-index value for the particulate parameters and I_k is the sub-index for faecal coliform. In addition, three scaling coefficients are prefixed, which address the sub-indices of temperature (C_{temp}), pH (C_{pH}) and toxic substances (C_{Tox}), respectively. Hanh et al. (2011) also employed a similar hybrid aggregation method (of additive and multiplicative forms) to aggregate the sub-indices to produce a final index value.

In addition to the methods explained above, a significant contribution for final aggregation was introduced in the development of the CCME WQI (CCME 2001). In this method, all parameters are standardized, and three factors on which the index is founded are calculated. These three factors are scope, frequency and amplitude, which are denoted by notations F_1, F_2 and F_3, respectively. F_1 refers to the number of parameters that do not meet the water quality standards (calculated using Eq. (16)), whereas frequency defines the frequency with which the objectives are not met (Eq. (17)). Amplitude corresponds to the amount by which the objectives are not met. The calculation of F_1 and F_2 is relatively straightforward, but F_3 requires some additional steps. F_3 is calculated in three steps. In the first step, the number of times by which an individual concentration is greater than the objective of a parameter (or less than, when the objective is a minimum) is termed an "excursion" and is calculated using Eq. (18) (when the test value must not exceed the objective). Then, the collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives). This variable, referred to as the "normalized sum of excursions", or *nse*, is calculated using Eq. (19). The amplitude F_3 is then calculated using Eq. (20) and the final index is calculated using Eq. (21) (CCME 2001).

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of tests}}\right) \times 100 \tag{16}$$

$$F_2 = \left(\frac{\text{Number of failed variables}}{\text{Total number of tests}}\right) \times 100 \tag{17}$$

$$\text{excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_i}\right) - 1 \tag{18}$$

$$nse = \left(\frac{\sum_{i=1}^{n} \text{excursions}}{\text{number of tests}} \right) \quad (19)$$

$$F_3 = \left(\frac{nse}{0.01nse + 0.001} \right) \quad (20)$$

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{(F_1) + (F_2)^2 + (F_3)^2}}{1.732} \right) \quad (21)$$

where 1.732 is a constant that normalizes the resultant values to a range between 0 and 100, where 0 represents the "worst" and 100 represents the "best" water quality. Tyagi et al. (2013) pointed out some demerits of this aggregation method, especially indicating that F_1 does not work appropriately when too few variables are considered or when too much covariance exists among them.

Another final aggregation method was proposed by Said et al. (2004). They used a simplified mathematical expression for final aggregation, which is presented in Eq. (22). The advantage of this method is that it is able to determine the final aggregated index through direct calculations using the selected parameters and without generating the sub-indices. However, this equation was developed for a specific region and it might not be suitable for other regions.

$$\text{WQI} = log \left[\frac{\text{DO}^{1.5}}{(3.8)^{\text{TP}} (\text{Turb})^{0.15} (15)^{\frac{\text{FCol}}{1000}} + 0.14(SC)^{0.5}} \right] \quad (22)$$

where DO is the dissolved oxygen (% oxygen saturation), Turb is the turbidity (in nephelometric turbidity units [NTU]), TP is the total phosphorus (mg/L), FCol is the faecal coliform bacteria (counts/100 mL) and *SC* is the specific conductivity (in MS/cm at 25 °C).

Important water quality indices

Although 30 WQIs were reviewed in this study, only seven of those WQIs (first seven indices listed in the Appendix) were selected and explained in detail in this section based on their popularity. The popularity of a WQI was decided based on two criteria, namely the number of their applications in refereed journals and by government agencies. The indices presented in Table 2 are listed in the order of their popularity, with the first WQI in the list (CCME WQI) being the most popular, with its applications presented in 14 journal papers and in more than ten government agency reports. These applications are listed in columns 3 and 4 of Table 2.

The following sub-sections discuss the seven selected WQIs, especially with emphasis on the four steps in developing a WQI. It should be noted that once a WQI is developed, the final index value will have to be interpreted to assess the water quality for its suitability for specific purposes. Hence, for each of the seven WQIs, a discussion on how the final index value was interpreted is also presented.

Canadian Council of Ministers of the Environment Index

The CCME WQI was developed by the Canadian Council of Ministers of the Environment as a tool to assess and report water quality information to both management institutions and the public (CCME 2001). Several studies in the literature have applied this index for various purposes. In Canada, it was used to evaluate the water quality status of several river basins (Khan et al. 2003; Lumb et al. 2006; Davies 2006), to evaluate drinking water quality (Khan et al. 2004; Hurley et al. 2012) and to assess water quality in metal mines (de Rosemond et al. 2009). In addition to the above-mentioned applications of CCME WQI in Canada, this index also has been adopted in several other countries. For example, it was employed in Turkey (Boyacioglu 2010), India (Sharma and Kansal 2011), Spain (Terrado et al. 2010), Chile (Espejo et al. 2012), Albania (Damo and Icka 2013) and Iran (Mostafaei 2014).

a) Selection of parameters

The CCME WQI allows flexibility to select parameters so that the index users can easily modified and adopted according to local conditions and issues. For instance, Alberta State in Canada used four groups of parameters, metals (up to 22 parameters), nutrients (6 parameters), bacteria (2 parameters) and pesticides (17 parameters), while New Brunswick State used only 14 parameters in applying the CCME WQI.

b) Generation of sub-indices

The CCME WQI index does not use this step to obtain sub-indices.

c) Establishing weights

Since sub-indices are not generated in this WQI, there are no weights associated with them.

d) Index aggregation

As explained earlier, the CWQI provides a straightforward mathematical framework for aggregating the final index value (with Eq. (21) used to calculate the final index).

e) Final index value interpretation

A grade of 0 to 100 is considered to interpret the final index value. The CCME WQI values are classified into five different categories, namely excellent quality (from 95 to 100), good quality (from 80 to 94), fair quality (from 65 to 79), marginal quality (from 45 to 64) and poor quality (from 0 to 44).

National Sanitation Foundation Index

The National Sanitation Foundation (NSF) WQI is one of the earliest WQIs, which was developed during the early 1970s (Brown et al. 1970). The index obtained credibility among other available WQIs since more than hundred water quality experts from throughout the USA were considered in the development of this index. Although originally developed in the USA, this WQI or its modified version has been applied in various countries including Brazil (Simões et al. 2008), India (MPCB 2014) and Iran (Mojahedi and Attari 2009).

a) Selection of parameters

The NSF WQI used the Delphi technique to finalize a fixed set of parameters. Based on the consensus of water quality experts from across the USA, nine parameters were selected as presented in Table 1 (column 2). Later, two more parameters (pesticides and toxic elements) were added to the set of nine parameters.

b) Generation of sub-indices

The sub-indices for NSF WQI were also established through the Delphi technique. This information was later used to produce "an average curve" which represented the general pattern of all sub-indices, except for pesticides and toxic elements. These two sub-indices were established through categorical scaling of 0 and 1. If both parameters exceed the permissible limits, the status of water quality is automatically registered as 0 (the worst level).

c) Establishing weights

Using the Delphi technique, another questionnaire was constructed to identify individual weights for the selected parameters. Based on this procedure, the final weights (in brackets) were as follows: DO (0.17), FC (0.16), pH (0.11), BOD_5 (0.11), temperature (0.10), TP (0.10), NO_3 (0.10), turbidity (0.08) and TS (0.07). The sum of all individual weights is equal to 1.

d) Index aggregation

In the index originally proposed by Brown et al. (1970), the aggregation of the sub-indices was undertaken using the additive method. In the course of using the index, it was found that the arithmetic formulation, although easy to understand and calculate, as highlighted in Lumb et al. (2011a), lacked sensitivity in terms of the effect a single bad parameter value would have on the WQI. This led Brown et al. (1973) to propose a variation of NSF WQI in which the multiplicative aggregation is used.

e) Final index value interpretation

The final index values ranged from 0 (very bad water quality) to 100 (very good water quality). Brown and McClelland (1974) suggested the following classification of the index scores for grading the quality of water in the NSF WQI: excellent (90–100), good (70–89), medium (50–69), bad (25–49) and very bad (0–24).

Oregon Index

The Oregon Water Quality Index (OWQI) was developed in the 1970s (Dunnette 1979) for the purpose of summarizing and evaluating water quality status and trends in Oregon. The original OWQI was discontinued in 1983 due to the enormous resources required for calculating and reporting the results. With the advancements in computer technology, enhanced tools of data display and visualization and a better understanding of water quality, the OWQI was updated by Cude (2001) by refining the original sub-indices and improving the aggregation method. The purpose of the updated OWQI was to express ambient water quality for general recreational use. However, it has been widely used by the Oregon Department of

Environment Quality (ODEQ) to evaluate the overall water quality of Oregon's rivers (ODEQ 2014). The OWQI was also used by the Idaho Department of Environmental Quality (IDEQ 2002) to conduct an integrated approach in assessing ecological of Idaho's rivers. The OWQI is also part of a suite of popular WQIs that were incorporated in an automated software called Qualidex (Sarkar and Abbasi 2006).

a) Selection of parameters

The selection of parameters was conducted based on water quality data of the Willamette River basin in Oregon (Dunnette 1979). The author undertook an exhaustive process for parameter selection, which involved several stages in consecutive order, namely literature review of previous WQIs, a parameter selection procedure based on rejection rationales, a modified Delphi technique and consideration of major impairment categories.

In the first stage, 90 possible parameters were listed based on a literature review of available WQIs. Then, three rejections were used to reject parameters, namely availability of data, parameters being of questionable significance and not being present in harmful amounts. These rejections reduced the number of parameters from 90 to 30. Then, the Delphi technique was applied to the 30 parameters. Unlike in the NSF WQI, only staff members of the ODEQ were considered as respondents. Through their consensus, 14 parameters were selected and subjected to another rejection rationale of redundancy and impairment categories. The redundancy rejection is usually carried out by examining Pearson's correlation coefficient, while in the impairment rejection, the water quality was classified according to the impairment categories of oxygen depletion, eutrophication or potential for excess biological growth, dissolved substances and health hazards. Finally, six parameters were selected, as presented in Table 1 (column 2).

In addition to the originally selected six parameters, Cude (2001) argued that two additional parameters (TP and temperature) should be added to the set of parameters. These parameters were added based on a better understanding of their significance to water quality in Oregon's streams.

b) Generation of sub-indices

To generate sub-indices in the updated OWQI, Cude (2001) developed non-linear regression rating curves for the original six parameters based on the original logarithmic graphs proposed when OWQI was originally developed. The rating curve for TP was developed based on the risk of eutrophication in Oregon's streams and that for temperature was developed with the protection of cold water fisheries (Cude 2001). For each sub-index, parameter measurements were converted to a relative quality rating between 10 (worst case) and 100 (ideal).

c) Establishing weights

The original OWQI (Dunnette 1979) used the Delphi technique to generate weights. The weights of the six selected parameters were obtained as follows: DO (0.4), FC (0.2), pH (0.1), nitrate + ammonia-N (0.1), TS (0.1) and BOD (0.1). On the contrary, Cude (2001) argued that unequal weights for the parameters is only suitable for WQIs that were developed for a specific use, not for general use, in which some parameters might play a more important role than the others. Therefore, equal weight parameters were used for this index.

d) Index aggregation

The original OWQI (Dunnette 1979) used additive method for index aggregation. Once all six different sub-index values were obtained, they were aggregated using the additive method to produce the final index value (using Eq. 7). Since there was an eclipsing problem, in the updated index, Cude (2001) adopted an unweighted harmonic square formula (presented in Eq. 14) to aggregate the sub-indices.

e) Final index value interpretation

The water quality is evaluated by the OWQI according to five classes, which are as follows: excellent (final index value from 90 to 100), good (85 to 89), fair (80 to 84), poor (60 to 79) and very poor (10 to 59).

Bascarón index

The Bascarón index was developed by Bascarón (1979) specifically for Spain. This index has been used in several studies, particularly from South American countries. For example, it was used and applied in Argentina (Pesce and Wunderlin 2000), in Chile (Debels et al. 2005), in Brazil (Abrahão et al. 2007), in Spain

(Sánchez et al. 2007), in India (Kannel et al. 2007) and in Turkey (Koçer and Sevgili 2014).

a) Selection of parameters

The Bascarón index enables flexibility in the inclusion and exclusion for parameter selection (Bascarón 1979 in Abrahão et al. 2007; Lumb et al. 2011a); however, it was recommended that 26 parameters be considered in the final index aggregation (which was earlier presented in Table 1 (column 2)).

b) Generation of sub-indices

The sub-indices (term C_i in Eq. (10)) were obtained by normalizing the actual parameter values to a common scale ranging from 0 to 100. Using the normalization factors, the sub-indices can take one of the values from 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100. The value will depend on the permissible limits of the respective parameter, which is derived from water quality directives.

c) Establishing weights

In the Bascarón index, different weights are assigned for different parameters. The values of weights vary from 1 to 4, with the sum of all weights being 54. This sub-indices had weights as presented in brackets—pH (1), BOD_5 (3), DO (4), temperature (1), TC (3), colour (2), turbidity (4), permanganate reduction (3), detergents (4), hardness (1), DO (2), pesticides (2), oil and grease (2), SO_4 (2), NO_3 (2), cyanides (2), sodium (1), free CO_2 (3), ammonia-N (3), Cl (1), conductivity (4), Mg (1), P (1), NO_2 (2), Ca (1) and apparent aspect (no weight given).

d) Index aggregation

Index aggregation is undertaken using a modified version of the additive method, which was presented in Eq. 10 (Bascarón 1979 in Abrahão et al. 2007).

e) Final index value interpretation

The interpretation of the final index is done based on five categories: good (final index value from 91 to 100), acceptable (61 to 90), regular (31 to 60), bad (16 to 30) and very bad (0 to 15).

House's Index

This index was developed by House (1986). The author developed four indices, in which each could be used separately or in combination when the users needed a more detailed picture of river water quality status. The first of these four indices was a general WQI developed to be used as an indicator of river health for routine monitoring programs. The other three indices were potable water supply index (PWSI), aquatic toxicity index (ATI) and potable sapidity index (PSI). The PWSI, ATI and PSI were specially used in evaluating suitability of potable water supply, toxicity in aquatic and wildlife population, respectively. Although no formal reports from environmental agencies were found regarding the application of these indices, there were some publications in the literature presenting the application of this WQI in the UK, where many reaches were evaluated using the general WQI (House 1989, 1990; Tyson and House 1989; House and Ellis 1987). In addition, Carvalho et al. (2011) adopted rating class of House's Index when assessing water quality status of a small river in Portugal.

a) Selection of parameters

The author conducted rigorous interviews with water authorities and river purification boards to ascertain which parameters should be included for the indexing system. Parameters were selected based on routinely monitored parameters of water authorities and river purification boards, based on interviews with officers and also based on the permissible limits for different uses.

These four indices have different selected parameters. The general WQI used nine parameters, as presented previously in column 2 of Table 1. The PWSI consisted of thirteen parameters, which included nine parameters from the general WQI and four additional parameters, which were sulphates, F, colour and dissolved iron. The ATI considered heavy metals, pesticides and hydrocarbon parameters for a more detailed monitoring of water quality and it had twelve parameters as presented in column 2 Table 1. The last index, which is the PSI, also had the same parameters with those of the ATI. The only difference was in the form of the substances (in the ATI most of the selected parameters were in dissolved forms, while in the PSI, they were in total substance forms).

b) Generation of sub-indices

These indices used a scale of 10–100, with a score of 10 reflecting poor water quality akin to sewage and that of 100 indicating waters of high purity. Rating curves were developed using the permissible limits of available water quality standards for different uses. If a particular parameter had two or more standards, the median of these permissible limits was selected and converted into specific sub-index values.

c) Establishing weights

Different weights for individual parameters were established using the Delphi technique. The panellist consisted of personnel in the pollution prevention organizations and water experts. Final weights were then established based upon the median rankings. The general WQI had weights of DO (0.2), BOD_5 (0.18), ammoniacal nitrogen (0.16), suspended solids (0.11), total coliforms (0.11), nitrates (0.09), pH (0.09), Cl (0.04) and temperature (0.02). The PWSI had weights for its 13 parameters, involving total coliforms (0.14), ammoniacal N (0.10), NO_3 (0.10), SS (0.10), colour (0.10), pH (0.09), iron (0.09), BOD_5 (0.09), DO (0.05), fluorides (0.05), chlorides (0.04), SO_4 (0.02) and temperature (0.02). Weights were not developed for the ATI and the PSI as all parameters had equal importance and were considered very harmful for human and aquatic life.

d) Index aggregation

There was no grouping of parameters to form aggregated sub-indices within these WQIs. Therefore, after transforming the actual values of the parameters into sub-indices, they were aggregated to the final index using a variance of the additive method developed by the SRDD. The aggregation formula adopted is presented in Eq. 9 (House 1989).

e) Final index value interpretation

The interpretation of the index is divided into four classifications, involving highly polluted water (10–30) which is used for non-contact recreational uses, sewage transport and navigation; moderately polluted water (31–50) that can be used for potable water supply after advanced treatment, indirect contact sports and breeding fish population; water of reasonable quality (51 to 70) suitable for potable water supply with conventional treatment, fisheries, indirect contact sports and some industrial uses at moderate costs; and finally water of high quality (71–100) suitable for potable water supply, game fisheries, contact recreation and high quality industrial uses.

Scottish Research Development Department index

The Scottish Research Development Department (SRDD) index was developed by the Engineering Division of the SRDD (SRDD 1976) based on steps similar to those in the NSF WQI. It is also called as the Scottish WQI. Although the SRDD index was originally developed for Scotland, it has later been modified and used to evaluate the status of water quality in several river basins from different countries (for example, Thailand (Bordalo et al. 2001), Spain (Bordalo et al. 2006), Portugal (Carvalho et al. 2011) and Iran (Dadolahi-Sohrab et al. 2012)). The steps used for the application of SRDD index are as follows:

a) Selection of parameters

The Delphi technique was used for the selection of parameters in the SRDD index. Several rounds of questionnaires were distributed to the local water experts from around Scotland (SRDD 1976). Following the same path as the NSF WQI, the SRDD index selected a fixed set of ten parameters as presented in column 2 of Table 1.

b) Generation of sub-indices

Sub-indices of the SRDD index were developed based on the convergence of panellists' judgement. The respondents were asked to decide the possible lowest and highest values of each sub-index. The SRDD index considered that values of all sub-indices started from 0 (the lowest sub-index value) to 100 (the highest sub-index value).

c) Establishing weights

The Delphi technique was again used in establishing the weights for each of the selected parameters as indicated in brackets: DO (0.18), BOD_5 (0.15), free and saline ammonia (0.12), pH (0.09), total oxidized nitrogen (0.08), phosphate (0.08), SS (0.07), temperature (0.05), conductivity (0.06) and *Escherichia coli* (0.12).

d) Index aggregation

The SRDD index used the modified additive method for index aggregation (using Eq. 9). Since this index does not have any grouping of parameters, there is only one level of index aggregation. The final index value is obtained by directly aggregating sub-index values of each parameter.

e) Final index value interpretation

Similar to the NSF WQI, higher values of the SRDD index indicate better overall water quality.

There are seven levels of water quality status in the SRDD index, namely clean (final index from 90 to 100), good (80 to 89), good water quality with some treatment (70 to 79), tolerable (40 to 69), polluted (30 to 39), severely polluted (20 to 29) and finally water akin to piggery waste (0 to 19).

Fuzzy-based indices

In the recent past, several index developers have started applying fuzzy-based indices, which were developed based on fuzzy logic technique (Zadeh 1965). Fuzzy logic is used to define classes of objects that have an ambiguous status. In many environmental problems, including water quality, such an ambiguity exists. Hence, it is not easy to quantify water quality using crisp data or limited indicators (Ocampo-Duque et al. 2013). Instead, Mahapatra et al. (2011) suggested to consider water quality as a fuzzy term appropriately estimated with linguistic computations.

In a fuzzy-based index, only two steps namely, parameter selection and weighing, are undertaken as in conventional indices. The two other steps (including classifying for interpretation) are completely obtained by rules (using expert's judgement) and sets of linguistic computation, e.g. fuzzification, evaluation of inference rules and defuzzification. The development and application of this index have been applied in Spain (in Ocampo-Duque et al. 2006), in Iran (in Nikoo et al. 2011) and in Brazil (in Lermontov et al. 2009).

a) Selection of parameters

Fuzzy-based indices use open system. Thus, any parameter can be selected based on water quality monitoring programs or a fixed set of parameters can be adopted from existing WQIs.

b) Generation of sub-indices

In a fuzzy-based index, parameters are normalized and grouped through a fuzzy interference system (FIS) wherein the numerical values (inputs) are fuzzified into a qualitative state (outputs) and processed by an inference engine, membership functions, rules, sets and operators in a qualitative state (Lermontov et al. 2009).

c) Establishing weights

Successful application of an FIS depends on an accurate weight assignment to the parameters involved in the fuzzy rules (Ocampo-Duque et al. 2006; Lermantov 2009). The pair-wise comparison matrix in the AHP can be used for obtaining different weights for individual parameters (Ocampo-Duque et al. 2006) or for a different set of parameters (Nikoo et al. 2011).

d) Index aggregation

Index aggregation was undertaken through a certain set of rules written by the index developers. To obtain the final index, defuzzification is conducted. Defuzzification is a process of transforming the fuzzy outputs into non-fuzzy or numerical outputs (Ocampo-Duque et al. 2006).

e) Final index value interpretation

In Lermontov et al. (2009), the interpretation of the final aggregated index was then performed based on the following classification scheme: water quality is interpreted as poor (final index from 0 to 19), bad (20 to 36), fair (37 to 51), good (52 to 79) and excellent (80 to 100).

Summary, conclusions and recommendations

A water quality index (WQI) is a tool to assess the status of water quality at certain times and locations. It aggregates water quality parameters into useful information that is simple and easily understandable and thus can be used by the water authorities as well as the general public. The review presented in this paper on the development of river WQIs aimed to provide significant inputs to river water authorities worldwide for using or customizing existing indices for their application and contribute to future river WQI development studies. With this aim, this study reviewed 30 available WQIs and discussed them in light of the four steps that should be considered in the development of WQIs. These steps are the selection of parameters, generation of sub-indices, generation of parameter weights and final index aggregation process.

In this study, seven WQIs were identified as the most important based on their wider use, and they were discussed in detail. A main factor that influences the wider use of any WQI is the support and encouragement that is provided by the government and authorities to implement the index as the main indicator or tool to evaluate the status of the rivers in that region (or country). The Canadian Council of Ministers of the Environment (CCME) WQI and Oregon Water Quality Index

(OWQI) are good examples of this support and encouragement provided by the government since they have been widely used in all states of Canada and two states in the USA (Oregon and Idaho).

In general, it can be concluded that there is no worldwide accepted method in constructing a WQI. The index developers might consider all the four steps in developing a WQI or they could consider some of the steps. Moreover, there is no method by which 100 % objectivity or accuracy can be achieved in the development of a WQI, specifically for the selection of parameters, generation of sub-index values, generation of parameter weights and the choice of index aggregation method. Thus, problems like rigidity, eclipsing and ambiguity will always be a challenge in the development of a WQI.

Since there is subjectivity and uncertainty involved in the steps of developing a WQI, it can also be concluded that statistical-based methods, which include correlation analysis, principal component analysis (PCA), cluster analysis (CA) and discriminant analysis (DA), might be useful methods in minimizing uncertainty in steps like the parameter selection process. For example, Wang et al. (2013), Juahir et al. (2011), Shrestha and Kazama (2007), Singh et al. (2005), Singh et al. (2004) and Wunderlin et al. (2001) applied the CA and DA for seeking the optimal selection of water quality parameters for cost-effective monitoring purpose. In addition, Khalil et al. (2010, 2014) applied correlation analysis and CA to select the best set of parameters that can be used for water quality index development. However, statistical methods are still subjective as they rely on the data provided for analysis. Thus, it is recommended that the opinion of local water quality experts is taken into account (through techniques like the Delphi method) in each of the steps in developing a WQI. For example, in the National Sanitation Foundation (NSF) WQI in the USA, the involvement of water quality experts is very high and this has become a standard approach for developing the methodology for other indices such as the Ross' Index (Ross 1977), SRDD index (SRDD 1976), Oregon Index (Dunnette 1979), Dinius' index (Dinius 1987), House's Index (House 1986), Smith's index (Smith 1990) and Almeida's Index (Almeida et al. 2012).

In this review, it was also observed that uncertainty and sensitivity analysis was rarely undertaken to minimize the uncertainty associated with the development of a WQI. Uncertainty analysis aims to identify sources and quantify the uncertainty involved in the development of a WQI and to investigate the influences of those uncertainties on the final index values. The sources of uncertainties can be the inclusion or exclusion of the parameters, the selection of normalization schemes, the weights and the choice of aggregation methods. On the other hand, sensitivity analysis aims to study the response of an output variable (i.e. the final index value) to variations in or influence of the input uncertainties (Nardo et al. 2005; CCME 2006).

It is worth mentioning that only the CCME WQI had undertaken a sensitivity analysis for all the steps in the development of their WQI (CCME 2006), which involved investigation of the final index values with respect to the number of selected parameters, number of data samples, index aggregation methods and the water quality objectives. Other WQIs applied such an analysis only for some of the steps. For example, it was undertaken through inclusion or exclusion of several parameters (Rickwood and Carr 2009), selection of different aggregation equations (Brown et al. 1970; Landwehr and Deininger 1976; Dunnette 1979; House 1989; Smith 1990; Liou et al. 2004; Said et al. 2004), selecting different number of parameters (Bhargava 1985) and using different weighting methods (Smith 1990). Hence, this study also recommends that the sources of uncertainty are identified in every step of the development process and that those uncertainties are quantified. Quantification of the uncertainty in every step of the index development process increases the credibility of an index, as well as it helps index developers and their users to have a better understanding of the strengths and weaknesses of an index.

It is also recommended that a common WQI is used within a region or province. With regard to the selection of parameters, it is preferable that each river basin should have a unique set of parameters. However, this has a practical disadvantage that comparison of WQIs between different river catchments in a region will not be possible because of the constituent parameters being different. Hence, to facilitate comparison of WQIs between river basins, it is also recommended to have a common WQI (with a fixed set of parameters) for river basins within a province or region.

Appendix

Table 2 List of reviewed WQIs (during the period 1987–2014) along with their applications

Index name	Region or country where applied	Applications: Applications of WQIs reported by authorized government agencies (all web links accessed in December 2014)	Applications: Applications of WQIs reported in journal/ conference articles	Purpose of WQI application
Canadian Council of Ministers of the Environment (CCME) Water Quality Index	• All states in Canada • One state in India • Albania • Chile • Egypt • Iran • Spain • Turkey • Poland	• *CCME Water Quality Index 1.0 User's Manual*. http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf • Canadian Water Quality Index, Government of Newfoundland and Labrador. <http://www.env.gov.nl.ca/env/waterres/quality/background/cwqi.html> • The British Columbia Water Quality Index. <http://www.env.gov.bc.ca/wat/wq/BCguidelines/indexreport.html> • Alberta River Water Quality Index <http://esrd.alberta.ca/water/reports-data/alberta-river-water-quality-index.aspx> • Water Quality results for New Brunswick watersheds. <http://www2.gnb.ca/content/gnb/en/departments/elg/environment/content/water/content/watersheds.html> • Water Quality Management in Nova Scotia, Canada. <http://www.novascotia.ca/nse/surface.water/surfacewater.tools.asp> • Water Quality Index calculations for Prince Edward Island, Canada <http://www.gov.pe.ca/photos/original/elj_sswqi_rpt.pdf> • British Columbia and Yukon Territory Water Quality Report (2001–2004). An Application of the Canadian Water Quality Index. <http://publications.gc.ca/collections/collection_2007/ec/En84-51-2007E.pdf> • Data Sources and Methods for the Freshwater Quality Indicator. <http://www.ec.gc.ca/indicateurs-indicators/5D193531-BD55-44B5-AA00-58B81E93199A/FreshwaterQuality_en.pdf> • Freshwater Quality in Canadian Rivers. <https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En&n=68DE8F72-1> • Technical guidance document for Water Quality Indicator practitioners reporting under the Canadian Environmental Sustainability Indicators (CESI) initiative 2008. <http://publications.gc.ca/collections/collection_2011/ec/En4-138-2010-eng.pdf> • Environmental Monitoring Program on Water Quality, Government of Kerala, India. <http://www.indiawaterportal.org/sites/indiawaterportal.org/files/Environmental_monitoring_programme_on_water_quality_in_Kerala_KSCSTE_CWRDM_2009.pdf>	• Khan et al. 2003 • Khan et al. 2004 • Davies 2006 • Lumb et al. 2006 • Tobin et al. 2007 • Boyacioglu 2010 • Nikoo et al. 2011 • Terrado et al. 2010 • De Rosemond et al. 2009 • Sharma and Kansal 2011 • Espejo et al. 2012 • Hurley et al. 2012 • Damo and Icka 2013 • Mostafaei 2014	The original index for general water quality assessment, but later modified versions are used for specific uses such as assessing impact of forestry-related activities on water quality, suitability for drinking water supply and aquaculture

Table 2 (continued)

Index name	Region or country where applied	Applications: Applications of WQIs reported by authorized government agencies (all web links accessed in December 2014)	Applications: Applications of WQIs reported in journal/ conference articles	Purpose of WQI application
National Sanitation Foundation (NSF) Index	• USA • Brazil • India • Iran	• Maharashtra Pollution Control Board (2014). Compilation of Water Quality Data Recorded by MPCB 2011-12. <http://mpcb.gov.in/ereports/pdf/Water_Quality_Report_2011-12_TERI.pdf> • Central Pollution Control Board, Government of India (2003). <http://mpcb.gov.in/images/pdf/WaterQuality0709/Chapter3_WQ.pdf> • USEPA (1974). Water Quality Index Application in Kansas River Basin. <http://nepis.epa.gov/Exe/ZyPDF.cgi/20008TH7.PDF?Dockey=20008TH7.PDF>	•*Brown et al*. 1970; Brown et al. 1973 •Deininger 1980 •Simões et al. 2008 •Mojahedi and Attari 2009 •Bonanno and Giudice 2010 •Lumb et al 2011b •Babbar 2013	General assessment of the state of water quality but it cannot be used for toxicity evaluation
Oregon Index	• OR, USA • ID, USA	• Oregon Department of Water Quality. (2014). <http://www.deq.state.or.us/lab/wqm/docs/wqiAnnualRep2014.pdf> • Oregon Department of Water Quality. (2013). <http://www.deq.state.or.us/lab/wqm/docs/OWQISummary12.pdf> • Oregon Department of Water Quality. (2012). <http://www.deq.state.or.us/lab/wqm/docs/12-LAB-002.pdf> • Oregon Department of Water Quality. (2008). <http://www.deq.state.or.us/lab/wqm/docs/09-LAB-008.pdf> • Oregon Department of Water Quality. (2007). <http://www.deq.state.or.us/lab/wqm/docs/OWQISummary06.pdf> • Oregon Department of Water Quality. (2006). <http://www.deq.state.or.us/lab/wqm/docs/OWQISummary05.pdf> • Oregon Department of Water Quality. (2005). <http://www.deq.state.or.us/lab/wqm/docs/OWQISummary04.pdf> • Oregon Department of Water Quality. (2004). <http://www.deq.state.or.us/lab/wqm/docs/OWQISummary03.pdf> • Oregon Department of Environmental Quality. (1994). <http://www.oregondeq.org/lab/wqm/wqindex/powder3.htm> • Oregon Department of Environmental Quality. (1993). <http://www.oregondeq.com/lab/wqm/wqindex/malowy3.htm> • Idaho Department of Environmental Quality (2002). <https://www.deq.idaho.gov/media/457032-assessment_river_entire.pdf>	•*Dunnette* 1979 •Cude 2001 •Sarkar and Abbasi 2006	General water quality assessment
Bascarón index	• Spain • Argentina • Brazil • Korea • India	• NA	• *Bascaron* 1979 • Pesce and Wunderlin 2000 • Debels et al. 2005 • Abrahão et al. 2007 • Sánchez et al. 2007 • Kannel et al. 2007 • Koçer and Sevgili 2014	The original index for general water quality assessment, but later modified indices were used for specific uses such as assessing suitability for aquaculture
House's index	• UK	• NA	• *House* 1986	

Table 2 (continued)

Index name	Region or country where applied	Applications		Purpose of WQI application
		Applications of WQIs reported by authorized government agencies (all web links accessed in December 2014)	Applications of WQIs reported in journal/conference articles	
	• Spain		• House and Ellis 1987 • House 1989 • Tyson and House 1989 • Carvalho et al. 2011	General water quality assessment and specific uses such as potable water supply and assessing aquatic toxicity levels
Scottish Research Development Department (SRDD) index	• Scotland • Spain • Portugal • Thailand • Iran	• *SRDD* (1976). *Applied Research & Development Report Number ARD3*, *Engineering Division*, *Edinburg*, *UK*	• Bordalo et al. 2001 • Bordalo et al. 2006 • Carvalho et al. 2011 • Dadolahi-Sohrab et al. 2012	General water quality assessment but it cannot be used for toxicity evaluation
Fuzzy index	• Spain • Iran • India • Brazil • Columbia	• NA	• *Ocampo-Duque et al*. 2006 • Lermontov et al. 2009 • Mahapatra et al. 2011 • Nikoo et al. 2011 • Ocampo-Duque et al. 2013	General water quality assessment
Bhargava's index	• India	• NA	• *Bhargava* 1985 • Al-Ani et al. 1987 • Avvannavar and Shrihari 2008	Specific use of assessing suitability for drinking water supply
Malaysian index	• Malaysia	• *DoE Malaysia* (2002). *Malaysia environmental quality report 2001. Putrajaya*, *Malaysia*: *Department of Environment*, *Ministry of Science*, *Technology and Environment*	• Shuhaimi-Othman et al. 2007 • Gazzaz et al. 2012	General water quality assessment
Status and Sustainability index	• France	• NA	• *Oudin et al*. 1999 • Fulazzaky 2010	General water quality assessment
Dalmatian index	• Serbia	• NA	• *Štambuk-Giljanović* 1999 • Štambuk-Giljanović 2003	General water quality assessment
Dinius' index	• UK	• NA	• *Dinius* 1987 • Sarkar and Abbasi 2006	General water quality assessment
Diljido's index	• Serbia	• NA	• *Dojlido et al*. 1994	General water quality assessment
The River Ganga Index of Ved Prakash et al.	• India	• NA	• The River Ganga Index of *Ved Prakash et al.* (as cited in Abbasi and Abbasi 2012) • Bhutiani et al. 2014	General water quality assessment
Water pollution index	• USA	• NA	• *Nemerow and Sumitomo* 1970	Specific uses of assessing suitability for direct human contact use (drinking, swimming, etc), indirect

Table 2 (continued)

Index name	Region or country where applied	Applications: Applications of WQIs reported by authorized government agencies (all web links accessed in December 2014)	Applications: Applications of WQIs reported in journal/ conference articles	Purpose of WQI application
			• Xu et al. 2010	contact use (fishing, agriculture, etc) and remote contact use (navigation, industries, etc)
Almeida's index	• Argentina	• NA	• *Almeida et al.* 2012	Specific use of assessing suitability for recreational use
Boyacioglu's index	• Turkey	• NA	• *Boyacioglu* 2007	Specific use of assessing suitability for drinking water supply
Contact recreation index	• New Zealand	• NA	• *Nagels et al.* 2001	Specific use of assessing suitability for recreational use
Hallock's index	• USA	• *Hallock, D. (*2002*). A Water Quality Index for Ecology's Stream Monitoring Program. Washington Department of Ecology.* <http://www.ecy.wa.gov/biblio/0203052.html>	• NA	General assessment
Hanh's index	• Vietnam	• NA	• *Hanh et al.* 2011	General water quality assessment
Harkins' index	• USA	• NA	• *Harkins* 1974	General water quality assessment
Indian pollution index	• India	• NA	• *Sargaonkar and Deshpande* 2003	General water quality assessment
Liou's index	• Taiwan	• NA	• *Liou et.* 2004	General water quality assessment
Prati's index	• Italy	• NA	• *Prati et al.* 1971	General water quality assessment
Ross' index	• UK	• NA	• *Ross* 1977	General water quality assessment
Said's index	• USA	• NA	• *Said et al.* 2004	General water quality assessment
Smith's index	• New Zealand	• NA	• *Smith* 1990	Specific use of assessing suitability for bathing, water supply and fish spawning
Stoner's index	• USA	• *Stoner, J D. (*1978*). Water Quality Indices for Specific Water Uses, U.S. Geological Survey Circular 770.* <http://pubs.usgs.gov/circ/1978/0770/report.pdf>	• NA	Specific use of assessing suitability for irrigation
Storet index	• North America	• NA	• *Ministry of the Environment Indonesia* 2003	General water quality assessment
Walski and Parker's index	• USA	• NA	• *Walski and Parker* 1974	Specific use of assessing suitability for recreational use.

The report or paper that originally developed the index is indicated in italics (in column 3 or 4)

References

Abbasi, T., & Abbasi, S. A. (2012). *Water quality indices*. Burlington: Elsevier Science.

Abbasi, T., & Abbasi, S. A. (2011). Water quality indices based on bioassessment: the biotic indices. *Journal of Water and Health, 9*(2), 330–348.

Abrahão, R., Carvalho, M., da Silva Junior, W. R., Machado, T. T. V., Gadelha, C. L. M., & Hernadez, M. I. M. (2007). Use of index analysis to evaluate the water quality of a stream receiving industrial effluents. *Water SA, 33*, 459–466.

Al-Ani, M. Y., Al-Nakib, S. M., Ritha, N. M., & Nouri, A. H. (1987). Water quality index applied to the classification and zoning of Al-Jaysh canal, Baghdad—Iraq. *Journal of Environmental Science and Health, Part A: Environmental Science and Engineering, 22*(4), 305–319. doi:10.1080/10934528709375351.

Almeida, C., González, S., Mallea, M., & González, P. (2012). A recreational water quality index using chemical, physical and microbiological parameters. *Environmental Science and Pollution Research, 19*(8), 3400–3411. doi:10.1007/s11356-012-0865-5.

Avvannavar, S., & Shrihari, S. (2008). Evaluation of water quality index for drinking purposes for river Netravathi, Mangalore, South India. *Environmental Monitoring And Assessment, 143*(1-3), 279–290. doi:10.1007/s10661-007-9977-7.

Babbar, R. (2013). A Bayesian model to evaluate water quality of polluted river in northern India. Proceedings of the Congress - International Association for Hydraulic Research; 150. International Association for Hydro-Environment Engineering and Research. World congress; 35th, International Association for Hydro-Environment Engineering and Research.

Bascarón, M. (1979). Establishment of a methodology for the determination of water quality. *Boletin Informativo del Medio Ambiente, 9*, 30–51.

Bhargava, D. (1985). Expression for drinking water supply standards. *Journal of Environmental Engineering, 111*(3), 304–316. doi:10.1061/(ASCE)0733-9372(1985)111:3(304).

Bhutiani, R., Khanna, D. R., Kulkarni, D., & Ruhela, M. (2014). Assessment of Ganga river ecosystem at Haridwar, Uttarakhand, India with reference to water quality indices. *Applied Water Science*, 1-7, doi:10.1007/s13201-014-0206-6.

Bonanno, G., & Lo Giudice, R. (2010). Application of two quality indices as monitoring and management tools of rivers. Case study: the Imera Meridionale River, Italy. *Environmental Management, 45*(4), 856–867. doi:10.1007/s00267-010-9450-1.

Bordalo, A., Teixeira, R., & Wiebe, W. (2006). A water quality index applied to an international shared river basin: the case of the Douro River. *Environmental Management, 38*(6), 910–920. doi:10.1007/s00267-004-0037-6.

Bordalo, A. A., Nilsumranchit, W., & Chalermwat, K. (2001). Water quality and uses of the Bangpakong River (Eastern Thailand). *Water Research, 35*(15), 3635–3642. doi:10.1016/S0043-1354(01)00079-3.

Boyacioglu, H. (2010). Utilization of the water quality index method as a classification tool. *Environmental Monitoring and Assessment, 167*(1-4), 115–124.

Boyacioglu, H. (2007). Development of a water quality index based on a European classification scheme. *Water SA, 33*(1), 101–106.

Brown, R. M., & McClelland, N. I. (1974). *Up from chaos: the water quality index as an effective instrument in water quality management* (p. 27). Ann Arbor, Michigan: National Sanitation Foundation.

Brown, R.M., McClelland, N.I., Deininger, R.A., Landwehr, J.M. (1973). Validating the WQI. The paper presented at national meeting of American Society of Civil Engineers on water resources engineering, Washington, DC.

Brown, R. M., McClelland, N. I., Deininger, R. A., & Tozer, R. G. (1970). A water quality index—do we dare? *Water and Sewage Works, 117*(10), 339–343.

Carvalho, L., Cortes, R., & Bordalo, A. (2011). Evaluation of the ecological status of an impaired watershed by using a multi-index approach. *Environmental Monitoring And Assessment, 174*(1-4), 493–508. doi:10.1007/s10661-010-1473-9.

CCME (2006). A sensitivity analysis of the Canadian Water Quality Index. (Accessed in December 2014). <http://www.ccme.ca/files/Resources/water/pn_1355_wqi_sensitivity_analysis_rpt.pdf>.

CCME (2001) Canadian water quality guidelines for the protection of aquatic life. CCME water quality index 1.0, User's Manual, Winnipeg, Manitoba, Canada. (Accessed in December 2014). <http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf>.

Chapman, D. (UNESCO, WHO, and UNEP). (1992). *Water quality assessment*. London: Chapman & Hall.

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), 125–137. doi:10.1111/j.1752-1688.2001.tb05480.x.

Dadolahi-Sohrab, A., Arjomand, F., & Fadaei-Nasab, M. (2012). Water quality index as a simple indicator of watersheds pollution in southwestern part of Iran. *Water and Environment Journal, 26*(4), 445–454. doi:10.1111/j.1747-6593.2011.00303.x.

Davies, J.-M. (2006). Application and tests of the Canadian Water Quality Index for assessing changes in water quality in lakes and rivers of central North America. *Lake and Reservoir Management, 22*(4), 308–320. doi:10.1080/07438140609354365.

Damo, R., & Icka, P. (2013). Evaluation of water quality index for drinking water. *Polish Journal of Environmental Studies, 22*(4), 1045–1051.

de Rosemond, S., Duro, D. C., & Dubé, M. (2009). Comparative analysis of regional water quality in Canada using the Water Quality Index. *Environmental Monitoring And Assessment, 156*(1-4), 223–240. doi:10.1007/s10661-008-0480-6.

Debels, P., Figueroa, R., Urrutia, R., Barra, R., & Niell, X. (2005). Evaluation of water quality in the Chillán River (central Chile) using physicochemical parameters and a modified water quality index. *Environmental Monitoring and Assessment, 110*(1-3), 301–322.

Deininger, R. A. (1980). A water quality index for rivers. *Water International, 5*(3), 16–21.

Delbecq, A. L., Ven, A. H. V. d. & Gustafon, D. H. (1975). Group techniques for program planning: a guide to nominal group and Delphi processes, Glenview, Illinois.

DoE (Department of Environment) Malaysia. (2002). *Malaysia environmental quality report 2001*. Putrajaya, Malaysia: Department of Environment, Ministry of Science, Technology and Environment.

Dinius, S. H. (1987). Design of an index of water quality. *Water Resources Bulletin, American Water Resources Association., 23*(5), 823–843.

Dojlido, J., Raniszewski, J., & Woyciechowska, J. (1994). Water quality index applied to rivers in the Vistula River basin in Poland. *Environmental Monitoring and Assessment, 33*(1), 33–42.

Dunnette, D. A. (1979). A geographically variable water quality index used in Oregon. *Journal Water Pollution Control Federation, 51*(1), 53–61. doi:10.2307/25040240.

Espejo, L., Kretschmer, N., Oyarzún, J., Meza, F., Núñez, J., Maturana, H., et al. (2012). Application of water quality indices and analysis of the surface water quality monitoring network in semiarid North-Central Chile. *Environmental Monitoring And Assessment, 184*(9), 5571–5588. doi:10.1007/s10661-011-2363-5.

EPI (2010). Environmental Performance Index: summary for policymakers. (Accessed in December 2014) <http://epi.yale.edu/files/2010_epi_summary_for_policymakers.pdf>.

Fulazzaky, M. (2010). Water quality evaluation system to assess the status and the suitability of the Citarum River water to different uses. *Environmental Monitoring And Assessment, 168*(1-4), 669–684. doi:10.1007/s10661-009-1142-z.

Gazzaz, N. M., Yusoff, M. K., Aris, A. Z., Juahir, H., & Ramli, M. F. (2012). Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. *Marine Pollution Bulletin, 64*(11), 2409–2420. doi:10.1016/j.marpolbul.2012.08.005.

Hallock, D. (2002). A water quality index for ecology's stream monitoring program. Washington Department of Ecology. <http://www.ecy.wa.gov/biblio/0203052.html> (Accessed in December 2014).

Hanh, P. T. M., Sthiannopkao, S., Ba, D. T., & Kim, K. W. (2011). Development of water quality indexes to identify pollutants in Vietnam's surface water. *Journal of Environmental Engineering, 137*(4), 273–283.

Harkins, R. D. (1974). An objective water quality index. *Journal Water Pollution Control Federation, 46*(3), 588–591. doi:10.2307/25038160.

Hèbert, S. (2005). Comparison between the index of overall quality of water in Quebec (IQBP) the water quality index CCME (WQI) for the protection of aquatic life, Quebec. Ministry of Sustainable Development, Environment and Parks Department in Monitoring the State of Environment, Québec. ISBN: 2-550-45900-8.

Horton, R. K. (1965). An index number system for rating water quality. *Journal of Water Pollution Control Federation, 37*(3), 300–306.

House, M. A. (1990). Water quality indices as indicators of ecosystem change. *Environmental Monitoring and Assessment, 15*(3), 255–263.

House, M. A. (1989). A water quality index for river management. *Journal of the Institution of Water and Environmental Management, 3*, 336–344.

House, M. A., & Ellis, J. B. (1987). The development of water quality indices for operational management. *Water Science and Technology, 19*(9), 145–154.

House, M. A. (1986). Water quality indices. PhD thesis, Middlesex Polytechnic.

Hurley, T., Sadiq, R., & Mazumder, A. (2012). Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. *Water Research, 46*(11), 3544–3552. doi:10.1016/j.watres.2012.03.061.

IDEQ, (2002). Idaho River Assessment Framework. (Accessed in December 2014). <https://www.deq.idaho.gov/media/457032-assessment_river_entire.pdf>.

Juahir, H., Zain, S., Yusoff, M., Hanidza, T. I. T., Armi, A. S. M., Toriman, M., et al. (2011). Spatial water quality assessment of Langat River Basin (Malaysia) using environmetric techniques. *Environmental Monitoring And Assessment, 173*(1-4), 625–641. doi:10.1007/s10661-010-1411-x.

Juwana, I., Muttil, N., & Perera, B. J. C. (2012). Indicator-based water sustainability assessment—a review. *Science of the Total Environment, 438*(0), 357–371. doi:10.1016/j.scitotenv.2012.08.093.

Juwana, I., Perera, B. J. C., & Muttil, N. (2010). A water sustainability index for West Java—part 2: refining the conceptual framework using Delphi technique. *Water Science and Technology, 62*(7), 1641–1652.

Kannel, P. R., Lee, S., Lee, Y. S., Kanel, S. R., & Khan, S. P. (2007). Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment, 132*(1-3), 93–110.

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., & Zanacic, E. (2014). Statistical assessment of the surface water quality monitoring network in Saskatchewan. *Water, Air, & Soil Pollution, 225*(10).

Khalil, B., Ouarda, T. B. M. J., St-Hilaire, A., & Chebana, F. (2010). A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. *Journal of Hydrology, 386*(1–4), 173–185. doi:10.1016/j.jhydrol.2010.03.019.

Khan, A. A., Paterson, R., & Khan, H. (2004). Modification and application of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for the communication of drinking water quality in Newfoundland and Labrador. *Water Quality Research Journal of Canada, 39*(3), 285–293.

Khan, F., Husain, T., & Lumb, A. (2003). Water quality evaluation and trend analysis in selected watersheds of the Atlantic region of Canada. *Environmental Monitoring and Assessment, 88*(1-3), 221–248. doi:10.1023/A:1025573108513.

Koçer, M. A. T., & Sevgili, H. (2014). Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. *Ecological Indicators, 36*(0), 672–681. doi:10.1016/j.ecolind.2013.09.034.

Kodikara, P. N., Perera, B. J. C., & Kularathna, M. (2010). Stakeholder preference elicitation and modelling in multi-criteria decision analysis—a case study on urban water supply. *European Journal of Operational Research, 206*(1), 209–220.

Ladson, A. R., White, L. J., Doolan, J. A., Finlayson, B. L., Hart, B. T., Lake, P. S., & Tilleard, J. W. (1999). Development and

testing of an Index of Stream Condition for waterway management in Australia. *Freshwater Biology, 41*, 453–469.
Landwehr, J. M., & Deininger, R. A. (1976). A comparison of several water quality indexes. *Journal Water Pollution Control Federation, 48*(5), 954–958. doi:10.2307/25038981.
Lermontov, A., Yokoyama, L., Lermontov, M., & Machado, M. A. S. (2009). River quality analysis using fuzzy water quality index: Ribeira do Igaupe river watershed, Brazil. *Ecological Indicators, 9*(6), 1188–1197.
Linstone HA, Turoff M. (2002). The Delphi method: techniques and applications. Addison-Wesley Publishers.
Liou, S. M., Lo, S. L., & Wang, S. H. (2004). A generalized water quality index for Taiwan. *Environmental Monitoring and Assessment, 96*(1-3), 35–52.
Lumb, A., Sharma, T. C., & Bibeault, J.-F. (2011a). A review of genesis and evolution of water quality index (WQI) and some future directions. *Water Quality, Exposure and Health, 3*(1), 11–24. doi:10.1007/s12403-011-0040-0.
Lumb, A., Sharma, T. C., Bibeault, J. F., & Klawunn, P. (2011b). A comparative study of USA and Canadian water quality index models. *Water Quality, Exposure and Health, 3*(3-4), 203–216. doi:10.1007/s12403-011-0056-5.
Lumb, A., Halliwell, D., & Sharma, T. (2006). Application of CCME water quality index to monitor water quality: a case of the Mackenzie River basin, Canada. *Environmental Monitoring and Assessment, 113*(1-3), 411–429.
Mahapatra, S. S., Nanda, S. K., & Panigrahy, B. K. (2011). A cascaded fuzzy inference system for Indian River water quality prediction. *Advances in Engineering Software, 42*(10), 787–796. doi:10.1016/j.advengsoft.2011.05.018.
Meyer, M. A., & Booker, J. M. (1990). Eliciting and analysing expert judgement: a practical guide / Mary A. Meyer, Jane M. Booker: Washington, DC : Division of Systems Research, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, 1990.
MoEI (Ministry of the Environment of Indonesia). (2003). The guidance of water quality status in Indonesia. Decree No. 115/2003 (Penentuan status mutu air: In Bahasa Indonesia).
Mojahedi, S. A., & Attari, J. (2009). A comparative study of water quality indices for Karun River. *World Environmental and Water Resources Congress, 2009*, 1–9.
Mostafaei, A. (2014). Application of multivariate statistical methods and water quality index to evaluation of water quality in the Kashkan River. *Environmental Management, 53*(4), 865–881. doi:10.1007/s00267-014-0238-6.
MPCB (2014). Compilation of water quality data recorded by MPCB 2011-12, Maharashtra Pollution Control Board, India. <http://mpcb.gov.in/ereports/pdf/Water_Quality_Report_2011-12_TERI.pdf> (Accessed in December 2014).
Nagels, J. W., Davies-Colley, R. J., & Smith, D. G. (2001). A water quality index for contact recreation in New Zealand. *Water Science & Technology, 43*(5), 285–292.
Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). *Handbook on constructing composite indicators: methodology and user guide* (Vol. 2005). Ispra, Italy: OECD Statistics Working Paper.
Nikoo, M. R., Kerachian, R., Malakpour-Estalaki, S., Bashi-Azghadi, S. N., & Azimi-Ghadikolaee, M. M. (2011). A probabilistic water quality index for river water quality assessment: a case study. *Environmental Monitoring and Assessment, 181*(1-4), 465–478.
Nemerow, N.L. and Sumitomo, H. (1970), Benefits of water quality enhancement, Syracuse University, Syracuse, N.Y., Report No. 16110 DAJ.
Ocampo-Duque, W., Osorio, C., Piamba, C., Schuhmacher, M., & Domingo, J. L. (2013). Water quality analysis in rivers with non-parametric probability distributions and fuzzy inference systems: application to the Cauca River, Colombia. *Environment International, 52*, 17–28. doi:10.1016/j.envint.2012.11.007.
Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J. L., & Schuhmacher, M. (2006). Assessing water quality in rivers with fuzzy inference systems: a case study. *Environment International, 32*(6), 733–742. doi:10.1016/j.envint.2006.03.009.
ODEQ, (2014). Oregon Water Quality Index Summary Report, Water Years 2004-2013. <http://www.deq.state.or.us/lab/wqm/docs/wqiAnnualRep2014.pdf> (Accessed in December 2014).
Ott, W. R. (1978). *Water quality indices: a survey of indices used in the United States, EPA—600\4-78-005*. Washington, D.C.: Environmental Protection Agency.
Oudin, L.C., Meybeck, M, & Roussel P. (1999). Système d'évaluation de la qualité de l'eau des cours d'eau. Rapport de presentation SEQ-Eau (version 1).Agence de l'eau Loire-Bretagne, France.
Pesce, S. F., & Wunderlin, D. A. (2000). Use of water quality indices to verify the impact of Córdoba City (Argentina) on Suquía River. *Water Research, 34*(11), 2915–2926. doi:10.1016/S0043-1354(00)00036-1.
Prati, L., Pavanello, R., & Pesarin, F. (1971). Assessment of surface water quality by a single index of pollution. *Water Research, 5*(9), 741–751. doi:10.1016/0043-1354(71)90097-2.
Rickwood, C. J., & Carr, J. M. (2009). Development and sensitivity analysis of a global drinking water quality index. *Environmental Monitoring and Assessment, 156*, 73–90.
Ross, S. L. (1977). An index system for classifying river water quality. *Water Pollution Control, 76*(1), 113–122.
Said, A., Stevens, D. K., & Sehlke, G. (2004). An innovative index for evaluating water quality in streams. *Environmental Management, 34*(3), 406–414.
Sánchez, E., Colmenarejo, M. F., Vicente, J., Rubio, A., García, M. G., Travieso, L., & Borja, R. (2007). Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecological Indicators, 7*(2), 315–328. doi:10.1016/j.ecolind.2006.02.005.
Sargaonkar, A., & Deshpande, V. (2003). Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. *Environmental Monitoring and Assessment, 89*(1), 43–67.
Sarkar, C., & Abbasi, S. A. (2006). Qualidex—a new software for generating water quality indices. *Environmental Monitoring and Assessment, 119*(1-3), 201–231. doi:10.1007/s10661-005-9023-6.
Sharma, D., & Kansal, A. (2011). Water quality analysis of River Yamuna using water quality index in the national capital territory, India (2000–2009). *Applied Water Science, 1*(3-4), 147–157. doi:10.1007/s13201-011-0011-4.
Shrestha, S. S., & Kazama, F. F. (2007). Assessment of surface water quality using multivariate statistical techniques: a case

study of the Fuji River basin, Japan. *Environmental Modelling and Software, 22*(4), 464–475.

Shuhaimi-Othman, M., Lim, E., & Mushrifah, I. (2007). Water quality changes in Chini Lake, Pahang, West Malaysia. *Environmental Monitoring and Assessment, 131*(1-3), 279–292. doi:10.1007/s10661-006-9475-3.

Simões, F. D. S., Moreira, A. B., Bisinoti, M. C., Gimenez, S. M. N., & Yabe, M. J. S. (2008). Water quality index as a simple indicator of aquaculture effects on aquatic bodies. *Ecological Indicators, 8*(5), 476–484. doi:10.1016/j.ecolind.2007.05.002.

Singh, K. P., Malik, A., & Sinha, S. (2005). Water quality assessment and apportionment of pollution sources of Gomti River (India) using multivariate statistical techniques—a case study. *Analytica Chimica Acta, 538*(1-2), 355–374.

Singh, K. P., Malik, A., Mohan, D., & Sinha, S. (2004). Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India)—a case study. *Water Research, 38*(18), 3980–3992.

Smith, D. G. (1990). A better water quality indexing system for rivers and streams. *Water Research, 24*(10), 1237–1244. doi:10.1016/0043-1354(90)90047-A.

Štambuk-Giljanović, N. (1999). Water quality evaluation by index in Dalmatia. *Water Research, 33*(16), 3423–3440. doi:10.1016/S0043-1354(99)00063-9.

Štambuk-Giljanović, N. (2003). Comparison of Dalmatian water evaluation indices. *Water Environment Research, 75*(5), 388–405.

Stoner, J D. (1978). Water quality indices for specific water uses, U.S. Geological Survey Circular 770. <http://pubs.usgs.gov/circ/1978/0770/report.pdf> (Accessed in December 2014).

SRDD. (1976). *Development of a water quality index. Scottish research development department, applied research & development report number ARD3* (p. 61). Edinburg, UK: Engineering Division.

Swamee, P., & Tyagi, A. (2007). Improved method for aggregation of water quality subindices. *Journal of Environmental Engineering, 133*(2), 220–225. doi:10.1061/(ASCE)0733-9372(2007)133:2(220).

Swamee, P., & Tyagi, A. (2000). Describing water quality with aggregate index. *Journal of Environmental Engineering, 126*(5), 451–455. doi:10.1061/(ASCE)0733-9372(2000)126:5(451).

Terrado, M., Barceló, D., Tauler, R., Borrell, E., Campos, S. D., & Barceló, D. (2010). Surface-water-quality indices for the analysis of data generated by automated sampling networks. *TrAC, Trends in Analytical Chemistry, 29*(1), 40–52. doi:10.1016/j.trac.2009.10.001.

Tobin, A., Khan, A. A., Khan, H., Moores, L., & Taylor, J. (2007). Forestry water quality index—a planning tool for the assessment and communication of the impacts of forestry activities on water quality. *Forestry Chronicle, 83*(2), 207–214.

Tyagi, S., Sharma, B., Singh, P., & Dobhal, R. (2013). Water quality assessment in terms of water quality index. *American Journal of Water Resources, 1*(3), 34–38.

Tyson, J. M., & House, M. A. (1989). The application of a water quality index to river management. *Water Science and Technology, 21*(10-11), 1149–1159.

Walski, T. M., & Parker, F. L. (1974). Consumers water quality index. *Journal of the Environmental Engineering Division, ASCE, 100*(3), 593–611.

Wang, Y., Wang, P., Bai, Y., Tian, Z., Li, J., Shao, X., Mustavich, L. F. & Li, B.-L. (2013). Assessment of surface water quality via multivariate statistical techniques: a case study of the Songhua River Harbin region, China. *Journal of Hydro-environment Research, 7*, 30–40.

Wunderlin, D. A., María Del Pilar, D., María Valeria, A., Fabiana, P. S., Cecilia, H. A., & María De Los Ángeles, B. (2001). Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: Suquía River basin (Córdoba-Argentina). *Water Research, 35*(12), 2881–2894.

Xu, G., Xie, J., Zhang, Y., Zhao, C., & Wu, Q. (2010). *Application of Nemerow pollution index in landscape river water quality assessment of Tianjin.* Paper presented at the 2010 4th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2010.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*, 338–353.

Chapter 3
Parameter Selection for Cost Effective Water Quality Monitoring

3.1. Introduction

In this chapter, a new methodology for the selection of parameters in a cost effective way is presented (and which in this study was used for developing a water quality index). The presented methodology was based on a statistical assessment for parameter redundancy and also incorporated the use of three critical factors (based on the cost of laboratory analysis of parameters, and the magnitude and frequency of the parameters exceeding their permissible limits). This methodology was demonstrated for a case study based on monitoring stations located in the main rivers across the West Java province, Indonesia. For this case study area, a uniform set of parameters was identified in this chapter, which then was used in developing a new WQI called the West Java Water Quality Index (WJWQI).

With regard to obtaining a uniform set of parameters for use in WQIs as highlighted in Chapter 2 (on literature review), researchers have used different approaches to select the water quality parameters, such as expert judgment using Delphi Method (Brown et al., 1970), literature review (Said et al., 2004, Kannel et al., 2007), data availability (Cude, 2001), redundancy of parameters (Dunnette, 1979), overall water quality status (Dunnette, 1979, Liou et al. 2004, Thi Minh Hanh et al., 2011) and the intended use of the water body (Hurley et al., 2012). To the best our knowledge, no researcher has undertaken studies in the past to select a uniform set of parameters for use in a WQI for rivers other than using approaches aforementioned. Thus, in the development of WJWQI, the application of the proposed methodology offered a novel approach to select parameters for developing a WQI.

The proposed generic methodology for the selection of water quality parameters for cost effective water quality monitoring comprised of three sequential steps:

- Two screening procedures to exclude monitoring stations that did not have a minimum number of consecutively monitored data. Screening was also undertaken to exclude unimportant parameters based on data availability and data being within the permissible limits.

- Statistical assessment for parameter redundancy to identify redundant parameters, This second step was performed to identify the parameters to be removed from further monitoring based on an enhanced version of the methodology developed by Ouarda et al. (1996), and later adopted by Khalil et al. (2010, 2014).
- Identification of common parameters (i.e. a uniform set of parameters) for use in a particular river basin or a region/country. A uniform set of parameters should also include at least one parameter belonging to each of the seven different groupings of water quality parameters.

Using water quality data from the monitoring stations of Citarum River, Indonesia, an example of the use of exploratory data analysis for screening using box plots and hierarchical cluster analysis (HCA) to exclude unimportant parameters were presented in Paper 1 of this chapter. The parameters available after applying this screening procedure were then used to implement the proposed generic methodology, which are presented in Paper 2 and Paper 3 of this chapter.

Through the application of the methodology, which was proposed and presented in this chapter to select the most significant water quality parameters in a cost effective manner, a uniform set of common parameters to be used across river basins/regions have been identified, wherein the number of parameters were reduced from 62 to 26 through the screening procedures. The number of parameters to be continuously monitored at all stations was then reduced from 26 to 13 using further stages of the proposed methodology. Therefore, only 13 parameters representing all the 7 different grouping of water quality parameters were recommended to be used for further steps in the development of the WJWQI (which are presented in Chapter 4 and 5 of this thesis).

This chapter contains the following papers, which demonstrates the use of statistical analysis for parameters selection used in the development of WJWQI:

1. Sutadian, A. D., N. Muttil, A. Yilmaz, and C. Perera. 2015. Use of exploratory data analysis for cost effective monitoring of water quality data. 36th Hydrology and Water Resources Symposium Hobart, Tasmania, 7-10 December 2015, 1147-1154.
2. Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016b. Parameter Selection for Cost Effective Water Quality Monitoring – Part 1: Developing the Methodology. Submitted to Journal of Environmental Management (Under review).
3. Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016c. Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java, Indonesia. Submitted to Journal of Environmental Management (Under review).

3.2

GRADUATE RESEARCH CENTRE

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Use of exploratory data analysis for cost effective monitoring of water quality data

Surname: Sutadian First name: Arief Dhany

College: College of Engineering & Science Candidate's Contribution (%): 85

Status:

Accepted and in press: ☐ Date:

Published: ☑ Date: 2015

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted]	30/03/2017
Signature	Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;

2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing		30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing		30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing		31/03/2017

Updated: June 2015

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

GRADUATE RESEARCH CENTRE

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Parameter Selection for Cost Effective Water Quality Monitoring – Part 1: Developing the Methodology

Surname: Sutadian
First name: Arief Dhany

College: College of Engineering & Science
Candidate's Contribution (%): 85

Status:
Accepted and in press: ☐ Date:
Published: ☐ Date:

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted] 30/03/2017

Signature Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. There are no other authors of the publication according to these criteria;
4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location**(s):

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing		30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing		30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing		31/03/2017

Updated: June 2015

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

GRADUATE RESEARCH CENTRE

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java

Surname: Sutadian First name: Arief Dhany

College: College of Engineering & Science Candidate's Contribution (%): 85

Status:

Accepted and in press: ☐ Date:

Published: ☐ Date:

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted]	30/03/2017
Signature	Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;

2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing		30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing		30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing		31/03/2017

Updated: June 2015

Use of exploratory data analysis for cost effective monitoring of water quality data by A.D. Sutadian, N. Muttil, A. Yilmaz and C. Perera was published in the peer review conference proceedings, *36th Hydrology and Water Resources Symposium: The art and science of water, 2015*

3.4 Parameter Selection for Cost Effective Water Quality Monitoring – Part I: Developing the Methodology

Arief Dhany Sutadian[1, 2 *], Nitin Muttil[1, 3], Abdullah Gokhan Yilmaz[4], B.J.C. Perera[1, 3]

[1]College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia.

[2]The West Java Environmental Management Agency, Indonesia, Jl. Naripan No. 25 Bandung, 40111, Indonesia.

[3]Institute for Sustainability and Innovation, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia

[4]University of Sharjah, College of Engineering, PO Box 27272, United Arab Emirates

(*author for correspondence, e-mail: arief.sutadian@live.vu.edu.au)

Abstract

This paper, which is the first in a two-part series, presents a new methodology for water quality parameter selection for cost effective monitoring of the parameters. Using the proposed methodology, parameters to be monitored continuously and those that are to be discontinued at the monitoring stations can be identified. The methodology will also provide a uniform set of common parameters to be monitored across all monitoring stations in a river basin or in a region/country. This methodology is developed based on the statistical assessment of parameter redundancy using association between different parameters and the use of three critical factors (based on the cost of the laboratory analysis of parameters and the magnitude and frequency of the parameters exceeding their permissible limits). Using the critical factors proposed in this study, an enhanced performance consolidated index is developed to identify the cost effective optimal set of parameters to be monitored for each monitoring station. Only parameters recommended to be monitored continuously at majority of the monitoring stations are then selected to be included in the uniform set of parameters to be monitored across a river basin or a region/country. The second paper of this series presents the application of the proposed methodology, which has been applied to a number of monitoring stations in rivers across the West Java province in Indonesia. Results of applying this methodology can be used either for the development of a Water Quality Index for rivers or for cost effective monitoring of parameters in future water quality monitoring programs.

Keywords: Parameter selection, Parameter redundancy, Critical factors, Water quality index, Monitoring network

1. Introduction

Water quality monitoring and assessment is an essential aspect of water resources management. In recent times, water quality deterioration has become a growing concern since poor water quality causes additional stress on water availability and aquatic ecosystems. To deal with this concern, during the last few decades, many countries have paid more attention to develop Water Quality Monitoring (WQM) programs (Debels et al., 2005). Such monitoring programs help to understand various water quality processes and provide the necessary information to water authorities for effective water resources management in general and specifically for improved water quality management (Khalil et al., 2010). In order to develop and implement a comprehensive water policy, adequate WQM and assessment on a long-term basis is necessary (Biswas et al., 1997), and therefore, providing representative and reliable monitoring of water quality is critical (Massoud, 2012).

Water quality parameters are generally defined under three broad categories viz. physical, chemical and biological, and each group has several parameters (Boyacioglu, 2010; Gazzaz et al., 2012; Swamee and Tyagi, 2007). Monitoring of all water quality parameters is an expensive and laborious task. Chapman (1996) recommends that the parameters to be monitored must be chosen carefully and as efficiently as possible by considering their relationships with the assessment objectives and specific local knowledge. Therefore, the water authorities should establish their own programs and priorities for resource allocation and develop WQM programs effectively for cost effective and sustainable water quality management.

The traditional approach to river water quality assessment is through comparing its compliance with water quality guidelines or objectives. (de Rosemond et al., 2009). This approach is carried out for each water quality parameter (CCME, 2001). However, this type of assessment cannot provide sufficient amount of information on the general status of water quality (Debels et al., 2005). One of the very important approaches considered in water quality studies is the use of time series analysis. It is commonly used for forecasting the future value of the investigated parameters, based on time series data of other water quality parameters (Asadollahfardi, 2014; Georgakarakos et al., 2006; Huck and Farquhar, 1974). Nevertheless, this approach needs high observation frequency and long periods of monitoring data (Chapman, 1996). Another approach to assess river water quality is using water quality simulation models. Such an approach can be used to assist in predicting the water quality impacts of water management policies and practices (Loucks et al., 2005). This approach is not easily applicable and requires significant efforts (Koçer and Sevgili, 2014). This difficulty is caused mainly due to the need for a large amount of data, significant financial resources, and expertise for model development and application (Kannel et al., 2007; SomlyóDy et al., 1998). Some other approaches have also been used for river water quality assessment, but the most commonly used approach is the use of Water Quality Indices (WQIs). Even though there are a few limitations of the use of the WQI, e.g. it cannot define the quality of water for all uses and all hazards (Cude et al., 1997), the WQI can be a useful tool to express the general state of water quality spatially and temporally; therefore, it can be used as a basis for improvement in water quality programs (Cude et al., 1997). A WQI transforms selected water quality parameters into a dimensionless number by aggregating the measurement of selected parameters so that the general status of river water quality can be defined. The WQI can also be applied as an operational management tool by water authorities (Ocampo-Duque et al., 2006).

Parameter selection is an essential step in the development of a WQI since the selected parameters are the main constituents of a WQI. Researchers have used different approaches in the past to select the water quality parameters for use in WQIs, such as expert judgment (Brown et al., 1970), literature review (Kannel et al., 2007; Said et al., 2004), data availability (Cude, 2001), redundancy of parameters (Dunnette, 1979), overall water quality status (Dunnette, 1979; Thi Minh Hanh et al., 2011) and the intended use of the water body (Hurley et al., 2012). To select the optimal set of water quality parameters in a cost effective manner, the number of selected parameters should be kept to a minimum and should potentially be representative of a larger number of parameters (Landwehr et al., 1974). Thus, statistical assessment of the association between different parameters can be used to identify the optimal set of water quality parameters. Such an approach will lead to a reduction in the number of parameters to be monitored without losing a substantial amount of information in representing the water quality.

This study proposes a methodology for parameter selection, which is an enhancement of the statistical assessment based methodology developed by Ouarda et al. (1996) for hydrometric network rationalization, and later adopted by Khalil et al. (2014; 2010) for parameter redundancy. The statistical assessment based methodology in general involves two main steps, namely (i) integration of criteria developed from record augmentation procedure with correlation analysis and Hierarchal Cluster Analysis (HCA) to identify highly correlated parameters, and (ii) application of a consolidated performance index (I_a) to systematically identify an optimal set of parameters to be monitored continuously and the parameters to be discontinued. However, there were limitations in the application of I_a in previous studies since often different sets of parameters to be continuously measured had the same I_a values. As a result, the water authorities and other users of this methodology will encounter difficulty in identification of the parameters to be continued and those to be discontinued. To deal with this difficulty, in this study, three critical factors were introduced to enhance the I_a developed by Ouarda et al. (1996) and later adopted by Khalil et al. (2010, 2014). These critical factors were proposed to be included in the calculation of I_a, since they reflect the criticality of water quality parameters for cost effective monitoring. The first factor represents the cost of monitoring of parameters, and the other two factors represent the magnitude and frequency of the parameter exceeding its permissible limits. This enhancement results in different I_a values and hence will assist in accurately selecting the parameters to be continuously monitored.

The application of a WQI in a river basin or in a region/country with multiple river basins requires a uniform set of common water quality parameters measured at all stations so that the general status of water quality from one monitoring station to another station can be compared through the WQI. To achieve this, the proposed methodology has to be first applied to each monitoring station. The water quality parameters identified to be monitored continuously for a majority of the monitoring stations can be proposed to be used as the parameters in the development of a WQI. In addition, such common parameters should incorporate parameters from different water quality groupings (i.e. physical, chemical, etc.). Therefore, at least one parameter from each grouping should be included in the final set of common parameters to be continuously measured at all stations. This methodology offers a novel approach to select parameters for developing a WQI, since such a methodology has not been used in the parameter selection of previous WQIs.

This paper, which is the first in a two-part series, presents the proposed methodology for parameter selection in a more cost effective manner. The main aim of the methodology is to provide a sound statistical basis for identifying the water quality parameters that have to be monitored continuously and those to be discontinued, thus making the WQM more cost effective. The specific objectives of this study are to develop a new methodology for: (i) identifying an optimal set of the water quality parameters based on statistical assessment for parameter redundancy and three critical factors (i.e., representing cost of parameter monitoring, and magnitude and frequency of the parameter exceeding its permissible limits), and (ii) selecting a uniform set of parameters to be monitored across stations in a cost effective way, which can then be used either for the development of a WQI for rivers or for future water quality monitoring programs.

This paper is structured as follows. Section 2 presents the proposed methodology used to identify the cost effective optimal set of water quality parameters that should be continuously monitored for each station. This section also presents identifying a set of common parameters to be used across all monitoring stations. Summary and conclusions drawn on parameter selection for cost effective water quality monitoring are presented in Section 3. The second paper of this two-part series presents a case study, which is the application of the proposed methodology in the water quality monitoring network of West Java Province, Indonesia.

2. Methodology

This section presents the proposed generic methodology for the selection of water quality parameters for cost effective WQM. It comprises three sequential steps, namely screening, statistical assessment for parameter redundancy to identify redundant parameters, and identification of common parameters (i.e. a uniform set of parameters) for use in a particular river basin or a region/country.

The first step (i.e. screening) was carried out to exclude monitoring stations that did not have a minimum number of consecutively monitored data. The screening was also undertaken to identify parameters that do not meet the minimum data criteria and parameters that are within the permissible limits. The second step (i.e. statistical assessment for parameter redundancy) is performed to identify the parameters to be removed from further monitoring based on the methodology developed by Ouarda et al. (1996), and later adopted by Khalil et al. (2014; 2010). It was done through identifying highly correlated clusters to assess redundancy information among the studied parameters. This is followed by calculating a consolidated performance index (I_a) to define optimal combinations of water quality parameters to be continued and discontinued. This consolidated index is an enhancement of the index developed by Ouarda et al. (1996), later adopted by Khalil et al. (2014; 2010). The final step (i.e. identification of a uniform set of common parameters) aims to define a uniform set of parameters for use either in the development of a WQI or for future WQM programs for a particular study area. To obtain this set, the parameters should meet one of the three criteria based on: (i) identified as single parameter clusters at least for 70% of water quality monitoring stations, (ii) commonly recommended to be monitored continuously at least for 80% of water quality monitoring stations, (iii) grouping of water quality parameters. Details of each step of the methodology are explained in the following sub-sections. This methodology is presented in Figure 1.

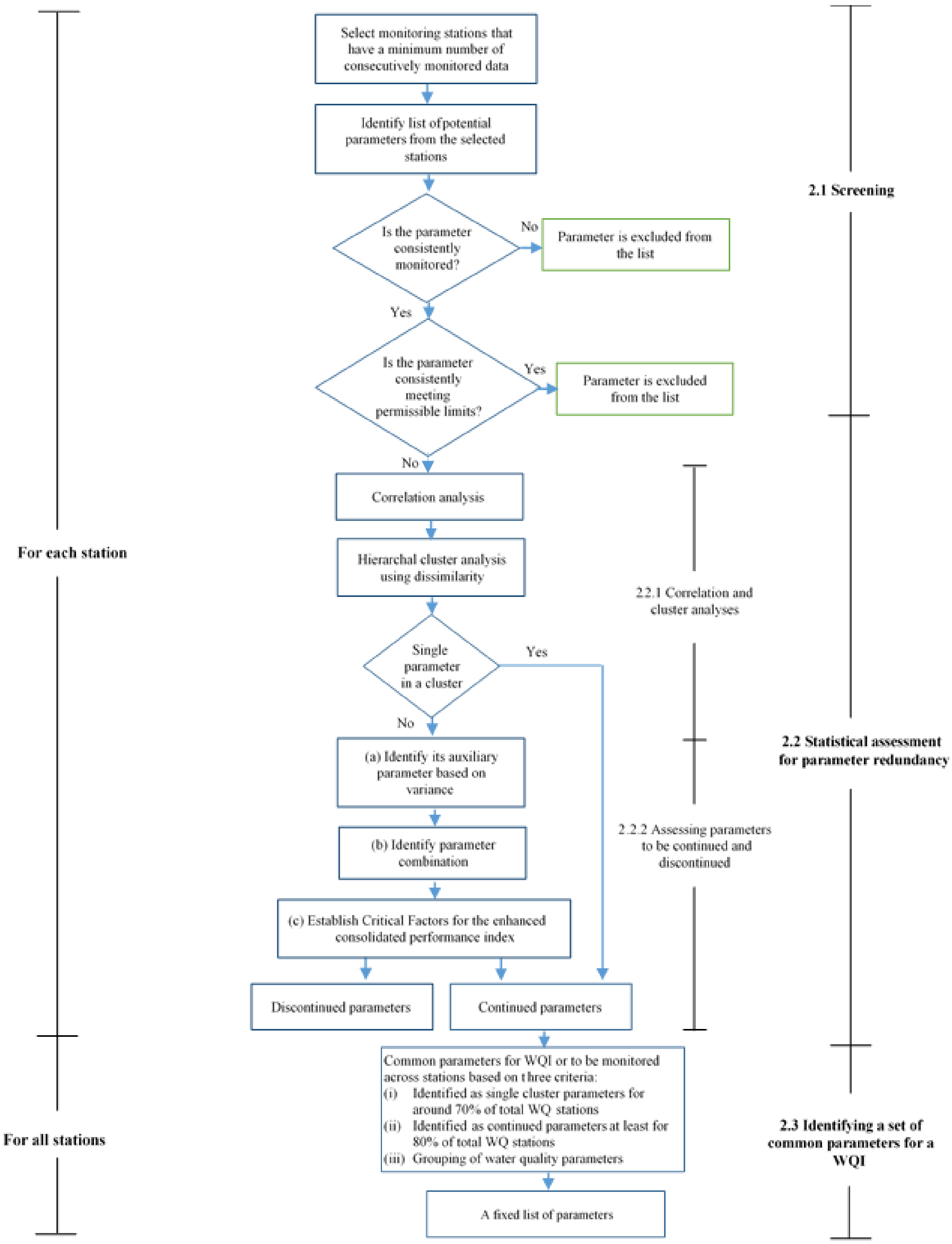


Figure 1 Methodology for the selection of cost effective water quality parameters

2.1 Screening

Screening is an initial step that consists of two criteria, that is, screening based on "data availability" (Dunnette, 1979; Thi Minh Hanh et al., 2011) and "data being within the permissible limits". Only stations and parameters which had a minimum of six or more consecutively monitored data were used in this study as the statistical assessment used in further analysis needs that requirement. Therefore, using data from the relevant stations, a list of potential parameters was compiled based on water quality parameters that have been monitored across a particular study area and then subjected to the above two rejection criteria.

In the first screening criteria, some parameters that were not consistently monitored were recommended to be removed from the list of potential water quality parameters based on the assumption that they were not consistently monitored because they were not considered that important. Moreover, since data are not consistent, they cannot be used in the subsequent step of statistical assessment (presented in Section 2.2). In this study, similar to screening for stations, the parameters that have less than a minimum of six or more consecutive years of valid records during the considered monitoring period were excluded from further analysis.

In the second screening criteria, box plot analysis was used to provide a summary visualization of the data. The box plot analysis shows a measure of central location (the median), a measure of spread (inter-quartile range), the skewness (orientation of the median relative to the quartiles) and potential outliers (marked individually). Details about box plots can be found in Muttil and Chau (2007). Box plot of particular parameters were then compared with their permissible limits using designated water uses for a particular study area. This type of designated water use may vary from one country to another and is usually outlined in Clean Water Acts or Water Quality Guidelines as water quality standards to protect the public health and enhance the quality of water. According to the permissible limits of the chosen designated water uses, the parameters that are always 'within the permissible limits' are not considered for further analysis as they are not present in significant amounts to be harmful to human or ecological health.

2.2 Statistical assessment for parameter redundancy

As mentioned earlier, the statistical assessment technique developed by Ouarda et al. (1996) for hydrometric network rationalization and later adopted by Khalil et al. (2014; 2010) specifically for parameter redundancy, was applied in this study. This statistical assessment was used to reduce water quality parameters by integrating criteria developed from a correlation procedure for augmenting hydrologic data (Matalas and Jacobs, 1964). This record augmentation procedure is a useful approach for estimating the mean and variance of short hydrological records by employing the cross-correlation between a long and a short sequence of data (Vogel and Stedinger, 1985). Such criteria help to develop a correlation coefficient threshold (dissimilarity distances) to be used in Hierarchal Cluster Analysis (HCA) in identifying highly correlated clusters of water quality parameters. This is then followed by the application of the consolidated index (I_a) to systematically identify the optimal set of parameters to be continued and those to be discontinued. The I_a was further enhanced in this study by considering three critical factors to be included in the calculation of I_a. This enhancement enables different multiple combinations of parameters to be continued and those to be discontinued to have different I_a values. Such an enhancement is useful for the water authorities to select parameters to be continued and those to be discontinued with certainty in their WQM programs.

2.2.1 Correlation and cluster analyses

An integration of the Pearson's correlation coefficient analysis with HCA was employed by Khalil et al. (2014; 2010) to identify clusters of highly correlated water quality parameters. The Pearson's correlation coefficient (r) provides a measure of level of association among parameters, whereas HCA is a common approach used to classify data into clusters (Singh et al., 2004). This integration as applied by Khalil et al. (2014; 2010) using the Pearson's correlation coefficients as 'dissimilarity distances' among parameters by converting their Pearson's correlation coefficient values into ($1 – r^2$). Subsequently, HCA was performed through average linkage method using such 'dissimilarity distances' to produce correlated water quality parameters in a cluster. Then, to identify the number of clusters, Khalil et al. (2014; 2010) adopted correlation coefficient thresholds (i.e. as developed by Ouarda et al. (1996)) so that a high correlation among water quality parameters can be defined with certainty.

Khalil et al. (2010) reviewed that correlation together with regression analysis is often used for the assessment and reselection of water quality parameters. Moreover, Khalil et al. (2010) identified two main deficiencies in this correlation – regression approach, namely: (i) the absence of a correlation coefficient threshold to identify a high correlation among water quality parameters, and (ii) the absence of an objective criterion to identify the optimal combination of water quality parameters to be discontinued and parameters to be continued to be monitored. To address these deficiencies, Khalil et al. (2010) modified the correlation – regression approach for reselection of water quality parameters by using criteria from record augmentation procedure (developed by Ouarda et al. (1996) for hydrometric network rationalization) to identify a correlation coefficient threshold and used a consolidated index (I_a) to evaluate all possible combinations of parameters to be continued and discontinued.

The background of the record augmentation procedure used by Khalil et al. (2014; 2010) is described as follows. Assume that there is a pair of parameters measured in parallel (denoted as parameters *y* and *x*). After a certain period, it was decided to stop monitoring parameter *y*, but parameter *x* was continued to be monitored. The parameter *y* (the short sequence) is assumed to be stopped after n_1 years, while the parameter *x* (the long sequence) is continued to be measured for another n_2 years after parameter *y* is stopped, as indicated below:

$x_1, x_2, x_3 \dots\dots\dots\ x_{n_1}, x_{n_1+1}, x_{n_1+2} \dots\dots\dots\ x_{n_1+n_2}$

$y_1, y_2, y_3 \dots\dots\dots y_{n_1}$

After n_2 years, assessment and reselection of parameters to be continued and discontinued to be monitored will take place. In the record augmentation procedure, the mean of population (μ_y) and population variance (σ_y^2) of the variable *y* after n_2 years (i.e. the extended series of variable *y* although it was not monitored after n_1 years) can be estimated by using the relationship through the period n_1 of variable y and the period of $n_1 + n_2$ of variable *x* (the long sequence). Matalas and Jacobs (1964) developed a procedure for obtaining both unbiased estimators for the mean ($\hat{\mu}_y$) and variance ($\hat{\sigma}_y^2$) of the extended series of variable *y*. They can be estimated from Equations (1) and (2):

$$\hat{\mu}_y = \bar{y}_1 + \frac{n_1}{n_1 + n_2}\hat{\beta}(\bar{x}_2 - \bar{x}_1) \quad (1)$$

$$\hat{\sigma}_y^2 = \hat{\beta}^2 s_x^2 + \left[1 - \frac{(n_1 + n_2 - 3)}{(n_1 - 3) + (n_1 + n_2 - 1)}\right]\frac{n_1 - 1}{n_1 - 2} s_{y_1}^2 - \hat{\beta} s_{x_1}^2 \quad (2)$$

where $\bar{y}_1$ and $\bar{x}_1$are the mean values of variable *y* and *x* (both are the short sequences), which are measured during the period of concurrent records *i=1,…,* n_1, $\bar{x}_2$ is the mean value of variable *x* recorded during the extension period *i*=n_{1+1},..., n_2, the parameter $\hat{\beta}$ is the estimated regression coefficient, s_x^2 is the variance estimated based on the entire *x* series, and $s_{y_1}^2$and $s_{x_1}^2$are the standard deviations of variable *y* and *x* (the short sequences). Based on this formulation, Cohran (1953) showed that the variance of the mean value of the extended series of variable *y* can be estimated by using Equation (3), while Matalas and Jacobs (1964) showed the variance of the variance of the extended series of variable *y* can be estimated by using Equation (4).

$$Var\{\hat{\mu}_y\} = \frac{\sigma_y^2}{n_1}\left[1 - \frac{n_2}{(n_1 + n_2)}\left(\rho^2 - \frac{1 - \rho^2}{n_1 - 3}\right)\right] \quad (3)$$

$$Var\{\hat{\sigma}_y^2\} = \frac{2\sigma_y^4}{(n_1-1)} + \frac{n_2\sigma_y^4}{(n_1n_2-1)^2(n_1-3)}(A\rho^2 + B\rho + C) \tag{4}$$

where σ_y^2 is the population variance, ρ is the population correlation between variable *x* and *y*. For practical use, σ_y^2 and ρ may be replaced by their estimates based on data available during the n_1 years of data (Khalil et al., 2014; Khalil et al., 2010; Ouarda et al., 1996). Meanwhile, A, B, and C are constants and depend on n_1 and n_2. They are defined by Matalas and Jacobs (1964) as follows:

$$A = \frac{(n_2+2)(n_1-6)(n_1-8)}{(n_1-5)} + (n_1-4)\left(\frac{n_1n_2(n_1-4)}{(n_1-3)(n_1-2)} - \frac{2n_2(n_1-4)}{(n_1-3)} - 4\right) \tag{5}$$

$$B = \frac{6(n_2+2)(n_1-6)}{(n_1-5)} + 2(n_1^2 - n_1 - 14) +$$

$$(n_1-4)\left(\frac{2n_2(n_1-5)}{(n_1-3)} - 2(n_1+3) - \frac{2n_1n_2(n_1-4)}{(n_1-3)(n_1-2)}\right) \tag{6}$$

$$C = 2(n_1+1) + \left(\frac{3(n_2+2)}{(n_1-5)} - \frac{(n_1+1)(2n_1+n_2-2)(n_1-3}{(n_1-1)}\right) +$$

$$(n_1-4)\left(\frac{2n_2}{(n_1-3)} + 2(n_1+1) + \frac{n_1n_2(n_1-4)}{(n_1-3)(n_1-2)}\right) \tag{7}$$

Ouarda et al. (1996) and Khalil et al. (2014; 2010) stated in order to assess whether the variance of the mean and the variance of extended series provides additional information on the parameter *y*, their values must be compared with the variance obtained from the short sequence (n_1 years of data). In this case, the critical value of ρ should meet requirements as defined in Equation (8) for an improved estimator of the mean and Equation (9) for an improved estimator of the variance.

$$\rho_m^2 > \frac{1}{(n_1-2)} \tag{8}$$

$$\rho_v^2 > \frac{\left[-B \pm (B^2 - 4AC)^{1/2}\right]}{2A} \tag{9}$$

To integrate the correlation analysis with HCA, Khalil et al. (2014; 2010) then adopted Equation (8) and (9) to calculate the required correlation coefficient thresholds. Since dissimilarity ($1 - r^2$) was used to identify groups of highly correlated parameters, Khalil et al. (2014; 2010) converted Equation (8) and (9) to Equation (10) and (11). These two equations (Equation (10) and (11)) were then applied in the HCA to identify the number of clusters that can be created. The HCA was carried out in two consecutive steps: (1) identify distance among parameters by converting a correlation matrix (r^2) to dissimilarity matrix ($1- r^2$) and (2) identify the linkage distance, which is the distance between two clusters and defined at each step of clustering process using the average linkage function. The lower of the two criteria using Equation (10) and (11), i.e. d_v or d_m was used as the coefficient thresholds to identify the level of dissimilarity among parameters.

$$d_m < 1 - \frac{1}{(n_1 - 2)} \tag{10}$$

$$d_v < 1 - (-B \pm \sqrt{B^2 - 4AC})/2A \tag{11}$$

where, d_m and d_v correspond to dissimilarity measures (i.e. the coefficient threshold), n_1 is the number of concurrent years of measurements, and n_2 is the number of years after the assessment and reselection took place. According to such thresholds, the HCA results may have two different types of clusters: The first type is the single parameter clusters (i.e. only one parameter in a cluster), while the second type is multiple parameter clusters (i.e. two or more parameters in a cluster). In practice, if the linkage distance of correlated parameters is clustered above the coefficient threshold (either d_m or d_v), it is classified as single parameter clusters, whereas if the linkage distance of correlated parameters is clustered below the coefficient threshold (either d_m or d_v), it is classified as multiple parameter clusters.

In addition, as described and applied by Khalil et al. (2014; 2010), the selected parameters should ideally come from all clusters since information about a parameter in a particular cluster cannot be reconstituted from other clusters. Therefore, all single parameter clusters are recommended to be taken as parameters to be monitored continuously either for the development of a new WQI or used in the future WQM programs, since the information of these parameters cannot be provided by other parameters. Moreover, as this study aims to obtain a minimum number of parameters to be monitored, only one parameter is selected from multiple parameter clusters to represent its cluster. Therefore, for multiple parameter clusters, only one parameter should be considered to be continued, while the other(s) should be discontinued.

2.2.2 Assessing parameters to be continued and discontinued

The assessment of appropriate parameters to be measured continuously in the future monitoring program is applied only for multiple parameter clusters. Such an assessment involves the following 3 steps:

(a) Identification of best auxiliary parameters based on variance of the mean estimator

(b) Identification of possible combinations of parameters to be discontinued and continued parameters

(c) Establishment of critical factors for the enhanced I_a, for all possible combinations of parameters to be continued and discontinued.

The above 3 steps are discussed in detail below.

(a) Identification of best auxiliary parameter

Identification of the best auxiliary parameter was examined for each multiple parameter cluster separately. The auxiliary parameters are parameters used to reconstitute statistical information of discontinued parameters. This step aims to identify the best auxiliary parameter from a cluster if a particular parameter from that cluster is assumed to be discontinued. The approach assumes that within each cluster, each parameter will be discontinued (done one by one), and for each discontinued parameter the best auxiliary parameter is selected from the other parameters in the same cluster. This was done through the calculation of the variance of the mean estimator for parameters to be monitored continuously using Equation (3). For practical use, as stated by Ouarda et al. (1996) and applied by Khalil et al. (2014; 2010), the population variance of parameter *y* and the population correlation between *x* and *y* are replaced by their estimates based on the n_1 years data. To identify the best auxiliary parameter for a specific parameter to be discontinued in a cluster, Equation (3) was applied based on that specific parameter to be discontinued and all other parameters in the same cluster (i.e. their variance of the mean estimator should be separately calculated one by one), and the parameter that provides the least variance of the mean estimator (based on Equation (3)) was considered the best auxiliary parameter for that specific parameter to be discontinued.

(b) Identification of possible combinations of discontinued and continued parameters

Each cluster has different number and types of parameters. Therefore, they might have many combinations of parameters to be discontinued. To identify different combinations that can be formed, the binomial coefficient (C_k^w) was employed (2014; Khalil et al., 2010). C is the number of combinations for parameters to be continued and discontinued, *w* is number of all parameters that are in the list, while *k* is the number of parameters to be discontinued. Since the objective of this study is to select the optimal number of parameters to be monitored continuously, only one parameter in each multiple parameter cluster is taken as parameters to be continued, while the other parameters in the same cluster are to be discontinued. Therefore, to identify how many possible combinations of parameters to be continued and discontinued that could be possibly formed across multiple parameter clusters, multiplication of the binomial coefficient in each cluster has to be employed $(C_{k_1}^{w_1})\ (C_{k_2}^{w_2})\ (C_{k_3}^{w_3})\ \ldots..\ (C_{k_n}^{w_n})$ as combinations that involved more than one parameter to be continued from the same multiple parameter clusters were excluded. w_1, w_2, w_3 …… w_n is number of all parameters that are in the *n* cluster, while k_1, k_2, k_3……. k_n is the number of parameters to be discontinued in the *n* cluster. For example, consider a case where there are 10 parameters investigated at a particular station. After the cluster analysis, it is identified that there are 3 multiple parameter clusters (with 2 cluster has two parameters and the last cluster has 6 parameters). In this case, only one parameter in each multiple parameter cluster is taken as parameters to be continued, while the other parameters in the same cluster are to be discontinued. At this particular station, 1 out of 2 parameters (from the first and the second multiple parameter clusters) could be potentially discontinued, while 5 out of 6 parameters could be not be monitored any longer (from the last cluster that has 6 parameters). Thus, in the first and second clusters: w_1, and $w_2 = 2$, while k_1 and $k_2 = 1$. Meanwhile in the third cluster that has 6 parameters, $w_3 = 6$ and $k_3 = 5$. Using multiplication of the binomial coefficient, 24 possible combinations should be considered in making a decision to obtain the optimal set of parameters to be continued and discontinued.

(c) Establishment of critical factors for the enhanced consolidated performance index (I_a)

The I_a was used to assess the best combination of parameters to be continued and discontinued as it provides the decision maker with the rank of the best of combinations of parameters to be continued and discontinued. For practical comparison of the combinations, the I_a must be based on some kind of aggregated information; thus, I_a consists of the variance of the mean value estimator expected after n_2 years both for parameters to be continued and those to be discontinued (Khalil et al., 2014; Khalil et al., 2010; Ouarda et al., 1996). The combination that has the least value I_a is selected as an optimal combination of water quality parameters for future monitoring as it has the least of an aggregated variance of the mean estimator for all parameters investigated. Since the scale and the unit of parameters are different, I_a is applied using the standardized parameters to remove the dimensionality and the scale effects of the parameters. The I_a developed by Ouarda et al. (1996) for network hydrometric network rationalization, later adopted by Khalil et al. (2014; 2010) for parameter redundancy is defined as follow:

$$I_a = \sum_{Variable\ X} Var\{\hat{\mu}\{X\}\} \tag{12}$$

where X is the water quality parameter (including both parameters to be continued and discontinued) and $Var\{\hat{\mu}\{X\}\}$ is the variance of the mean value estimator expected after n_2 years.

As stated by Khalil et al. (2014; 2010), in the application of I_a, for those water quality parameters assumed to be discontinued, the variance of the mean value estimator expected after n_2 years is calculated using Equation (3), and the population parameters (variance and correlation) are replaced by their estimates based on data available during the n_1 years of data. Meanwhile, for parameters decided to be continuously monitored, the variance of the mean value after n_2 years is assumed to be equal to the variance of the mean after n_1 years multiplied by $(n_1-1)/(n_1+n_2-1)$ (Khalil et al., 2014; Khalil et al., 2010). The application of I_a is explained using the following example:

Assume a case where there is a cluster consisting of 3 parameters, namely parameters *x, y*, and *z*. A decision is made that two parameters are discontinued and one remaining parameter is continued to be monitored. Using the binomial coefficient, there are three combinations of parameters to discontinued and continued (C_2^3 = 3). In the first combination, suppose parameter *y* and *x* are assumed to be the discontinued parameters, while the parameter *z* is assumed to be continued. In this case, the parameter *z* should be the best auxiliary parameter for the parameters *y* and *x*. The variances of the mean value estimator after n_2 years for parameters to be discontinued are calculated using Equation (3). This equation should be applied separately based on: (i) the relationship of the parameter *y* and the parameter *z* and, (ii) the relationship of the parameter *x* and the parameter *z*. Meanwhile, since the parameter *z*, in this first combination, is assumed to be the continued parameter, its variance of the mean value estimator after n_2 years is estimated using its variance of the mean after n_1 years multiplied by (n_1-1/n_1+n_2-1). Thus, the summation of the variance of the mean value estimator expected after n_2 years both for parameters to be discontinued (the parameter *y* and *x*) and those to be continued (parameter *z*) is the value of I_a for the first combination. To calculate I_a for two other combinations, wherein the parameter *y* or the parameter *x* are assumed to be continued parameters, similar procedures are performed. Finally, after having examined all these 3 possible combinations, the combination that has the least I_a is the optimal combination of parameters to be continued and discontinued.

The I_a is calculated assuming that all water quality parameters have equal importance. Khalil. et al. (2010) also stated that the I_a can be modified by assigning different weights for each parameter (assuming that the parameters have unequal importance). As mentioned earlier, often different multiple combinations of parameters to be continued have the same I_a values. To overcome this limitation, three critical factors were introduced as an enhancement of the I_a. This enhancement aims to give different weights to individual parameters with regards to their relative importance and their influence on the I_a, so that different multiple combinations of parameters to be continued and discontinued provide different I_a values.

The first critical factor is associated with the monitoring cost (*c*) of a parameter. In this study, only the cost of laboratory analysis of the sampling was considered. The cost of laboratory analysis that is priced by an official regulation and issued by related authorities was used in this study. The other associated costs for the sample collection (e.g. labor, equipment, transportation, etc.) were not considered in this study as they cannot be defined and separated precisely based on individual parameters. Moreover, these associated costs used for sample collection will be dependent on the number of samples taken (monitoring frequency) (Erechtchoukovaa and Khaitera, 2013). The more expensive the parameter is, the more desirable it is to be discontinued.

The second critical factor is related to the frequency (*f*) of the parameter exceeding its permissible limit. As proposed and applied in CCME (2001), the frequency factor is calculated by dividing the number of measurements of that parameter exceeding the permissible limit to the total number of measurements of this parameter. A high frequency means that the measurements of the parameter are frequently not within permissible limits and therefore this parameter has high importance, so it should be continued to be monitored.

The last critical factor is the magnitude (*m*) of the parameter exceeding its permissible limit, which is the difference of the largest value recorded during the observation period over the permissible limit. If the concentration of a particular parameter is much larger than the permissible limit, then this parameter should be considered for continuous monitoring. On the other hand, if the concentration of a parameter is below the permissible limit, then the measurement of that parameter should be discontinued.

Establishment of each critical factor (*c*, *f* and *m*) for all parameters was developed based on deciles (the sorted data divided into ten equal parts) to make them in the same scale (1 to 5). Such an approach has been used by Gibbs and Maher (1967) to classify the drought index in Australia. As indicated earlier, the laboratory costs of sampling for each parameter was used to establish the classification based on an official regulation on laboratory cost. Similar to the cost factor, due to practical use, a common numerical scale for classifying the frequency and magnitude for all parameters was established (except for heavy metals). To establish that common scale for classifying the frequency and magnitude, only the minimum values of frequency and magnitude for each parameter calculated from different stations were considered and used for calculation the deciles as these minimum values are assumed to reflect the best pristine or natural condition across the study area. Thus, they (the minimum values of frequency or magnitude for each parameter) were ranked and divided into 5 classes (from accepted to extremely critical).

For heavy metal parameters, the classification of frequency and magnitude (of heavy metals) were not established based on deciles because they are regarded as toxic substances, and even small concentrations are not permissible. Instead, their classification is undertaken using a categorical scaling wherein the values must be either 1 or 5. For frequency, if all concentrations of a heavy metal parameter is below the permissible limit ($f = 0$), that parameter will fall to 1 (normal). Meanwhile, if there is concentration of a heavy metal parameter that is equal or above the permissible limit ($f > 0$), that parameter will fall to 5 (critical). For magnitude, the classification will be 1 (normal) if the largest concentration of a heavy metal parameter recorded during the observation period is never over the permissible limits ($m < 1$). Otherwise, the classification will fall to 5 if the largest concentration of a heavy metal parameter is above or exceeding the permissible limits ($m \geq 1$).

Each of the three factors, namely c, f, and m, for all parameters are computed separately by using the classification scheme described above. Then, the additive aggregation method as presented in Equation (13) was applied to aggregate the three different factors for each parameter, to form specific weights for the parameters. The additive aggregation was selected because of two reasons: (i) it offers simplicity wherein the final critical factor (cf) value is calculated by averaging the three critical factors and (ii) all aggregation methods are affected by eclipsing (i.e. one factor can show a poor/high quality, but the aggregated value may "eclipse" the poor/high quality of that single factor) (Swamee and Tyagi, 2000).

$$cf = \frac{c + f + m}{3} \tag{13}$$

The cf values are used as unequal weights for each parameter representing the relative importance and influence of that parameter. The I_a is modified in this study (as different than Ouarda et al. (1996) and Khalil et al. (2010, 2014) by considering the weights (cf values) to represent the unequal importance of the parameters, as shown below in Equation (14):

$$I_a = \sum_{Variable\ X} (cf)_X Var\{\hat{\mu}\{X\}\} \tag{14}$$

where $(cf)_X$ is the critical factor calculated using Equation (13), while the symbols of X and $\{\hat{\mu}\{X\}\}$ are the same as those used earlier in Equation (12). In this proposed enhancement of I_a, for those water quality parameters assumed to be discontinued, the variance of the mean value estimator expected after n_2 years is calculated using Equation (3). On the other hand, for the parameters assumed to be continuously monitored, as proposed by Khalil et al. (2014; 2010) in Equation (12), the variance of the mean value after n_2 years is assumed to be equal to the variance of the mean after n_1 years multiplied by $(n_1-1)/(n_1+n_2-1)$. Until this section, through inclusion of critical factors, an enhanced I_a was developed and applied to identify the cost effective optimal set of parameters to be monitored for each monitoring station for a particular study area.

2.3 Identifying a set of common parameters across monitoring stations

This final step was carried out to define a uniform set of parameters to be used in the development of a new WQI or in the future WQM programs for a particular study area. To achieve this, the application of the proposed methodology that was discussed in Section 2.2, has to be first applied to each relevant monitoring station across the study area. The results of the statistical assessment for parameter redundancy, with inclusion critical factors, may vary from one station to another station in a river basin or a region/country as some parameters might be important at a specific station, but they might not be important for other stations. Considering this fact, three criteria are proposed to be applied to obtain a uniform set of common parameters to be monitored across all stations. If a particular parameter meets any one of these three criteria, that parameter is recommended to be included in the uniform set of parameters to be monitored across all stations. The three criteria are as follows:

(i) Single parameter clusters for at least 70 % of the total monitoring network are recommended to be selected as the common parameters across all stations as the information of these parameters cannot be replaced by other parameters. This criteria is somewhat subjective since the more the percentage is, the less will be the number of parameters to be continued and are involved in the development of the WQI. Therefore, the index developers or water authorities can decide the percentage value of this criteria based on their preferences or on the significance of specific single parameter clusters in their own studies.

(ii) Only water quality parameters that are identified to be monitored continuously (i.e. based on results of single-parameter clusters (presented in Section 2.2.1) and the enhancement of the I_a in multiple-parameter clusters (Section 2.2.2) for at least 80% of the total monitoring network are proposed to be included in the uniform set of parameters across stations. Even though this criterion is somewhat arbitrary, this will increase the chance that some parameters that are commonly recommended to be continued at the majority of monitoring network, can be used as the common parameters in the development of a WQI. Subsequently, these parameters can be used as the auxiliary parameters to reconstitute statistical information of the discontinued parameters across stations in the future WQM programs.

(iii) The uniform set of parameters should include at least one parameter belonging to each of the seven different grouping of water quality parameters, involving physical, oxygen depletion, organics, nutrients, minerals, heavy metals, and biological parameters. The later criteria will ensure that the significance of each grouping of water quality parameters is considered in the final index aggregation of a WQI or in the future WQM programs. Therefore, if no parameter for a water quality grouping has been identified to be monitored continuously in a particular grouping of water quality parameters using the two criteria aforementioned, at least one parameter from that grouping should be included in the uniform set of parameters. Thus, a uniform set of water quality parameters representative of all water quality groupings can be identified for all monitoring stations for a particular river basin or a region/country.

3. Summary and Conclusions

This paper is the first part of a two-part series of papers on parameter selection for cost effective water quality monitoring. This paper presented a new methodology for selection of the most significant water quality parameters to be continuously monitored, thus leading to a cost effective monitoring of the parameters. The methodology consists of three sequential steps: (i) screening, (ii) the statistical assessment for parameters redundancy and the inclusion of three critical factors (based on cost of the laboratory analysis of the parameters and magnitude and frequency of the parameter exceeding its permissible limits), and (iii) identifying a uniform set of common parameters across all stations. Also an enhanced performance consolidated index was developed to identify the best combination of continued and discontinued parameters to be monitored at each monitoring station.

Since the proposed methodology is generic, it can be applied to any study area to identify the parameters to be continuously monitored and those that are to be discontinued from the network of monitoring stations. As a case study, the second paper of this series presents the application of the proposed methodology to a number of monitoring stations in rivers across the West Java province in Indonesia. Based on the results of applying the proposed methodology, parameters commonly recommended to be monitored continuously at the majority of monitoring stations will be selected as a uniform set of parameters to be monitored at all stations across the river basins of West Java.

Conclusions from this paper are summarized below:

- To select parameters for cost effective water quality monitoring, the number of selected parameters should be kept to a minimum and potentially be representative of a larger list or grouping of parameters. Thus, the exclusion of redundant parameters without losing important information in representing the surface water quality is important. In this study, the proposed methodology for parameter redundancy (i.e. through the inclusion of critical factors in calculation of I_a) provided a novel contribution to the previous research and lead to the selection of parameters to be continuously measured.
- It was also concluded that continuously monitored parameters across stations (based on the proposed generic methodology) can be used as a uniform set of common parameters for either the calculation/development of a WQI or as a set of "basic parameters" that should be included in the list of parameters to be monitored in a cost effective manner across stations in a river basin or a region for future water quality monitoring programs.

Acknowledgments

The authors would like to acknowledge and thank to the Australia Awards, which funded the first author for this study and the West Java Environmental Protection Agency, Indonesia, which had provided the data used in this study. The authors also would like to thank Dr. Bahaa Khalil for the helpful explanation of the methodology developed by him, which was enhanced in this study.

References

Asadollahfardi, G., 2014. Water quality management : assessment and interpretation. Heidelberg : Springer

Biswas, A.K., Ordoñez, E.B., Cabrera, J.G., 1997. Development of a Framework for Water Quality Monitoring in Mexico. Water International 22, 179-186.10.1080/02508069708686699

Boyacioglu, H., 2010. Utilization of the water quality index method as a classification tool. Environmental Monitoring and Assessment 167, 115-124

Brown, R.M., Mc Clelland, N.I., Deininger, R.A., Tozer, R.G., 1970. A water quality index-Do we dare? . Water and Sewage Works 117, 339-343

CCME, 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. Canadian Council of Ministers of the Environment Winnipeg.http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf (accessed 20.01.2015)

Chapman, D., 1996. Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring - Second Edition. E&FN Spon, an imprint of Chapman & Hall, Great Britain at the University Press, Cambridge

Cohran, W.G., 1953. Sampling technique. John Wiley, New York

Cude, C., Dunnette, D., Avent, C., Frankin, A., Gross, G., Hartman, J., Hayteas, D., Jenkins, T., Leben, K., Lyngdal, J., Marks, D., Morganti, C., Quin, T., 1997. Exploring Possibilities for An International Water Quality Index Applied to River System, in: Best, G., Bogacka, T., Niemirycz, E. (Eds.), International River Water Quality: Pollution and restoration. E & FN Spoon, London

Cude, C.G., 2001. Oregon water quality index a tool for evaluating water quality management effectiveness. JAWRA Journal of the American Water Resources Association 37, 125-137.10.1111/j.1752-1688.2001.tb05480.x

de Rosemond, S., Duro, D.C., Dubé, M., 2009. Comparative analysis of regional water quality in Canada using the Water Quality Index. Environmental Monitoring And Assessment 156, 223-240.10.1007/s10661-008-0480-6

Debels, P., Figueroa, R., Urrutia, R., Barra, R., Niell, X., 2005. Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified Water Quality Index. Environmental Monitoring and Assessment 110, 301-322.doi:10.1007/s10661-005-8064-1

Dunnette, D.A., 1979. A Geographically Variable Water Quality Index Used in Oregon. Journal Water Pollution Control Federation 51, 53-61.10.2307/25040240

Erechtchoukovaa, M.G., Khaitera, P.A., 2013. Cost estimates in cost-effectiveness analysis of water quality monitoring systems, 20th International Congress on Modelling and Simulation, Adelaide, Australia, pp. 2938 - 2944

Gazzaz, N.M., Yusoff, M.K., Aris, A.Z., Juahir, H., Ramli, M.F., 2012. Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. Marine Pollution Bulletin 64, 2409-2420.http://dx.doi.org/10.1016/j.marpolbul.2012.08.005

Georgakarakos, S., Koutsoubas, D., Valavanis, V., 2006. Time series analysis and forecasting techniques applied on loliginid and ommastrephid landings in Greek waters. Fisheries Research 78, 55-71.http://dx.doi.org/10.1016/j.fishres.2005.12.003

Gibbs, W.J., Maher, J.V., 1967. Rainfall deciles as drought indicators,

Huck, P.M., Farquhar, G.J., 1974. Water Quality Models Using the Box-Jenkins Method. Journal of the Environmental Engineering Division 100, 733-753

Hurley, T., Sadiq, R., Mazumder, A., 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Research 46, 3544-3552.http://dx.doi.org/10.1016/j.watres.2012.03.061

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R., Khan, S.P., 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environmental Monitoring and Assessment 132, 93-110

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., Zanacic, E., 2014. Statistical Assessment of the Surface Water Quality Monitoring Network in Saskatchewan. Water, Air, & Soil Pollution 225.10.1007/s11270-014-2128-1

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., Chebana, F., 2010. A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. Journal of Hydrology 386, 173-185.http://dx.doi.org/10.1016/j.jhydrol.2010.03.019

Koçer, M.A.T., Sevgili, H., 2014. Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. Ecological Indicators 36, 672-681.http://dx.doi.org/10.1016/j.ecolind.2013.09.034

Landwehr, J.M., Deininger, R.A., McClelland, N.L., Brown, R.M., 1974. An objective water quality index. Journal of the Water Pollution Control Federation 46, 1804-1807

Loucks, D.P., Beek, E.V., Stedinger, J.R., Dijkman, J.P., Villars, M.T., 2005. Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Paris: UNESCO

Massoud, M., 2012. Assessment of water quality along a recreational section of the Damour River in Lebanon using the water quality index. Environmental Monitoring and Assessment 184, 4151-4160.10.1007/s10661-011-2251-z

Matalas, N.C., Jacobs, B., 1964. A Correlation Procedure for augmenting hydrologic data, in: Interior, U.S.D.o.t. (Ed.). United States Government Printing Office, Washington

Muttil, N., Chau, K.-W., 2007. Machine-learning paradigms for selecting ecologically significant input variables. Engineering Applications of Artificial Intelligence 20, 735-744.http://dx.doi.org/10.1016/j.engappai.2006.11.016

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M., 2006. Assessing water quality in rivers with fuzzy inference systems: A case study. Environment International 32, 733-742.http://dx.doi.org/10.1016/j.envint.2006.03.009

Ouarda, T.B.M.J., Rasmussen, P.F., Bobée, B., Morin, J., 1996. Ontario Hydrometric Network Rationalization, Statistical Considerations, Research Report No. R-470. National Institute for Scientific Research, INRS-ETE, University of Quebec, Quebec, Canada, p. 75

Said, A., Stevens, D.K., Sehlke, G., 2004. An innovative index for evaluating water quality in streams. Environmental Management 34, 406-414

Singh, K.P., Malik, A., Mohan, D., Sinha, S., 2004. Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India) - A case study. Water Research 38, 3980-3992

SomlyóDy, L., Henze, M., Koncsos, L., Rauch, W., Reichert, P., Shanahan, P., Vanrolleghem, P., 1998. River water quality modelling: III. Future of the art. Water Science and Technology 38, 253-260.http://dx.doi.org/10.1016/S0273-1223(98)00662-3

Swamee, P., Tyagi, A., 2000. Describing Water Quality with Aggregate Index. Journal of Environmental Engineering 126, 451-455.doi:10.1061/(ASCE)0733-9372(2000)126:5(451)

Swamee, P., Tyagi, A., 2007. Improved Method for Aggregation of Water Quality Subindices. Journal of Environmental Engineering 133, 220-225.doi:10.1061/(ASCE)0733-9372(2007)133:2(220)

Thi Minh Hanh, P., Sthiannopkao, S., The Ba, D., Kim, K., 2011. Development of Water Quality Indexes to Identify Pollutants in Vietnam’s Surface Water. Journal of Environmental Engineering 137, 273-283.doi:10.1061/(ASCE)EE.1943-7870.0000314

Vogel, R.M., Stedinger, J.R., 1985. Minimum variance streamflow record augmentation procedures. Water Resources Research 21, 715-723.10.1029/WR021i005p00715

3.5. Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java, Indonesia

Arief Dhany Sutadian[1, 2 *], Nitin Muttil[1, 3], Abdullah Gokhan Yilmaz[4], B.J.C. Perera[1, 3]

[1]College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia.

[2]The West Java Environmental Management Agency, Indonesia, Jl. Naripan No. 25 Bandung, 40111, Indonesia.

[3]Institute for Sustainability and Innovation, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia

[4]University of Sharjah, College of Engineering, PO Box 27272, United Arab Emirates

(*author for correspondence, e-mail: arief.sutadian@live.vu.edu.au)

Abstract

A methodology for parameter selection for cost effective water quality monitoring was developed and presented in the first paper of this two-part series. Using the proposed methodology, parameters to be continuously monitored and those that are to be discontinued at the monitoring stations can be identified. The methodology will also provide a uniform set of parameters to be monitored across all monitoring stations in a river basin or a region/country. The proposed methodology comprises three sequential steps, namely screening to exclude parameters that are not critical from the list of potential measured parameters, the statistical assessment of parameter redundancy and inclusion of three critical factors to identify the parameters to be removed from further monitoring, and identifying a uniform set of parameters. An enhanced performance consolidated index was also developed to identify the best combination of parameters to continued and discontinued at each monitoring station. This paper, which is the second in the series, presents the application of the proposed methodology to a number of monitoring stations in rivers across West Java, Indonesia. Through the application of this methodology, the number of parameters was significantly reduced from 62 to 26 using the first step of screening. Then, several different parameters at each monitoring station were eliminated using the statistical assessment. Finally, only 13 parameters identified to be monitored at the majority of monitoring stations and representing different groupings of water quality parameters were recommended to be used as a uniform set of parameters to be monitored continuously across all stations in West Java. Such a

uniform set of parameters can be used for applications like the development of river Water Quality Indices (WQIs) or for future water quality monitoring programs.

Keywords: Parameter selection, Monitoring network, cost effective monitoring, West Java Province, Water quality indices

1. Introduction

Parameter selection is one of the important factors in water quality monitoring activities (Sanders et al., 1983). Parameter selection for cost effective water quality monitoring aims to obtain an optimal set of water quality parameters for individual station and a uniform set of parameters to be monitored across all monitoring stations in a river basin or region/country. To achieve such an aim, the selected parameters should be kept to a minimum and they should be representative of larger number of parameters (Landwehr et al., 1974). To achieve cost effective monitoring, Strobl and Robillard (2008) stated that it is necessary to reduce the number of parameters monitored without substantial loss of information and to allocate the available resources effectively (for example, by minimizing the cost of the laboratory analysis). Thus, statistical assessment of the association between different parameters can be used to identify the optimal set of water quality parameters in a cost effective manner. Such an assessment will keep a substantial amount of information in representing the water quality even though there is a reduction in number of parameters to be monitored.

In the first part of this two-part series, a new methodology for parameter selection for cost effective water quality monitoring was developed and presented. The proposed methodology comprises of three sequential steps: (i) screening using two rejection criteria, i.e. data availability and data being within the permissible limits. In the screening, parameters that were not consistently monitored were not to be used for further analysis based on the assumption that they were not considered that important, (ii) the statistical assessment of parameter redundancy and the inclusion of three critical factors to identify parameters to be continued and discontinued at individual stations, and (iii) identifying a uniform set of water quality parameters to be monitored across all monitoring stations, wherein such a uniform set of parameters can then be used either for the development of a Water Quality Index (WQI) or for future water quality monitoring programs.

With regard to obtaining a uniform set of parameters for use in WQIs, researchers have used different approaches to select the water quality parameters, such as expert judgment (Brown et al., 1970), literature review (Kannel et al., 2007; Said et al., 2004), data availability (Cude, 2001), redundancy of parameters (Dunnette, 1979), overall water quality status (Dunnette, 1979; Thi Minh Hanh et al., 2011) and the intended use of the water body (Hurley et al., 2012). To the best our knowledge, no researcher has undertaken studies in the past to select a uniform set of parameters of the WQI for rivers other than using approaches aforementioned. Thus, the application of the proposed methodology offers a novel approach to select parameters for developing a WQI.

The statistical assessment of parameter redundancy used in this study is the statistical assessment based methodology developed by Ouarda et al. (1996) for hydrometric network rationalization, and later adopted by Khalil et al. (2014; 2010) for parameter redundancy. As presented in the first part of this series, this statistical assessment involves two main steps, namely (i) integration of criteria developed from record augmentation procedure with correlation analysis and Hierarchal Cluster Analysis (HCA) to identify highly correlated parameters, and (ii) application of a consolidated performance index (I_a) to systematically identify an optimal set of parameters to be continuously measured and the parameters to be discontinued. However, in the applications of the I_a often different sets of parameters continued to be measured had the same I_a values. To deal with this difficulty, three critical factors (based on the cost of laboratory analysis of parameters, and magnitude and frequency of the parameter exceeding its permissible limits) was introduced to enhance the I_a developed by Ouarda et al. (1996). The inclusion of these critical factors also reflects the criticality of water quality parameters for cost effective monitoring. Detailed discussion on the I_a can be found in the first part of this series.

This paper, which is the second of this series, presents the application of the proposed methodology to a case study area. The statistical assessment of parameter redundancy and three critical factors included in the development of I_a was successfully applied to a number of individual monitoring station in rivers across the West Java Province in Indonesia. The application resulted in a significant reduction in the number of parameters to be monitored without substantial loss of information. Results of this statistical assessment at individual stations can be used as the selected parameters in the development of a WQI. Nevertheless, the application of a WQI in a river basin or in a region/country with multiple river basins requires a uniform set of water quality parameters measured at all stations. Such a uniform set of parameters will facilitate the comparison of the general status of water quality from one station to another through the use of the WQI. Therefore, only water quality parameters identified to be monitored continuously for a majority of the monitoring stations and representing different water quality groupings (i.e.

physical, chemical, etc.) were proposed to be used as the common parameters in the development of a WQI or for regular water quality monitoring programs across river basins.

This paper is structured as follows. Section 2 describes the case study area and datasets which includes its water quality monitoring network and the data used. Application of the proposed methodology, results and discussion are presented in the next section. Finally, summary and conclusions drawn from this study are presented.

2. Study area and datasets

The West Java Province is situated in the western part of Java Island, Indonesia. There are six main rivers across the province, which are used in this study, namely Cisadane, Ciliwung, Cileungsi, Citarum, Cimanuk and Citanduy rivers. These six rivers along with the water quality monitoring stations used in this study are presented in Figure 1. All these rivers have several tributaries and pass through various cities or regencies within the province. Their flows originate from the springs mostly located in the upstream mountainous areas, and flow either towards the northern or southern coast of Java Island.

All these six main rivers are valuable sources of water for various needs such as agriculture and industry. They also provide bulk water supply for many cities across the region, including the capital of Indonesia (Jakarta). However, as reported by the West Java Environmental Protection Agency (WJEPA) (WJEPA, 2013), most of these rivers are vulnerable to pollution and have poor water quality, particularly those rivers that are near or are passing through urban and industrial areas. Such situation arises since the rivers are easily accessible for disposal of domestic as well as industrial wastewater or other activities. For example, in the Citarum River, over the past two decades, rapid urbanization and industrial growth have resulted in growing quantities of untreated domestic wastewater and industrial effluents being dumped in the river. In addition to those two sources of pollutants, agriculture and livestock have also contributed to river pollution in the river (Juwana et al., 2014), leading to severe water pollution in the Citarum River (Fulazzaky, 2010). As a result, water quality of the river has deteriorated significantly, threatening public health and increasing economic losses (ADB and WB, 2013).

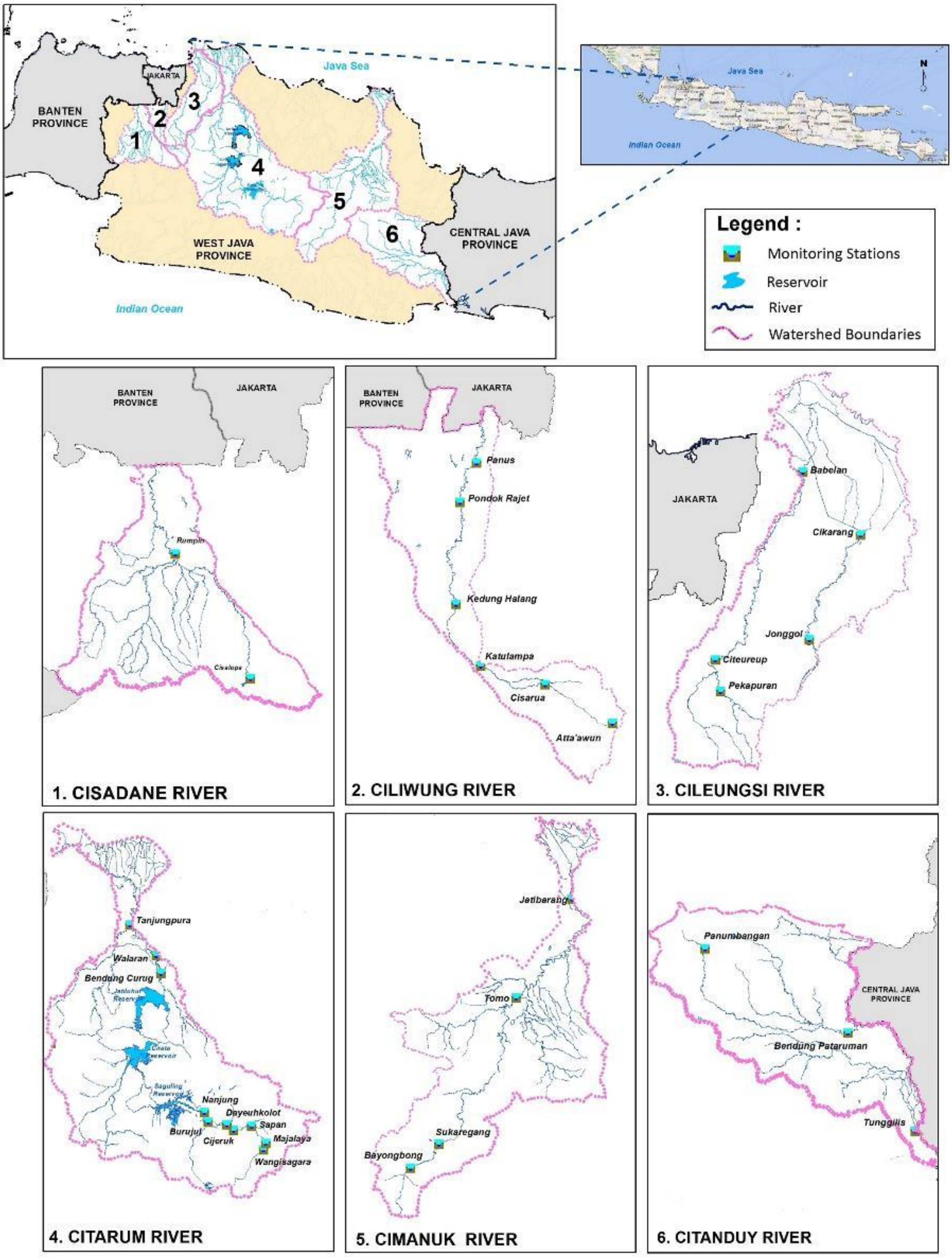


Figure 1 West Java Province with the six main rivers and their water quality monitoring stations

To deal with the above water quality problems, ambitious programs to clean the rivers have been launched and promoted for almost two decades by the Government of Indonesia (Afsah et al., 1996). Such programs aim to reduce the pollution load in the rivers and thus improve river water quality. They also aim to improve the water resources management capability of the water authorities (MoE, 1995). Under such programs, to date, around 54 water quality monitoring stations along the six main rivers have been established (seventeen stations in Citarum river, ten stations in Ciliwung, nine stations in Cileungsi, six stations in Cimanuk, four stations in Citanduy and eight stations in Cisadane River), wherein this WQM network is operated and managed by the WJEPA. Nevertheless, it is also worth mentioning here that even though there are 54 monitoring across the study area, only 30 stations consistently measured the majority of parameters and had the required consecutive records during the considered monitoring period were selected and used in this study.

The general objective of the WJEPA's water quality monitoring networks is to obtain necessary information on the physical, chemical and biological parameters of river water quality. The WJEPA periodically reports their compliances against the water quality objectives or standards, and specifically assesses the general status of river water quality through the calculation of a WQI. However, due to budgetary constraints and change of institutional settings and laws, the WJEPA did not identify a uniform set of parameters to be monitored at all stations. In many cases, from one station to another even within the same river, the WJEPA monitored different parameters, with irregular sampling frequencies (ranging from zero to five measurements per year). Some of the parameters were consistently monitored for almost all stations, but some others were only monitored at a few stations for less than a 3-year monitoring period. For example, water temperature was always monitored each year at all stations by the WJEPA, while potassium permanganate ($KMNO_4$) had been monitored only from 2004 to 2005 at one third of the stations in the monitoring network. Thus, not having a WQI with a uniform set of common parameters caused difficulty for the authority in comparing river water quality across stations within a river and across river basins in the region.

3. Application of methodology and results

This section presents the application of the methodology (that was presented in the first part of this series) for selecting the parameters to be continuously monitored at WJEPA's monitoring stations in a cost effective manner. Section 3.1 presents the results for the first of the 3 steps, namely screening of the parameters, to remove the unimportant parameters from further analysis. Section 3.2 presents the results of the second step, which is that of statistical assessment of parameter redundancy and the inclusion of critical factors to develop the enhanced I_a. This section identifies the parameters that are recommended to be continuously monitored and those to be discontinued. The results of the next step, namely identification a uniform set of common parameters for either the development of a new West Java WQI or for future monitoring programs is presented in Section 3.3.

3.1 Screening

According to the first rejection procedure in the screening step as described in the methodology (in Section 2.1 of the first part in this series), only stations and parameters which had a minimum of six or more consecutive monitoring period were selected in this study as the statistical assessment used for further analysis needs this requirement. Therefore, only 30 out of 54 monitoring stations were used in this study. From those 30 monitoring stations across the WJEPA's network within the West Java Province, a potential list of 62 different water quality parameters monitored between 2001 and 2012 was compiled. Data for each parameter was then scrutinized individually to identify their availability across the considered time period (i.e. 2001-2012).

In the first screening, it was observed that more than half of the parameters were monitored only for certain periods of the considered time period. These parameters were conductivity (EC), color, free ammonia (NH_3-N), total ammonia, alkalinity ($CaCO_3$), acidity (CO_2), total iron (Fe), orthophosphate (PO_4-P), total cadmium (Cd), potassium (K), calcium (Ca), hardness ($CaCO_3$), total chromium (Cr), magnesium (Mg), total manganese (Mn), sodium (Na), % sodium, nickel (Ni), total nickel (Ni), organic nitrogen (N), chlorine (Cl_2), residual sodium carbonate (RSC), total cooper (Cu), total lead (Pb), arsenic (As), Sodium adsorption ratio (SAR), total zinc (Zn), silica reactive (SiO_2), cobalt (Co), barium (B), cyanide (CN), sulphide (H_2S), selenium (S) and total coliform (TC). At the majority of monitoring stations, most of these parameters had been monitored intermittently or were only available for the period 2001 – 2006. These parameters that were not consistently monitored were recommended to be removed based on the assumption that they were not consistently monitored because they were not considered that important. Thus, only 27 parameters (out of the potential list of 62 parameters), which were consistently monitored between 2001 and 2012, were selected and used for further analysis. Table 1 shows these 27 parameters along with their units and permissible units.

Table 1 Water quality parameters used in this study

Water quality parameters	Symbol	Units	Permissible limits	Water quality parameters	Symbol	Units	Permissible limits
Temperature	Temp	°C	NA	Iron	Fe	mg/L	0.30
Dissolved solids	DS	mg/L	1,000	Manganese	Mn	mg/L	0.10
Suspended solid	SS	mg/L	50.00	Boron	B	mg/L	1.00
pH	pH	-	6 – 9	Fluoride	F	mg/L	0.50
Biochemical oxygen demand	BOD	mg/L	2.00	Chloride	Cl	mg/L	600
Chemical oxygen demand	COD	mg/L	10.00	Sulphate	$SO4^{2-}$	mg/L	400
Dissolved oxygen	DO	mg/L	6.00	Cadmium	Cd	mg/L	0.01
Nitrate	NO_3-N	mg/L	10.00	Chromium(IV)oxide	Cr	mg/L	0.05
Nitrite	NO_2-N	mg/L	0.06	Zinc	Zn	mg/L	0.05
Total ammonia	TA	mg/L	0.50	Copper	Cu	mg/L	0.02
Total phosphate	TP	mg/L	0.20	Lead	Pb	mg/L	0.03
Detergent as MBAS	Deter	µg/L	200	Mercury	Hg	mg/L	0.001
Phenol	Phen	µg/L	1.00	Faecal coliform	FC	MPN /100 mL	100
Fat-oil	FO	µg/L	1,000				

These 27 parameters were then subjected to the second rejection procedure in the screening using a box plot analysis. As explained in Section 2.1 of the first part of this series, the box plot analysis was used to provide a summary visualization of the data and compared it with the permissible criteria. In this second screening, each box plot analysis of particular parameters was compared with their permissible criteria in class I (raw water used for drinking water supply), which is defined in Government Decree of Government of Indonesia No. 81/2001 concerning Water Quality Control and Management (MoE, 2001). This quality criteria was selected due to two reasons: (i) class I water is the best reference for pristine water quality or ecological status in Indonesia, and (ii) in developing countries, the majority of population may be dependent on raw water for drinking purposes without any treatment (Helmer and Hespanho, 1997). According to that permissible criteria, the parameters that are always ‘within the permissible criteria’ were not considered for further analysis as they are not present in significant amounts to be harmful to human or ecological health.

The monitoring stations were plotted on the x-axis and the respective water quality parameters with their units were plotted on the y-axis in box plots. The permissible limits for those particular parameters were also indicated in box plots by the horizontal dotted line. The lower, middle and upper horizontal lines in the boxes represent their 1st quartile (Q_1), median, and 3rd quartile values (Q_3), respectively. As examples, box plot for two parameters, namely sulphate (SO_4^{2-}) and biochemical oxygen demand (BOD) are discussed in this section and the box plots for these parameters are presented in Figure 2(a) and (b), respectively. In Figure 2(a), the box plot indicated that SO_4^{2-} at all the 30 stations were within the permissible limit (of 400 mg/L) and hence was considered to be not harmful. Therefore, SO_4^{2-} was excluded from further analysis. Meanwhile, the box plot of BOD showed that they were well above 2 mg/L, indicating that this parameter at all stations often did not meet the permissible limit set up by the authorities for designated class I water use (drinking or bulk water). Thus, this parameter was considered for further analysis.

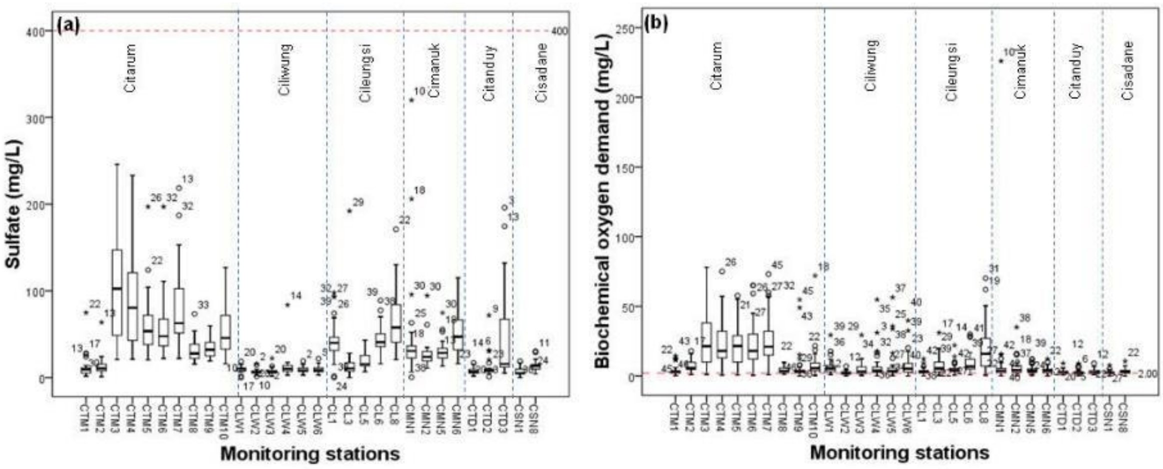


Figure 2 Box plots for (a) Sulphate and (b) Biochemical oxygen demand

Box plots of the remaining 25 parameters are shown in Appendix A of this paper. These 25 parameters showed a similar pattern to that of BOD, wherein the values of their upper quartile often exceeded the permissible limits at the majority of water quality stations. Thus, these parameters were also considered for further analysis. Thus, since SO_4^{2-} was the only parameter excluded based on the box plot analysis, the 27 parameters identified earlier for further analysis was reduced to 26.

Moreover, the box plots also indicated that most stations in the Citarum River for nearly all parameters clearly stood out as being the most polluted among rivers across the West Java Province (see Appendix 1). Their Q_1, Q_2 and Q_3 (nearly for all parameters) had relatively higher concentrations and more frequently did not meet the permissible limits when compared to the stations in other rivers. This shows that the Citarum River is the most vulnerable to pollution, and this is most probably a consequence of a failure or a less coverage of wastewater treatment along this river (Fulazzaky, 2010; Sutadian et al., 2015).

According to the above screening, only 30 out of 54 monitoring stations that had a minimum of six or more consecutive monitoring records were used for further analysis, while 24 monitoring stations were excluded from the analysis. Also, only 26 out of 62 parameters were thus selected and used for the following statistical assessment as they had been monitored consistently for the considered time period and often exceeded the permissible limits across the 30 monitoring stations.

3.2 Statistical assessment

To obtain the optimal combination of parameters to be continuously monitored and those that are to be discontinued, two different steps were performed under statistical assessment, 1) HCA-correlation coefficient thresholds, and 2) assessments of parameters to be continued and those to be discontinued at each individual station. As an example, the results of applying this step at the first monitoring station in Citarum River (located at Wangiasagara and henceforth called station CTM1 in this paper) are presented. A data preparation was carried out before conducting the statistical assessment as there were gaps in the data and inconsistency in measurements among different stations. This was undertaken to rearrange the water quality parameter data on a yearly basis since they were mostly monitored in different months with irregular sampling frequencies. If a water quality parameter was measured twice or more than twice during the same month, these two (or more than two) measurements were firstly averaged to obtain a single data for each month. Finally, all data values in the same year were averaged to have yearly data. Pre-analysis was also done before performing this statistical assessment by testing the shape of distribution and normal distribution of the selected data, to meet normality assumption of this statistical assessment. Therefore, Kolmogorov-Smirnov goodness of fit test was applied to check the normality of the water quality parameters used in this study (Khalil et al., 2011). If a particular parameter was found not to follow the normal distribution, the Box-Cox transformation was employed to satisfy the normal distribution requirement.

3.2.1 HCA – Correlation coefficient thresholds

As discussed in the methodology in the first part of this series, the integration of HCA, correlation analysis and the correlation coefficient thresholds was applied to identify groups of highly correlated water quality parameters. Figure 3 shows an example of cluster analysis results for water quality parameters monitored at the station CTM1. In this figure, the water quality parameters are plotted on the x-axis and the linkage distances (height) between clusters are plotted on the y-axis. Meanwhile, the d_v and d_m (calculated using Equation (10) and (11) presented in the first part of this series, respectively) are indicated by the horizontal dotted and dashed lines, respectively.

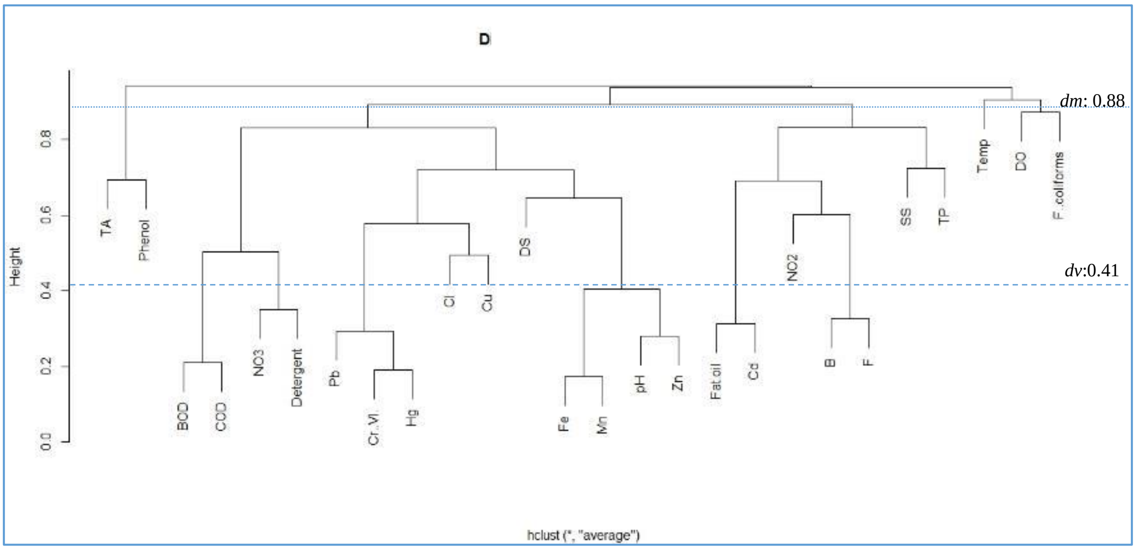


Figure 3 Cluster tree for water quality parameters monitored at the station CTM1

Results of HCA at CTM1 show that value of d_v (0.41) was smaller than that of d_m (0.88). Thus, d_v criterion (dashed line in Figure 3), was used to identify the clusters at CTM1. Water quality parameters at this station could be divided into seventeen different clusters, namely eleven single clusters (i.e. only one parameter in a cluster) and six multiple parameter clusters (i.e. two or more than two parameters in a cluster). The eleven single clusters include the parameters of TA, phenol, Cl, Cu, DS, NO_2, SS, TP, Temp, DO and FC. These eleven parameters should be continued to be monitored at CTM1 as their statistical information cannot be replaced by other parameters from different clusters. Meanwhile, the six multiple parameter clusters were considered for further statistical analysis (Section 3.2.2 of this paper). The first cluster consisted of BOD and DO. The second cluster was NO_3 and Detergent. The parameter fat oil and Cd formed the third cluster. The fourth cluster was composed of B and F. The two other clusters consisted of more than two parameters. The parameters Pb, Cr (VI), and Hg form the fifth cluster and the parameters Fe, Mn, pH, and Zn form the last multiple parameter cluster.

As discussed in the methodology in the first paper of this series, it should be noted that only one parameter from each multiple parameter cluster has to be identified to be continuously monitored, while the other parameters will be excluded from the list of parameters continued to be monitored. Thus, at station CTM1, to obtain the optimal selection of water quality parameters to be monitored, nine out of fifteen parameters (from six multiple clusters) could be discontinued. The parameters that could be potentially discontinued for the other twenty nine stations (other than CTM1) were also identified. Results show that the number of single and multiple parameter clusters can be different for stations. As a result, the number of parameters that could be potentially discontinued vary from one station to another, ranging between 4 and 10 parameters as presented in Appendix B. For example, four parameters should be discontinued at station CMN6, five parameters could be discontinued at CLW6, and ten parameters for CTM6.

3.2.2 Assessment of parameters to be continued and discontinued in monitoring

As discussed in Section 2.2.2 of the first part of this series, this assessment was applied only for multiple parameter clusters and involved the following steps:

(a) Identification of best auxiliary parameters

In all multiple parameter clusters, each parameter (within the cluster) was assumed to be discontinued, and its best auxiliary parameter was identified from other parameters in the same cluster using Equation (3) in the first paper of this series. For a multiple parameter cluster that consisted of two parameters, one parameter would be the discontinued parameter and the other would be its best auxiliary parameter. For an example, as presented in Figure 3, the first multiple parameter cluster at station CTM1 consisted of BOD and COD. The parameter to be continued and discontinued could be any one of them. If BOD was assumed to be the discontinued parameter, COD would be the best auxiliary parameter for BOD or vice versa. Then, the variance of the mean value of BOD or COD was estimated using the Equation (3) presented in the first paper of this series.

Meanwhile, within a multiple parameter cluster that consisted of more than two parameters, the best auxiliary parameter should be examined one by one from the parameters excluding the discontinued parameter in that cluster. If a specific parameter was discontinued, the variance of the mean value estimator for each continued parameters was calculated to find the best auxiliary for that specified discontinued parameter. This was done individually by applying Equation (3) to all other parameters in that cluster. The parameter that provided the least variance of the mean estimator was the best auxiliary parameter for that specified discontinued parameter. For an example, at CTM1, the fifth cluster consisted of three parameters, which were Pb, Cr(VI) and Hg. If Pb was assumed to be the discontinued parameter, using the Equation (3), the values of the mean estimator of Pb – Cr(VI) and Pb – Hg were estimated separately. Through this process, it was found that Cr(VI) was the best auxiliary parameter for Pb as the mean estimator value of Pb – Cr(VI) (0.0835) was smaller than that of Pb – Hg (0.0858). The same process was also applied to identify the best auxiliary parameter if Cr(VI) and Hg were assumed to be discontinued. Results of the variances of the mean value estimator to identify the best auxiliary parameters (using Equation 3 from the first part of this series) are presented in Table 2. As discussed in the first part of this series, the variance of the mean value presented in Table 2 was used in the calculation of the consolidated performance index without the inclusion of the critical factors (using Equation (12) from the first part of this series) or with the inclusion of the critical factors (using Equation (14) from the first part).

Table 2 One parameter to be discontinued and their best auxiliary parameter for CTM1

One parameter to be discontinued	Best auxiliary parameter	*Var*
BOD	COD	0.0706
COD	BOD	0.0706
Fe	Mn	0.0815
Mn	Fe	0.0815
Cr(VI)	Hg	0.0820
NO3	Detergent	0.0732
Detergent	NO3	0.0732
Pb	Cr(VI)	0.0835
Zn	pH	0.0843
Cd	Fat-oil	0.0852
B	F	0.0856
F	B	0.0856
Hg	Cr(VI)	0.0820
pH	Zn	0.0843
Fat-oil	Cd	0.0852

(b) Identification possible combinations of parameters to be discontinued and continued

If a specific parameter is to be discontinued from the list of parameters measured at a monitoring station, all the possible alternatives for the discontinued parameter should be considered using the binomial coefficient, i.e. C_k^w (as explained in Section 3.2.2(b) in the first part of this series). *C* is the number of combinations for continued and discontinued parameters, *w* is number of all parameters that are in the list, while *k* is the number of discontinued parameters. For a case, w = 15 and k = 1; thus, there were fifteen different alternatives of one discontinued parameter at CTM1. To identify the best parameters to be continued and those to be discontinued, the statistical assessment using $I_{a,}$ was applied. This is presented in the following sub-sections.

Since the objective of this study is to select the optimal number of parameters, only one parameter in each multiple parameter cluster is taken as continued parameter, while the other parameters in the same cluster are discontinued. As an example, the first multi-parameter cluster at CTM1 consists of BOD and COD. If the combinations have both of them as continued parameters, they should be excluded for further analysis. Therefore, as discussed previously in Section 3.2.1 (the result of HCA-Correlation coefficient thresholds), nine out of fifteen parameters monitored at CTM1 (as presented in Figure 3 and column 4 of Appendix 2) should be discontinued. Then, the multiplication of the binomial coefficient in each cluster, i.e. $(C_{k_1}^{w_1})$ $(C_{k_2}^{w_2})$ $(C_{k_3}^{w_3})$ $(C_{k_4}^{w_4})$ $(C_{k_5}^{w_5})$ $(C_{k_6}^{w_6})$ (using w_1 to w_4 = 2, w_5 = 3, w_6 = 4 and k_1 *to* k_4 *=1*, k_5 *= 2*, k_6 = 3) was then applied to identify how many possible combinations of these nine discontinued parameters could be possibly formed. Considering such an objective, using multiple of the binomial coefficient across multiple parameter clusters only 192 different combinations of continued and discontinued parameters were used for application of the I_a.

(c) *Establishment of critical factors for the enhanced consolidated performance index (I_a)*

The consolidated performance index *(I_a)* was used to assess the best combination of parameters to be continued and discontinued as it provides the decision maker with the rank of the best of combinations of parameters to be continued and discontinued (Khalil et al., 2014; Khalil et al., 2010). However, in the calculation of I_a, often different sets of parameters continued to be measured had the same I_a values as presented in Table C.1 and Table C.2 of Appendix C. Table C.1 presents the values of I_a if only one parameter was to be discontinued at CTM1. Results show that two parameters, which were BOD and COD had the least and the same value of I_a (which is 3.9919). Therefore, it is difficult to select either of these parameters as the discontinued parameter at CTM1 (if only one parameter is to be discontinued). Other parameters also had the same I_a value (Fe and Mn had I_a value of 3.9937 and Detergent and NO_3 had 3.9967). These parameters also had the same difficulty of identifying the optimal number of parameters to be discontinued. Table C.2 presents the first ten of optimal combinations for nine parameters to be discontinued and six parameters to be continued at CTM1 with their I_a values (calculated without critical factors). Results in Table C.2 show the same I_a value (of 4.1417) obtained for the first eight combinations. This again leads to an uncertain decision for the user with regards to identifying the optimal set of parameters if the analysis is based on the original I_a value.

To deal with this issue, as explained in the methodology in the first part of this series, the critical factors of laboratory cost of monitoring, and frequency and magnitude of the parameters exceeding the permissible limit were introduced into the calculation of the $I_{a.}$, to give different weights for each parameter with regards to their relative importance and their influence on the I_a. The critical factor was set based on deciles to make them in the same scale. Table 3 presents classification of parameters based on cost of laboratory analysis for all parameters. Table 4 and Table 5 present the classification of frequency and magnitude for all parameters, except heavy metals, respectively. Meanwhile, as explained in Section 2.2.2(c) of the first part of this series, the classification of frequency and magnitude (of heavy metals) were undertaken using a categorical scaling wherein the values must be either 1 or 5 since they are regarded as toxic substances, and even small concentrations are not permissible. The frequency and magnitude classification for heavy metals are presented in Table 6 and Table 7, respectively.

Table 3 Cost (c) classification used for all parameters

Threshold range	Cost range in Indonesian Rupiah (IDR)	Cost classification
Deciles 9-10 (Most expensive)	p > 128,000	1
Deciles 7-8 (Expensive)	88,000 < p < 128,000	2
Deciles 5-6 (Average)	48,750 < p < 88,000	3
Deciles 3-4 (Low)	32,500 < p < 48,750	4
Deciles 1-2 (Lowest)	p < 32,500	5

Threshold range is calculated based on deciles

Table 4 Frequency (f) classification used for all parameters (except heavy metals)

Threshold range	f	Frequency classification
Good	f < 0.7%	1
Low critical	0.7% < f < 1.4%	2
Critical	1.40% < f < 2.10%	3
Very critical	2.10% < f< 4.0%	4
Extremely critical	f > 4.0%	5

Threshold range is calculated based on deciles.

Table 5 Magnitude (m) classification used for all parameters (except heavy metals)

Threshold range	m (Max event/WQ standard)	Magnitude classification
Good	m < 0.30	1
Low critical	0.30 < m < 0.65	2
Critical	0.65 < m< 1.13	3
Very critical	1.13 < m < 2.20	4
Extremely critical	m > 2.20	5

Threshold range is calculated based on deciles

Table 6 Frequency classification for heavy metals

Threshold range	F	Frequency classifications
Normal	0	1
Critical	> 0	5

Table 7 Magnitude classification for heavy metals

Threshold range	*m* (Max event/WQ standard)	Frequency classifications
Normal	< 1	1
Critical	≥ 1	5

To demonstrate how to calculate the critical factors, an example of the classification scheme is applied to a particular station that has monitoring data (actual parameter values) of BOD for the period 2001 – 2012. This parameter has been monitored 48 times (number of measurements) during this period. Using official regulation concerning tariff and water quality guideline class 1, the laboratory cost of BOD per sample and the permissible limit of BOD are IDR 150,000 (in Indonesian Rupiah) and 4 mg/L, respectively. As can be seen from Table 3, the cost factor (*c*) for BOD at this example station lies in the range of most expensive parameters, as its laboratory cost is more than IDR 128,000. Thus, it has a *c* factor of 1. Meanwhile, Table 4 and Table 5 are used to compute *f* and *m* factors, as BOD is not regarded as a heavy metal. First, all actual parameter values of BOD are sorted either in increasing or decreasing order and compared with the permissible limit of BOD to identify how frequently BOD exceeds the permissible limit for the calculation of *f*. Meanwhile, the largest value recorded during the observation period is used for the calculation of *m*. According to the sorted data, it is identified that 12 out of 48 monitoring data exceeded the permissible limit and the largest value recorded is 4.25 mg/L. As mentioned in Section 2.2.2(b) of the first part of this two-part series, the frequency factor is calculated by dividing the number of measurements of that parameter exceeding the permissible limit with the total number of measurements (i.e., $f = 12/48*100\% = 25\%$), while the magnitude factor is defined as the largest value recorded during the observation period over the permissible limit (i.e., $m = 4.25/4 = 1.06$). Therefore, based on Tables 5 and 6, *f* and m factors for parameter BOD at this particular station are 5 and 3, respectively. Having obtained *c*, *f*, and *m* of BOD, Equation (13) in the first part of this series was used to calculate the critical factor (*cf*) for BOD. The *cf* values are used as unequal weights for each parameter representing the relative importance and influence of that parameter in the application of the I_a.

(d) *Application of the enhanced consolidated performance index*

Unequal weights for each parameter based on the use of the critical factors were incorporated into the calculation of the enhanced consolidated performance index to identify the best parameters to be continued and those to be discontinued. The combination that had the least value I_a was then selected as an optimal combination of water quality parameters for future monitoring as it had the least of an aggregated variance of the mean estimator for all parameters investigated. In this proposed enhancement of I_a, for those water quality parameters assumed to be discontinued, the variance of the mean value estimator expected after n_2 years is calculated using Equation (3) in the first part of this series. Detailed explanation on the variance of the mean value estimator used for discontinued parameters on the I_a has been already discussed in Section 3.2.2(a) and Table 2 of this paper. On the other hand, for the parameters assumed to be continuously monitored, as proposed by Khalil et al. (2014; 2010), the variance of the mean value after n_2 years is assumed to be equal to the variance of the mean after n_1 years multiplied by $(n_1-1)/(n_1+n_2-1)$. In this study, for CTM1, n_1 was 10 (based on the period of concurrent records for the two parameters), while n_2 was assumed to be 3 years.

Table 8 presents all the alternatives if a certain parameter was assumed to be discontinued (column 1), parameters to be discontinued (column 2), and their I_a values (column 3). According to values of the enhanced I_a, in Table 8, Cr(VI) has the highest priority to be excluded from the list of parameters to be monitored. Cr(IV) not only had relatively smaller variance of the mean variance value, but it is also more expensive and less critical than others. If our decision is to discontinue Cr(VI) at CTM1, Hg should be retained so that statistical information of Cr(VI) can be obtained from its best auxiliary parameter (Section 3.2.2(a) of this paper discussed the best auxiliary parameters). Meanwhile, eight other parameters involved Hg, BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd were continued to be monitored.

Table 8 One parameter to be discontinued for CTM1 based on the enhanced consolidated performance index (I_a)

One Parameter to be discontinued	Parameters to be continued	I_a
Cr(VI)	Hg, BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4415
Hg	Cr(VI), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4553
BOD	Hg, Cr(VI), COD, B, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4608
B	Hg, Cr(VI), COD, BOD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4621
COD	Hg, Cr(VI), B, BOD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4673
Detergent	Hg, Cr(IV), BOD, B, COD, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4735
Mn	Hg, Cr(IV), BOD, B, COD, Detergent, Fe, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4790
Fe	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, pH, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4790
pH	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, NO_3, Pb, Zn, Fat-oil, F, Cd	13.4823
NO3	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, Pb, Zn, Fat-oil, F, Cd	13.4833
Pb	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Zn, Fat-oil, F, Cd	13.4955
Zn	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Fat-oil, F, Cd	13.4964
Fat-oil	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, F, Cd	13.4969
F	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, Cd	13.4994
Cd	Hg, Cr(IV), BOD, B, COD, Detergent, Mn, Fe, pH, NO_3, Pb, Zn, Fat-oil, F	13.5092

In a similar way, the optimal number of parameters to be continued and those to be discontinued for all stations in the study area were identified. Table 9 shows the first ten combinations of nine parameters to be discontinued and their enhanced I_a values for the case when nine out of fifteen parameters could be considered for discontinuation at CTM1. Even though differences in the I_a values among different combinations were relatively small, the best combination of nine discontinued parameters to be chosen could be identified. As can be seen in Table 9, B, Fat-oil, BOD, Detergent, Cr, Hg, pH, Fe and Zn (the first combination) were the parameters that could be discontinued, whereas the six parameters, namely F, Cd, COD, NO_3, Pb and Mn were identified to be monitored for future monitoring programs. Until this point, the application of proposed methodology was able to identify the optimal combination of parameters that could be discontinued at each monitoring station for a more cost effective monitoring. This will lead to a reduction in the number of parameters to be monitored without losing a substantial amount of information in representing the water quality for the regular monitoring programs for each station.

Table 9 Combination of nine parameters to be discontinued and six parameters to be continued at CTM1 using the enhanced consolidated performance index (I_a)

Nine parameter to be discontinued	Six parameters to be continued	*Ia*
B, Fat-oil, BOD, Detergent, Cr, Hg, pH, Fe, Zn	F, Cd, COD, NO_3, Pb and Mn	13.8780
B, Fat-oil, COD, Detergent, Cr, Hg, pH, Fe, Zn	F, Cd, BOD, NO_3, Pb and Mn	13.8845
B, Fat-oil, BOD, NO3, Cr, Hg, pH, Fe, Zn	F, Cd, COD, Detergent, Pb and Mn	13.8877
B, Cd, BOD, Detergent, Cr, Hg, pH, Fe, Zn	F, Fat-oil, COD, NO_3, Pb and Mn	13.8902
B, Fat-oil, COD, NO3, Cr, Hg, pH, Fe, Zn	F, Cd, BOD, Detergent, Pb and Mn	13.8942
B, Cd, COD, Detergent, Cr, Hg, pH, Fe, Zn	F, Fat-oil, BOD, NO3, Pb and Mn	13.8968
B, Cd, BOD, NO3, Cr, Hg, pH, Fe, Zn	F, Fat-oil, COD, Detergent, Pb and Mn	13.9000
B, Fat-oil, BOD, Detergent, Cr, Hg, pH, Mn, Zn	F, Cd, COD, NO_3, Pb and Fe	13.9033
B, Cd, COD, NO3, Cr, Hg, pH, Fe, Zn	F, Fat-oil, BOD, Detergent, Pb and Mn	13.9065
B, Fat-oil, COD, Detergent, Cr, Hg, pH, Mn, Zn	F, Cd, BOD, NO_3, Pb and Fe	13.9098

3.3 Identification a uniform set of parameters

To identify a uniform set of parameters for use in the proposed WQI for rivers in the West Java, the statistical assessment that was presented in Section 2.2 of the first part of this series had to be first applied to each monitoring station across the study area. According to this statistical assessment, there were two types of cluster of parameters, first, those identified as single parameter clusters, i.e. clusters with only one parameter and hence that parameter cannot be replaced by other parameters. And the second type of cluster is the multi-parameter clusters, where the best auxiliary parameter is obtained using the enhanced I_a. Since the parameters to be continuously monitored varied from one station to another, three criteria were then applied to obtain a uniform set of parameters. As presented in Section 2.3 of the first part of this series, the parameters that were recommended to be included in the uniform set of parameters should meet one of the following three criteria:

(i) Parameter identified as single parameter cluster for at least 70 % of the total monitoring network.

(ii) Parameters identified as those taken from single parameter clusters and the parameters obtained from multi-parameter clusters using the enhanced I_a for at least 80% of the total monitoring network.

(iii) The uniform set should include at least one parameter belonging to each of the seven different grouping of water quality parameters, namely physical, oxygen depletion, organics, nutrients, minerals, heavy metals, and biological grouping of parameters.

Figure 4 presents the results of identifying a uniform set of parameters that are to be used in the development of a WQI or for monitoring programs across stations in the study area. The 26 parameters used in this study were plotted on the x-axis of Figure 4, and the total of number of stations where the respective parameter would be continuously monitored was plotted on the primary y-axis (left side). The secondary y-axis (right side) of Figure 4 indicates the number of stations to be continuously monitored as a percentage of the total number of stations. As mentioned in Section 3.1 of this paper, a total of 30 stations were used in this study. The parameters to be continuously monitored taken from single-parameter clusters were shown using blue shaded bars whereas the parameters to be continuously monitored obtained from multi-parameter clusters under the enhanced I_a values were shown in grey shaded bars. Meanwhile, thresholds of the first and second criteria for identification of a uniform set of parameters to be used across all monitoring stations were indicated by dashed and dotted lines, respectively. As an example, TP as single parameter cluster was identified to be monitored at 27 monitoring stations (the blue shaded bar) and based on the enhanced I_a values for multiple-parameter clusters, this parameter was recommended to be monitored at 2 stations (grey shaded bar). Therefore, the total of number stations identified for monitoring TP was 29 stations (or 96.67% of the total network of 30 stations). On the other hand, Cr(IV) was considered to be continuously monitored at 2 and 1 station from single parameter clusters and based on the application of the enhanced I_a, respectively. Thus, only 3 stations were recommended for continuous monitoring of Cr(IV).

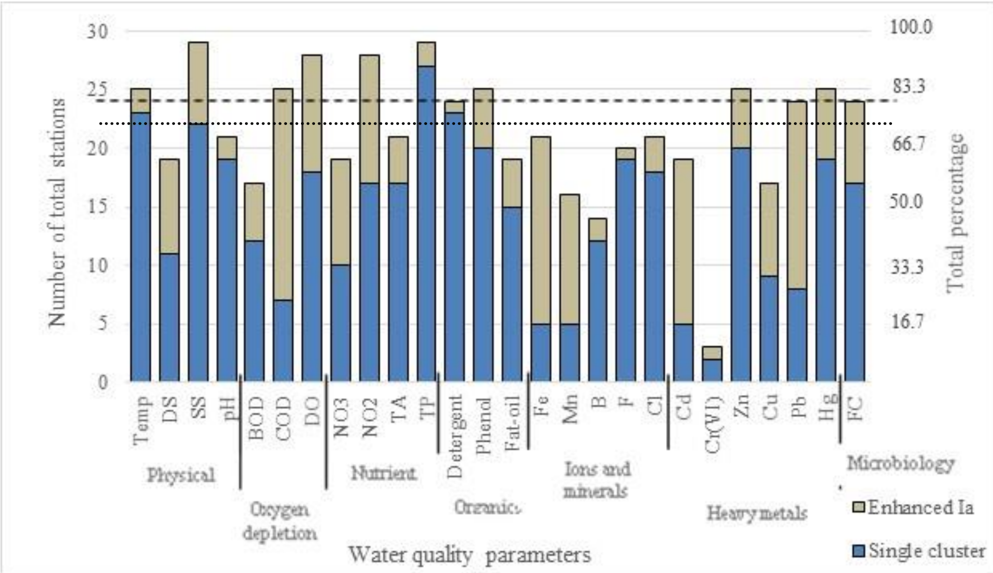


Figure 4 Number of stations where the parameters are to be continuously monitored

From Figure 4, it can be seen that there were 4 parameters that met the first criteria for selecting a uniform set of parameters, namely that of parameter identified as being in a single cluster for at least 70% of the stations (indicated by the dotted line in Figure 4). These 4 parameters were Temperature, SS, TP and Detergent. Temperature, SS, TP and Detergent were identified to be monitored at 23, 21, 27, 23 stations, respectively. Thus, they were selected to be included in the uniform set of parameters. Then, using the second criteria (indicated by the dashed line in Figure 4), 8 parameters were selected to be included in the uniform set of parameters to be continuously monitored. These 8 parameters are COD, DO, NO_2, Phenol, Zn, Pb, Hg and FC, which were identified to be continuously monitored at at least 80% of the 30 stations. COD, DO, NO_2, Phenol, Zn, Pb, Hg and FC were to be monitored at 25, 28, 28, 25, 25, 24, 25, 24 stations, respectively. In addition to these two criteria, the third criteria stated that the uniform set of parameters should include at least one parameter belonging to each of the seven groupings of water quality parameters. With respect to this criterion, it can be observed from Figure 4 that the grouping of ions and minerals has no parameter that was proposed to be continuously monitored. Therefore, in addition to the twelve parameters mentioned above, one of the parameters under ions and minerals grouping should also be selected to be included in the uniform set of parameters to be continuously monitored. Considering this, Cl (Chloride) was selected as the parameter representing ions and mineral grouping rather than any one of the other parameters (i.e. Fe, Mn, B, F) because of the following reasons:

- Cl along with Fe had the highest number of stations (21 stations) where they were identified to be continuously monitored when compared to the other parameters in the same grouping. But Cl had more number of stations where it was present as a single parameter cluster and hence did not have an alternate representative parameter.
- Cl is more frequently selected as the main constituent of a WQI than other ion and mineral parameters in previous WQIs (Dinius, 1987; Dojlido et al., 1994; Gazzaz et al., 2012; Horton, 1965; House, 1989; Prati et al., 1971; Sargaonkar and Deshpande, 2003).
- Cl is recommended as one of the basic parameters measured for monitoring of streams under the United Nations Global Environment Monitoring System (GEMS) Water Programme (Chapman, 1996).
- No preservation or special treatment for monitoring of Cl is required and can be stored at room temperature (Chapman, 1996). Thus, there is no additional cost involved in the monitoring of Cl.

Thus, 13 parameters have been identified for continuous monitoring through a comprehensive statistical assessment. These parameters will be used as a uniform set of parameters for the proposed cost effective WQI for the rivers in West Java, which will be developed in the future. Moreover, these parameters should always be used as the “basic parameters” to be monitored for all the stations if the water authorities intend to undertake WQM in a cost effective manner.

4. Summary and conclusions

This study presented an application of the methodology (which was proposed and presented in the first part of this two-part series) to select the most significant water quality parameters in a cost effective manner. Parameters that are to be continued and discontinued to be monitored at each monitoring station have been identified. Also a uniform set of common parameters to be used across river basins/regions has also been identified through the proposed methodology, which included the introduction of the critical factors in the calculation of the enhanced performance consolidated index (I_a). The proposed methodology was successfully applied to a number of monitoring stations across river basins in the West Java Province of Indonesia. Sixty two parameters that had been monitored by the authority across stations for the considered time period (i.e. 2001-2012) were compiled and listed. The number of parameters was then reduced from 62 to 26 through screening. The number of parameters to be continuously monitored at all stations was then reduced from 26 to 13 using the proposed methodology.

The conclusions drawn from this study are summarized below:

- The results of application of the statistical assessment for parameters redundancy and the enhanced performance consolidated index with the inclusion of the critical factors leads to a significant reduction in the number of parameters to be continuously monitored at each monitoring station.
- The results of study indicated that redundancies exist among water quality parameters. Through such statistical assessments undertaken separately for each individual station, only 13 parameters representing all the 7 different grouping of water quality parameters were recommended to be monitored continuously across the network of stations in West Java. These parameters are Temperature and SS (physical), COD and DO (oxygen depletion), NO_2 and TP (nutrients), Detergent and Phenol (organics), Cl (ions and minerals), Zn, Lead (Pb) and Hg (heavy metals) and fecal coliform (microbiology). These parameters are recommended as a uniform set of common parameters to be used in the development of a new West Java WQI that will be undertaken in a future study. Such a uniform set of parameters will also be highly beneficial for cost-effective monitoring in water quality monitoring programs.

Acknowledgments

The authors would like to acknowledge and thank to the Australian Awards, which funded the first author for this study and the West Java Environmental Protection Agency, Indonesia, which had provided the data used in this study. The authors also would like to thank Dr. Bahaa Khalil for the helpful explanation of the methodology developed by him, which was enhanced in this study.

References

ADB, WB, 2013. Downstream Impacts of Water Pollution in the Upper Citarum River, West Java, Indonesia - Economic Assessment of Interventions to Improve Water Quality. Technical Report, WATER AND SANITATION PROGRAM

Afsah, S., Laplante, B., Makarim, N., 1996. Program-Based Pollution Control Management. The Indonesian PROKASIH Program, Policy research working paper The World Bank. Policy Research Department. Environment and Infrastructure Division

Brown, R.M., Mc Clelland, N.I., Deininger, R.A., Tozer, R.G., 1970. A water quality index-Do we dare? . Water and Sewage Works 117, 339-343

Chapman, D., 1996. Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring - Second Edition. E&FN Spon, an imprint of Chapman & Hall, Great Britain at the University Press, Cambridge

Cude, C.G., 2001. Oregon water quality index a tool for evaluating water quality management effectiveness. JAWRA Journal of the American Water Resources Association 37, 125-137.10.1111/j.1752-1688.2001.tb05480.x

Dinius, S.H., 1987. DESIGN OF AN INDEX OF WATER QUALITY. Water Resources Bulletin 23, 833-843

Dojlido, J., Raniszewski, J., Woyciechowska, J., 1994. Water quality index - Application for rivers in Vistula river basin in Poland. Water Science and Technology 30, 57-64

Dunnette, D.A., 1979. A Geographically Variable Water Quality Index Used in Oregon. Journal Water Pollution Control Federation 51, 53-61.10.2307/25040240

Fulazzaky, M., 2010. Water quality evaluation system to assess the status and the suitability of the Citarum river water to different uses. Environmental Monitoring and Assessment 168, 669-684.10.1007/s10661-009-1142-z

Gazzaz, N.M., Yusoff, M.K., Aris, A.Z., Juahir, H., Ramli, M.F., 2012. Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. Marine Pollution Bulletin 64, 2409-2420.http://dx.doi.org/10.1016/j.marpolbul.2012.08.005

Helmer, R., Hespanho, I., 1997. in: UNEP, WSSCC, WHO (Eds.), Water Pollution Control - A guide to the use of water quality management principles First edition 1997 ed. E & FN Spon, an imprint of Thomson Professional, 2-6 Boundary Row, London SE1 8HN

Horton, R.K., 1965. An index number system for rating water quality. Journal of Water Pollution Control Federation 37, 300-306

House, M.A., 1989. A water quality index for use in the operational management of river water quality in Europe, in: Wheeler, D., Richardson, M.L., Bridges, J. (Eds.), Watershed 89. Pergamon, pp. 159-168.http://dx.doi.org/10.1016/B978-1-4832-8379-1.50018-5

Hurley, T., Sadiq, R., Mazumder, A., 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Research 46, 3544-3552.http://dx.doi.org/10.1016/j.watres.2012.03.061

Juwana, I., Muttil, N., Perera, B.J.C., 2014. Application of West Java water sustainability index to Citarum catchment in West Java, Indonesia. Water Science and Technology: Water Supply 14, 1150-1159.10.2166/ws.2014.075

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R., Khan, S.P., 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environmental Monitoring and Assessment 132, 93-110

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., 2011. Statistical analyses of the adequacy of the surface water quality monitoring network in Saskatchewan. Statistical Hydrology Research Group. Institut national de la recherche scientifique Centre Eau, Terre et Environnement (INRS-ETE)

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., Zanacic, E., 2014. Statistical Assessment of the Surface Water Quality Monitoring Network in Saskatchewan. Water, Air, & Soil Pollution 225.10.1007/s11270-014-2128-1

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., Chebana, F., 2010. A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. Journal of Hydrology 386, 173-185.http://dx.doi.org/10.1016/j.jhydrol.2010.03.019

Landwehr, J.M., Deininger, R.A., McClelland, N.L., Brown, R.M., 1974. An objective water quality index. Journal of the Water Pollution Control Federation 46, 1804-1807

MoE, 1995. Keputusan Menteri Negara Lingkungan Hidup Nomor 35 tentang Program Kali Bersih (Ministrial's Decree No. 35 on Clean River Program),

MoE, 2001. Peraturan Pemerintah Nomor 82 Tahun 2001 tentang Pengelolaan kualitas air dan pengendalian pencemaran air (Government Regulation No. 82 on Water quality control and management) in: MoE (Ed.). The Government of Indonesia Secretary of State, Jakarta

Ouarda, T.B.M.J., Rasmussen, P.F., Bobée, B., Morin, J., 1996. Ontario Hydrometric Network Rationalization, Statistical Considerations, Research Report No. R-470. National Institute for Scientific Research, INRS-ETE, University of Quebec, Quebec, Canada, p. 75

Prati, L., Pavanello, R., Pesarin, F., 1971. Assessment of surface water quality by a single index of pollution. Water Research 5, 741-751.http://dx.doi.org/10.1016/0043-1354(71)90097-2

Said, A., Stevens, D.K., Sehlke, G., 2004. An innovative index for evaluating water quality in streams. Environmental Management 34, 406-414

Sanders, T.G., Ward, R.C., Loftis, J.C., Steele, T.D., Adrian, D.D., Yevjevich, V., 1983. Design of networks for monitoring water quality. Water Resources Publication, LLC, Highland Ranch, Colorado, USA

Sargaonkar, A., Deshpande, V., 2003. Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. Environmental Monitoring and Assessment 89, 43-67

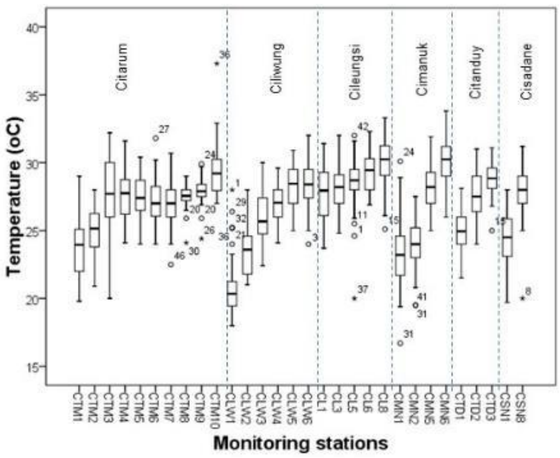
Strobl, R.O., Robillard, P.D., 2008. Network design for water quality monitoring of surface freshwaters: A review. Journal of Environmental Management 87, 639-648.http://dx.doi.org/10.1016/j.jenvman.2007.03.001

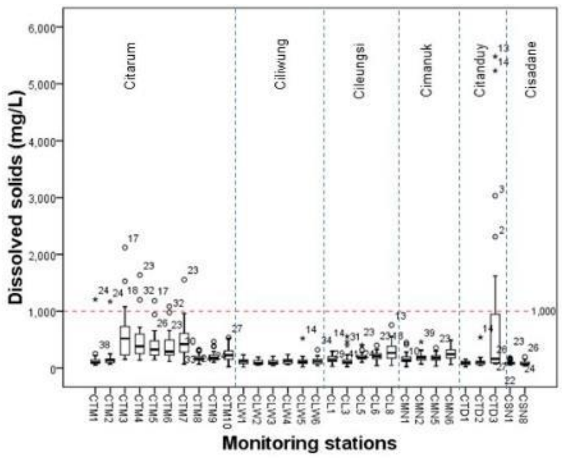
Sutadian, A.D., Muttil, N., Yilmaz, A., Perera, C., 2015. Use of exploratory data analysis for cost effective monitoring of water quality data, 36 th Hydrology and Water Resources Symposium Hobart, Tasmania

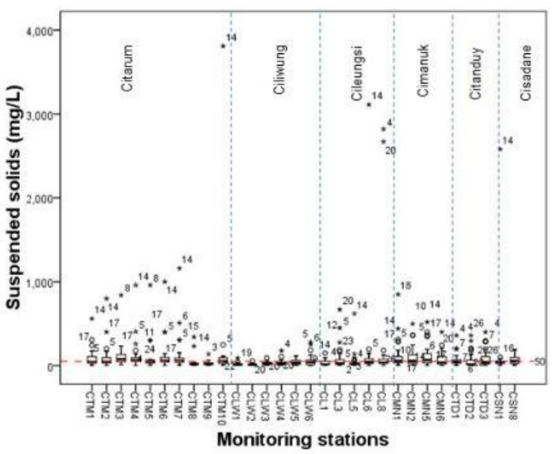
Thi Minh Hanh, P., Sthiannopkao, S., The Ba, D., Kim, K., 2011. Development of Water Quality Indexes to Identify Pollutants in Vietnam's Surface Water. Journal of Environmental Engineering 137, 273-283.doi:10.1061/(ASCE)EE.1943-7870.0000314

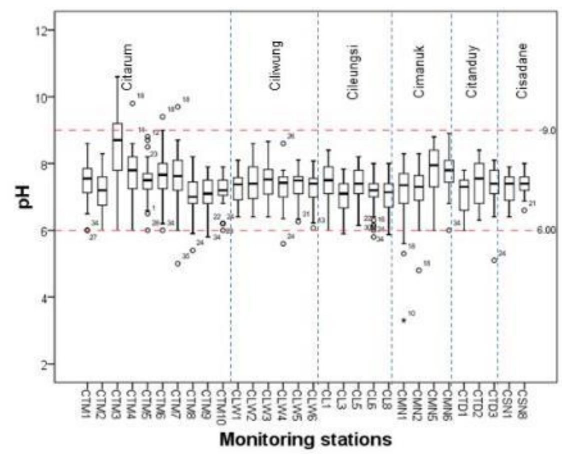
WJEPA, 2013. Status Lingkungan Hidup Provinsi Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia

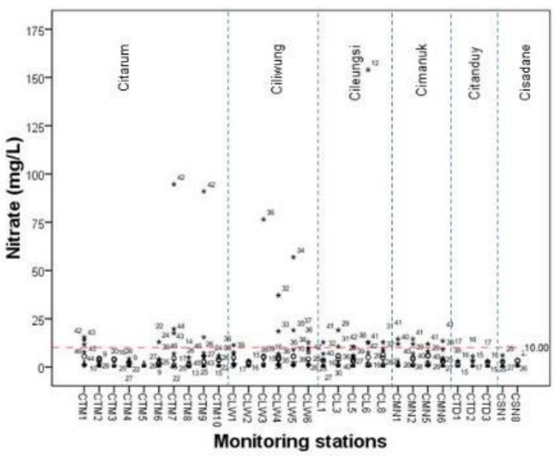
Appendix A Box plot analysis for the 25 parameters used for further analysis (statistical assessments)

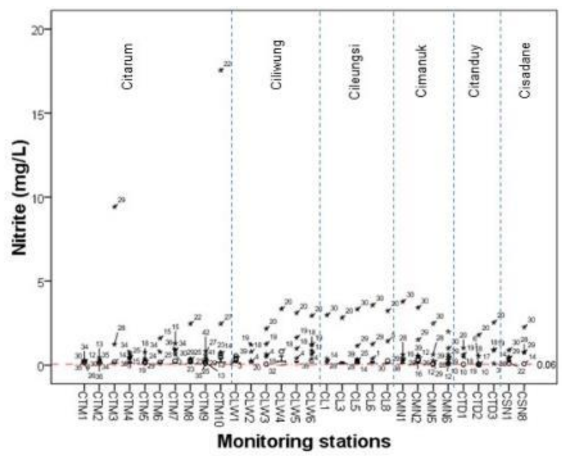


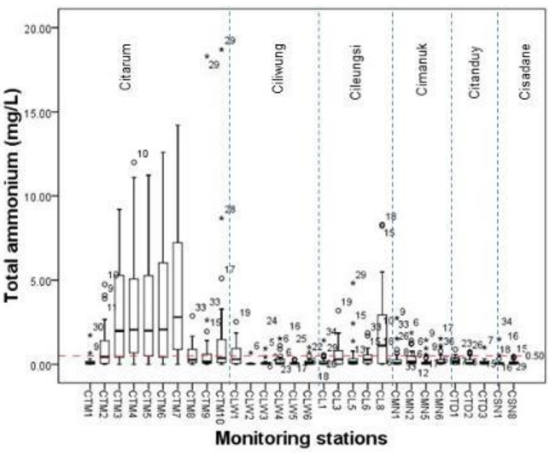


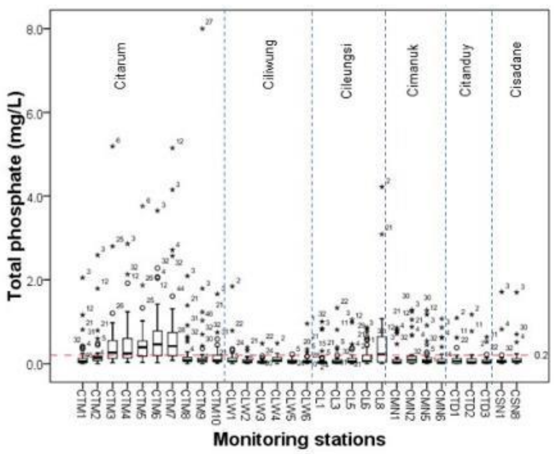


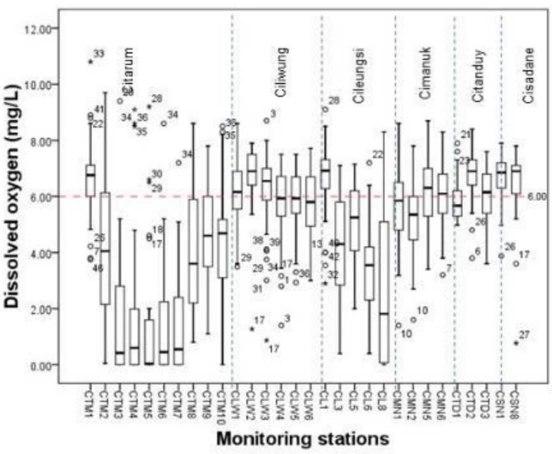


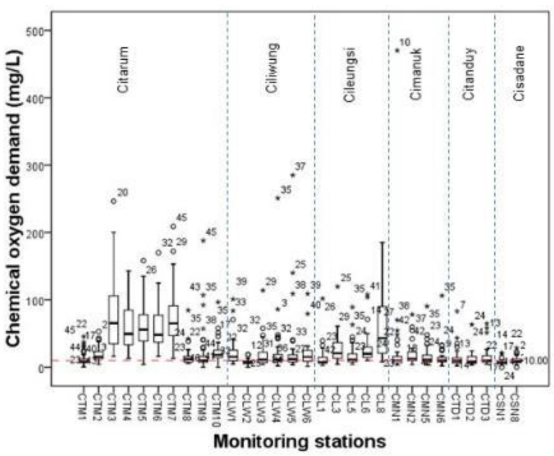


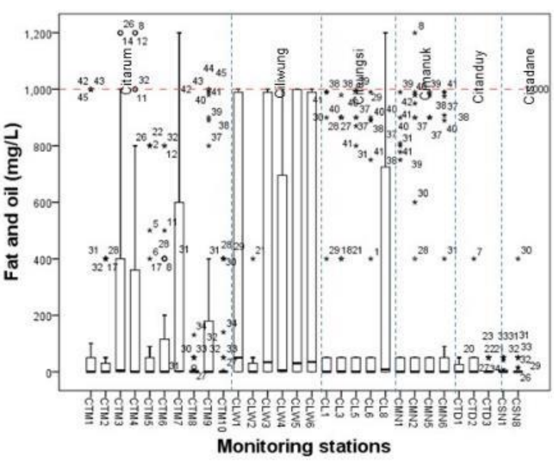


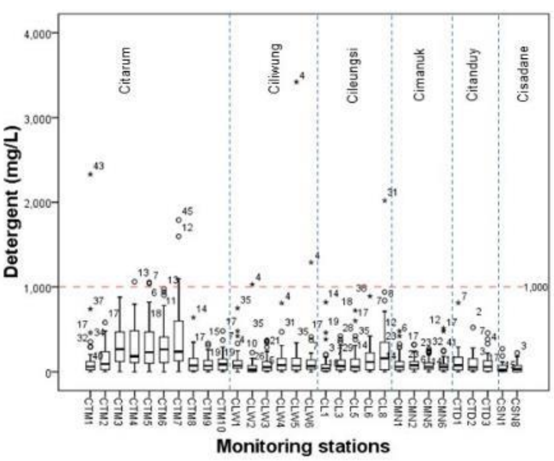

Total ammonium (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane

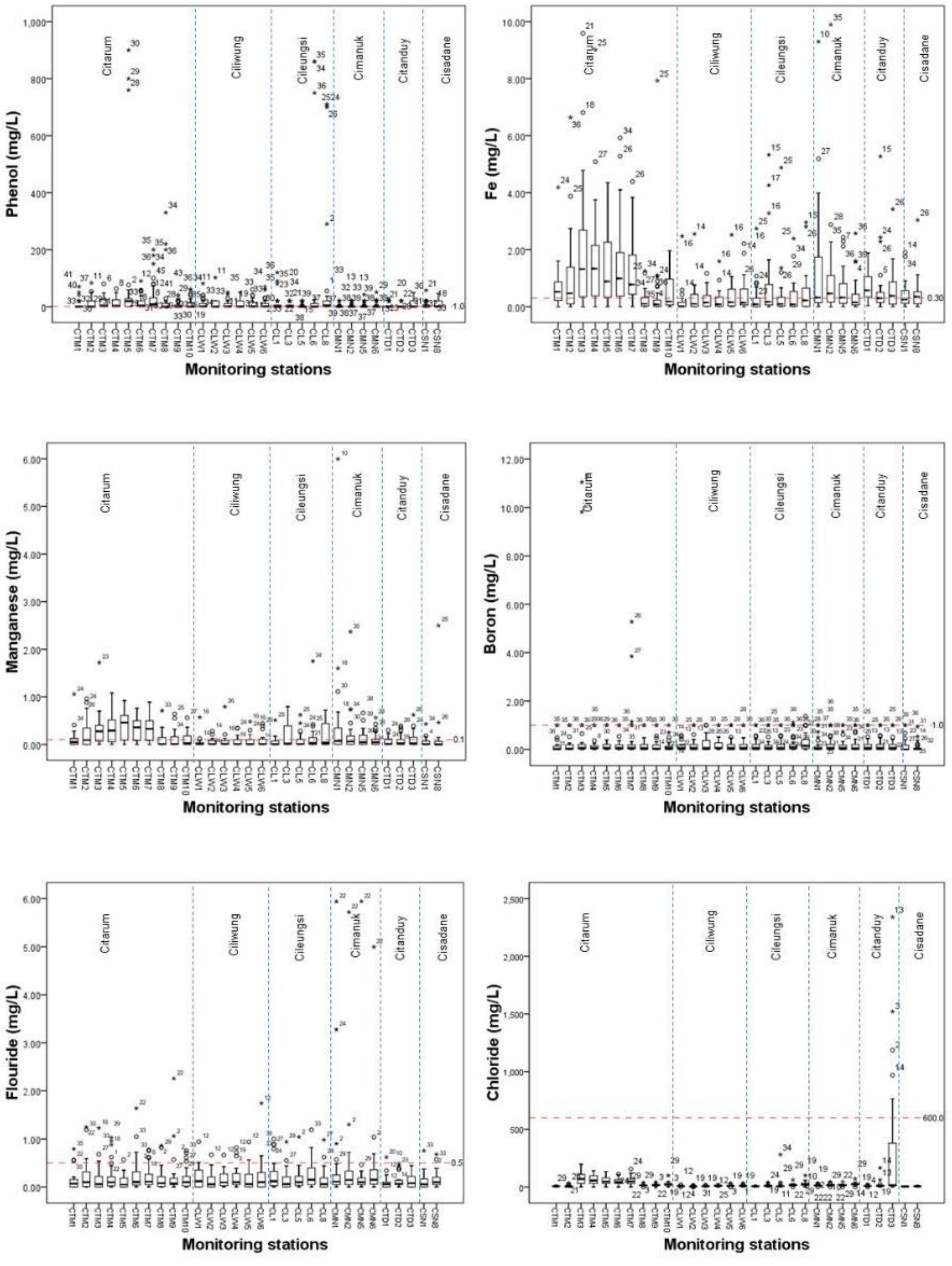

Total phosphate (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane

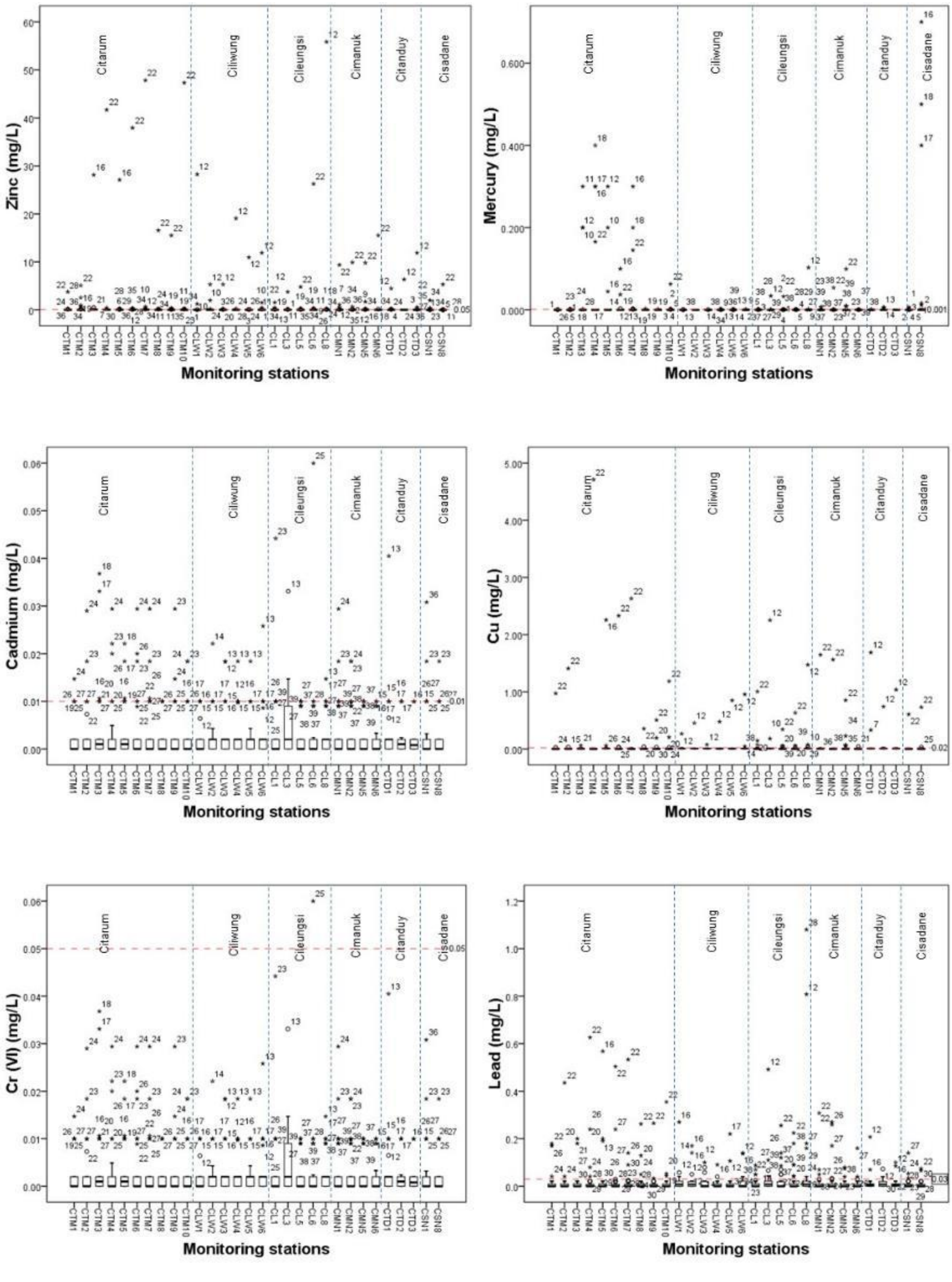

Dissolved oxygen (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane

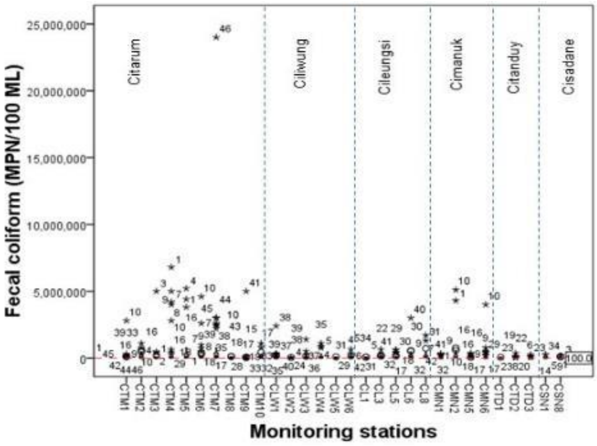

Chemical oxygen demand (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane


Fat and oil (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane


Detergent (mg/L)
Monitoring stations
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane


Phenol (mg/L)
Fe (mg/L)
Manganese (mg/L)
Boron (mg/L)
Flouride (mg/L)
Chloride (mg/L)
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane
1.0
0.30
0.1
1.0
0.5
600.0
Monitoring stations
Monitoring stations
Monitoring stations
Monitoring stations
Monitoring stations
Monitoring stations


Zinc (mg/L)
Mercury (mg/L)
Cadmium (mg/L)
Cu (mg/L)
Cr (VI) (mg/L)
Lead (mg/L)
Citarum
Ciliwung
Cileungsi
Cimanuk
Citanduy
Cisadane
Monitoring stations



Appendix B Maximum number of parameters to be discontinued for each monitoring station

Name of river	Monitoring Stations	Code	Maximum number of discontinued parameters
Citarum	Wangiasagara	CTM1	9
	Majalaya	CTM2	9
	Sapan	CTM3	7
	Cijeruk	CTM4	9
	Dayeuh Kolot	CTM5	6
	Burujul	CTM6	10
	Nanjung	CTM7	8
	Bendung Curug	CTM8	8
	Walahar	CTM9	9
	Tanjungpura	CTM10	9
Ciliwung	Atta'awun	CLW1	9
	Cisarua	CLW2	7
	Katulampa	CLW3	7
	Kedung Halang	CLW4	10
	Pondok Rajet	CLW5	7
	Panus	CLW6	8
Cileungsi	Cileungsi-Pekapuran	CL1	9
	Cikeas-Citeureup	CL3	8
	Cikarang-Jonggol	CL5	8
	Cikarang-Cikarang	CL6	5
	Bekasi-Babelan	CL8	6
Cimanuk	Bayongbong	CMN1	6
	Sukaregang	CMN2	7
	Tomo	CMN5	6
	Jatibarang	CMN6	4
Citanduy	Panumbangan	CTD1	8
	Bendung Paturaman	CTD2	10
	Tunggilis	CTD3	10
Cisadane	Cisalopa	CSN1	9
	Rumpin	CSN8	6

Appendix C

Table C.1 One parameter to be discontinued, their best auxiliary parameters and their I_a (calculated without critical factors using the Equation (12) form Part I paper)

Discontinued parameter	Best auxiliary parameter	I_a
BOD	COD	3.9919
COD	BOD	3.9919
Fe	Mn	3.9937
Mn	Fe	3.9937
Cr(VI)	Hg	3.9946
NO3	Detergent	3.9967
Detergent	NO3	3.9967
Pb	Cr(VI)	3.9972
Zn	pH	3.9986
Cd	Fat-oil	4.0002
B	F	4.0007
F	B	4.0007
Hg	Cr(VI)	4.0126
pH	Zn	4.0166
Fat-oil	Cd	4.0181

Table C.2 Ten Combinations of nine parameters to be discontinued-six parameters to be continued and their *Ia* at CTM1 (calculated without critical factors using the Equation (12) from Part I paper)

Nine parameter discontinued	Six parameters to be continued	*Ia*
B, Cd, BOD, NO_3, Cr, Pb, Fe, Mn, Zn	F, Fat-oil, COD, Detergent, Hg, pH	4.1417
B, Cd, BOD, Detergent, Cr, Pb, Fe, Mn, Zn	F, Fat-oil, COD, NO_3, Hg, pH	4.1417
F, Cd, BOD, NO_3, Cr, Pb, Fe, Mn, Zn	B, Fat-oil, COD, Detergent, Hg, pH	4.1417
F, Cd, BOD, Detergent, Cr, Pb, Fe, Mn, Zn	B, Fat-oil, COD, NO_3, Hg, pH	4.1417
B, Cd, COD, NO_3, Cr, Pb, Fe, Mn, Zn	F, Fat-oil, BOD, Detergent, Hg, pH	4.1417
B, Cd, COD, Detergent, Cr, Pb, Fe, Mn, Zn	F, Fat-oil, BOD, NO_3, Hg, pH	4.1417
F, Cd, COD, NO_3, Cr, Pb, Fe, Mn, Zn	B, Fat-oil, BOD, Detergent, Hg, pH	4.1417
F, Cd, COD, Detergent, Cr, Pb, Fe, Mn, Zn	B, Fat-oil, BOD, NO_3, Hg, pH	4.1417
B, Cd, BOD, NO_3, Cr, Pb, pH, Fe, Zn	F, Fat-oil, COD, Detergent, Hg, Mn	4.1444
B, Cd, BOD, Detergent, Cr, Pb, pH, Fe, Zn	F, Fat-oil, COD, NO_3, Hg, Mn	4.1444

Chapter 4
Identifying Parameter Weights using Analytical Hierarchy Process

4.1. Introduction

Chapter 3 presented a generic methodology for selection of parameters in a cost effective manner. This was undertaken through an enhancement of the statistical assessment based methodology used for parameter redundancy. This methodology was applied for the case study area in Chapter 3 and only 13 parameters representing all the 7 different grouping of water quality parameters were recommended to be used for the subsequent steps in the development of West Java Water Quality Index (WJWQI).

This chapter presents one of the most important steps in the development of WJWQI, which was that of establishing the weights of the 13 water quality parameters identified in the previous chapter. As per the recommendations from the second chapter, it is highly desirable to obtain local stakeholder's opinion in the development of a WQI. Taking into account the advantages of Analytic Hierarchy Process (AHP) and its recent successful applications for estimating weights, it was concluded that the AHP (in compared to other methods) was most appropriate to determine the weights of water quality parameters in this study. Two AHP models were then employed to calculate weights of the 13 selected parameters for the rivers in West Java, Indonesia. These parameter weights were identified based on local experts' opinion, which also addressed one of the limitations of the currently used indices in West Java. This step is expected to increase the credibility and acceptability of WJWQI to be used by related authorities and users of WJWQI in West Java. The results of the second AHP model demonstrated in this chapter would be then used for the remaining steps in the development of the WJWQI. These steps include aggregation of the sub-indices to produce the final index and undertaking uncertainty and sensitivity analysis of the WJWQI.

This chapter contains the following journal paper, which demonstrates the use of AHP to identify the weights of the water quality parameters:

1. Sutadian, A. D., Muttil, N., Yilmaz, A. G., & Perera, B. J. C. (2017). Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index. Ecological Indicators, 75, 220-233. doi:http://dx.doi.org/10.1016/j.ecolind.2016.12.043.

4.2

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

GRADUATE RESEARCH CENTRE

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index

Surname: Sutadian First name: Arief Dhany

College: College of Engineering & Science Candidate's Contribution (%): 85

Status:

Accepted and in press: ☐ Date:

Published: ☑ Date: 2017

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted]	30/03/2017
Signature	Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. There are no other authors of the publication according to these criteria;
4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing		30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing		30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing		31/03/2017

Updated: June 2015

Ecological Indicators 75 (2017) 220–233

Contents lists available at ScienceDirect

Ecological Indicators

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

4.3

Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index

Arief Dhany Sutadian[a,b,*], Nitin Muttil[a,c], Abdullah Gokhan Yilmaz[a,c], B.J.C. Perera[a,c]

[a] College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
[b] The West Java Environmental Protection Agency, Jl. Naripan No. 25 Bandung, 40111, Indonesia
[c] Institute for Sustainability and Innovation, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia

ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form
28 November 2016
Accepted 23 December 2016
Available online 6 January 2017

Keywords:
AHP
Weights
WQIs
Water quality parameters
West java

ABSTRACT

One of the most common approaches used to evaluate the state of water quality in a water body is through the use of water quality indices (WQIs). This paper presents one of the most important steps in the development of a WQI, which is that of establishing the weights of the water quality parameters. The Analytic Hierarchy Process (AHP) was employed to calculate weights based on 13 selected parameters from within 7 water quality groupings for rivers in West Java, Indonesia. Thus, two AHP models were employed in this study, the first had 13 pairwise questionnaires to be compared (individual form) and the second model had 7 comparisons (group form). A pool of respondents from related stakeholders with different backgrounds in West Java was surveyed to obtain their judgement independently. In the first AHP model, both chemical oxygen demand (weights in the range 0.102–0.185) and dissolved oxygen (weights in the range 0.103–0.164) consistently received relatively high weights, compared to other water quality parameters. Meanwhile, in the second model, oxygen depletion (weights in the range 0.160–0.233) and microbiology (weights in the range 0.098–0.249) had high weights. Thus, both models estimated relatively high weights for COD, DO and FC. However, considering that the second AHP model can provide individual weights as well as weights of parameter groupings, this model was preferred in this study. Therefore the results of the second AHP model will be used for the remaining steps in the development of the West Java WQI in the future.

1. Introduction

One of the most common approaches used to evaluate the state of water quality in a water body is through the use of water quality indices (WQIs). A WQI transforms and aggregates selected water quality parameters into a dimensionless number so that the status of river water quality can be defined in a simple manner. Even though the WQI approach has certain limitations, e.g. it cannot determine the quality of water for all uses nor can it provide complete information on water quality (Cude et al., 1997), it is able to express the general state of water quality spatially and temporally, and is easy to interpret and can be used as a basis for improvement of river water quality through various implementation programs. More importantly, this approach can be used for reporting to policy makers and the public in a simple and an understandable manner (CCME, 2001). Therefore, the WQI has been one of the most effective ways to communicate information about water quality in a water body (Walsh and Wheeler, 2012).

The West Java is situated in the western part of Java Island, Indonesia. It is the second most densely populated province in the country (BPS, 2016; Juwana et al., 2016b). There are several main rivers across this province, which are valuable sources of water for various needs. However, as reported by the West Java Environmental Protection Agency (WJEPA) (WJEPA, 2013), most of the rivers are vulnerable to pollution and have poor water quality due to domestic, agricultural and industrial activities. To assess the general status of river water quality, the WJEPA uses two indices, namely the Storet and the Water Pollution Index (WPI) (MoE, 2003). Although these WQIs have been used with some success, they both had been developed based on other specific case study areas without considering local knowledge or local conditions of the West Java, e.g. stakeholder's opinion on parameter weights. Therefore, the West Java WQI will be specifically developed taking into account the above notions, after which appropriate programmes can be designed to improve the water quality of rivers throughout the province.

* Corresponding author.
E-mail address: arief.sutadian@live.vu.edu.au (A.D. Sutadian).

http://dx.doi.org/10.1016/j.ecolind.2016.12.043
1470-160X/

There are in general four steps undertaken for the development of a WQI, which are the selection of parameters, obtaining sub-index values, establishing the weights of water quality parameters and aggregation of sub-indices to produce the final index (Abbasi and Abbasi, 2012). The establishing parameter weights aims to provide relative importance of the parameters and their influence on the final index value (Sutadian et al., 2016a). Equal weights are assigned if the parameters of an index are equally important, whereas unequal weights are assigned if some parameters have greater or lesser importance than others.

A few methods are available in the literature for estimating unequal weights of parameters or indicators in the development of an index. However, there is no generally accepted method to determine such weights (Böhringer and Jochem, 2007). Moreover, all methods have their own advantages and disadvantages (Fetscherin and Stephano, 2016; OECD, 2008). In general, in assigning different weights on parameters or indicators, OECD (2008) classifies weighting techniques into two broad categories, which are statistical-based methods (objective) and participatory-based methods (subjective). In the first category, weights are assigned based on the analysis on the data of the parameters or indicators using statistical-based approaches. In the second category, weights are assigned using judgement of related experts, policy makers and practitioners from different agencies of a certain area. As highlighted in OECD (2008), regardless of which method is used, weights are essentially value judgements. Therefore, although the first category seems to be more objective than the second category, the first is still subjective as it relies on the data provided for analysis. Also the statistical-based methods are less acceptable because of two reasons, namely the weight identification procedure is not very clear compared to that of the participatory-based methods (Zardari et al., 2015) and parameters or indicators that are theoritically insignificant could have high values (Böhringer and Jochem, 2007).

Methods such as the principal component/factor analysis (PCA/PFA) and the objective dynamic weight method are examples of the statistical-based methods. The weight identification procedure of the PCA/PFA has been applied in the environmental sustainable index (Esty et al., 2005), social sustainable development index (Panda et al., 2016) and the Langat River WQI (Mohd Ali et al., 2013). The PCA/PFA assigns weights based on the loading factor of each indicator. The PCA/PFA considers interrelationships between the parameters, and the weights cannot be estimated if no correlation exists between indicators (OECD, 2008). The disadvantage of the PCA/PFA is that this method has a strict assumption of linear relationships among parameters, but in general non-linear relationships exist among parameters (Mohd Ali et al., 2014). In addition, regarding the required sample sizes, Hutcheson and Sofroniou (1999) recommended that at least 150–300 cases are needed to obtain satisfactory results in using PCA/PFA. Meanwhile, this study had small sample sizes due to limited data availability. Considering these disadvantages, the PCA/PFA was not considered in this study for identifying the parameter weights.

The objective dynamic weight method assumes different weights on a monthly or seasonally basis for each station (Yan et al., 2015) or based on site-specific polluting parameters (Sargaonkar et al., 2008). The weight identification procedure of the objective dynamic weight method has been applied in a dynamic WQI (Sargaonkar et al., 2008; Yan et al., 2015). The weights are assigned using the concentration ratio (water quality data over the surface water quality standards). This method has flexibility with respect to degree of pollution of the parameters that frequently varies with time, wherein it cannot be reflected with fixed weights. However, there is difficulty in making comparisons of the final index value among monitored stations, since different stations have different weights (although they are monitored at the same period monitoring) and hence is not considered in this study.

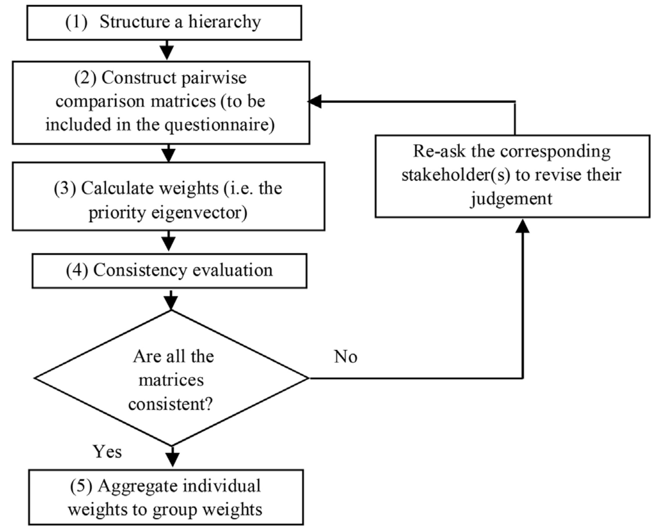


Fig. 1. Steps used in the AHP for establishing the weights.

In the participatory-based methods, techniques such as the revised Simos' procedure, the subjective dynamic weight, the Delphi and the Analytic Hierarchy Process (AHP) methods are available. The revised Simos' procedure is simple and easy to use (Zardari et al., 2015). The weights of the indicators are computed based on order of cards representing the stakeholder's preferences (Figueira and Roy, 2002). However, the revised Simos' procedure method is less popular in WQI studies. This method has been applied to determine weights of indicators for indices other than WQIs. For example, this method has been used in the development of water sustainability index by Juwana et al. (2016a). In the subjective dynamic weight method, weights are assigned based on relative significance of parameters obtained using researchers' own judgements (Yan et al., 2015). As discussed in the objective dynamic weight method in the previous paragraph, this method was not selected in this study mainly because of the inability to compare the final index values among stations or rivers. The Delphi method has been commonly used for summing up individual expert opinions to establish parameter weights for various WQIs (Almeida et al., 2012; Brown et al., 1970; Dunnette, 1979; House, 1989; Semiromi et al., 2011; Smith, 1990; SRDD, 1976). It is undertaken based on opinions of the stakeholders involved in a research through several rounds of questionnaries. Nevertheless, to reach convergence of the stakeholders' opinion, it is a lengthy and time consuming process (Franklin and Hart, 2007; Hartwich, 1999). As a result, it is more expensive than other methods (Zardari et al., 2015). Therefore, the Delphi method was not selected to be used in this study. On the other hand, the AHP is a mature and easy concept to gain experts judgement for assigning weights to the parameters. This method collects the related stakeholders' judgement using a sequence of pairwise comparison on a relative value of one over another between two quantities, wherein the judgement might be based on thoughts, experiences, and knowledge of the related stakeholders (Saaty, 1980). The advantages and disadvantages, along with a number of studies that have used the AHP method for estimating weights of parameters or indicators are discussed in Section 2.

Methods to identify weights of the currently used WQIs in the case study area (West Java Province), namely the Storet and the WPI were also investigated. Both methods assign equal weights. In addition, these two methods do not provide any guidelines for the selection of parameters. Consequently, applications of such WQIs might vary from one place to another because the selected parameters could be different, both spatially as well as temporally. Thus, comparison between the weights obtained based on the AHP in this study and these two currently used methods cannot be undertaken. Moreover, to the best of our knowledge, no research has been undertaken in the past to identify weights of the WQI for rivers in West Java Province using methods other than these two methods.

Taking into account the advantages of AHP and its recent successful applications for estimating weights (as discussed in Section 2), it was concluded that the AHP is more appropriate to determine the weights of water quality parameters in this study for the development of a WQI for West Java.

This paper presents a thorough description of the use of the AHP to identify parameter weights, which would then be used for developing a WQI for rivers in West Java. The structure of this paper is as follows. Firstly, an overview of the AHP is presented in Section 2. Details of the steps used in the AHP to establish parameter weights are then presented in Section 3. The process used for the identification of water quality related-stakeholders involved in the AHP is presented in Section 4. A detailed discussion and the results based on the water quality related-stakeholders' judgement are then presented in Section 5. Finally, a summary and conclusions drawn from this study are presented in Section 6.

2. Overview of AHP

The AHP is a Multi-Criteria Decision Analysis method that is used to determine relative weights of available alternatives. Based on these weights, the AHP can effectively prioritise choices among those alternatives. Many researchers have successfully applied this method in a large number of diverse research areas, such as in architecture (Bitarafan et al., 2015), banking (Kamil et al., 2014), defence (Sahni and Das, 2015), education (Bodin and Gass, 2004; Dorado et al., 2011), energy (Ishizaka et al., 2016), fishery (Jennings et al., 2016), food (Sun, 2015), medicine (Gupta, 2015; Kuruoglu et al., 2015), supply chain (Gorane and Kant, 2016).

Recent studies have also used the AHP for identifying relative weights of indicators and sub-indices, for example, tourism index (Tongqian et al., 2016), resources and environment efficiency evaluation (Li and Zhang, 2015), the development of product sustainability index (Hassan et al., 2012), satisfaction index for workplace environments (Khamkanya et al., 2012), deprivation indices to analyse health inequalities (Cabrera-Barona et al., 2015), legislative budgetary institution index (Chunsoon, 2014), and development of water and environment related indices (Kang et al., 2016; Nasiri et al., 2013; Shabbir and Ahmad, 2015). These also include few applications for establishing parameter weights in WQI studies (Abtahi et al., 2015; Chakraborty and Kumar, 2016; Ocampo-Duque et al., 2006; Tallar and Suen, 2016).

The AHP has been discussed in detail by its supporters and many other researchers. The AHP is theoretically sound, readily understandable and easily implemented (Forman and Gass, 2001). It also provides a better focus on multiple attribute decision making criteria for eliciting weights (Ishizaka et al., 2011; Ishizaka and Labib, 2009). Another advantage of the AHP is related to integration of the diverse judgements and preferences for group decision making (Basak and Saaty, 1993; Oddershede et al., 2007; Saaty, 1989). With regard to simplicity, the AHP also has the ability to decompose a complex decision problem using hierarchical levels in systematic ways (Saaty, 1980; Shen et al., 2015). Moreover, the AHP is easy to use due to the use of pairwise comparisons (Mulder, 2011). And it even enables to quantify both the experts' objective and subjective judgments in order to make a trade-off and to determine the priority (relative weight of each element over another) (Lewis et al., 2006).

In spite of these advantages, just as with any research tool, disadvantages exist in the use of the AHP. Various disadvantages of the AHP have been also discussed thoroughly by a few researchers. For instance, Warren (2004) has identified uncertainties of theoretical aspects in the AHP, such as scale misinterpretation and the axiomatic foundation. In addition to the above disadvantages, Hartwich (1999) highlighted that the AHP does not give any constructive guidance to the structuring of the problem. While, with respect to which point scale and the aggregation process to use, Ishizaka et al. (2011) pointed out that there were different competing preference point scales and aggregation methods to be used within the AHP. Therefore, different choices of point scales and the aggregation methods will lead different weight values.

In spite of the above discussed disadvantages of the AHP, the advantages outweigh the disadvantages and hence the AHP is an attractive tool that can be used to establish weights of different water quality parameters. Once the weights are obtained, further work can be undertaken towards the development of a WQI for West Java.

3. Steps used in AHP for establishing weights

In this study, the AHP was applied to establish the weights of the water quality parameters for developing the West Java WQI. The procedure used to establish the weights using the AHP method includes several steps (Shen et al., 2015): (1) structure a hierarchy, (2) construct the pairwise comparison matrix, (3) calculating the weights (i.e. the priority eigenvector), (4) consistency evaluation, and (5) aggregate individual weights to obtain the group weights. Fig. 1 presents these steps used in the AHP method to establish weights as a flowchart.

Each of the above mentioned steps used in the AHP are discussed below:

(1) Structure a hierarchy

In general, the hierarchy is set by defining a specific goal at the highest level. This is followed by lower level(s) used to achieve that goal. In this study, establishing weights of the water quality parameters is the goal at the highest level and the lower level(s) is water quality parameters either in individual or in group forms.

The results from our previous study for parameter selection to achieve cost effective water quality monitoring was used to develop the hierarchy (Sutadian et al., 2016b,c). In this previous study, an enhanced version of the statistical assessment for parameter redundancy developed by Khalil et al., (2014, 2010) was applied in order to obtain the selected parameters. This was undertaken using several screening procedures, statistical assessment for parameter redundancy to identify redundant parameters, and identification of common parameters across stations. The screening procedures were carried out to exclude parameters that did not meet the minimum data criteria and parameters that are within the permissible limits. The statistical assessment was performed to identify the parameters to be removed from further monitoring based on a parameter redundancy based methodology developed by Ouarda et al. (1996), and later adopted by Khalil et al. (2014, 2010). The identification of common parameters was undertaken to identify a uniform set of parameters across stations, which is necessary for the development and use of a WQI.

In the first screening procedure, only stations which had a minimum of six or more consecutive years of monitored data were considered since the statistical assessment for further analysis needed this requirement of consecutive data. Out of 54 monitoring stations in rivers of West Java, only 30 qualified under this criteria, and hence these stations were considered in the subsequent screen-

Table 1
Stages used for the selection of parameters.

No	Water quality parameters	Units	Screening			Statistical assessment	Common parameters across stations
			Based on stations	Based on parameters			
				Data availability	Within permissible limits		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
I	Physical						
1	pH	–	x	x	x	x	
2	Electrical conductivity	umhos/cm	x				
3	Turbidity	NTU	x				
4	**Temperature**	**°C**	**x**	**x**	**x**	**x**	**x**
5	Color	Unit PtCo	x				
6	Dissolved solids	mg/L	x	x	x	x	
7	**Suspended solids**	**mg/L**	**x**	**x**	**x**	**x**	**x**
8	Alkalinity	mg/L $CaCO_3$	x				
9	Acidity	mg/L CO_2	x				
II	Oxygen depletion						
1	Biochemical oxygen demand	mg/L	x	x	x	x	
2	**Chemical oxygen demand**	**mg/L**	**x**	**x**	**x**	**x**	**x**
3	**Dissolved oxygen**	**mg/L O_2**	**x**	**x**	**x**	**x**	**x**
III	Nutrients						
1	Free ammonia	mg/L NH_3-N	x				
2	Total ammonia	mg/L NH_3-N	x	x	x	x	
3	Orthophosphate	mg/L PO_4-P	x				
4	**Total phosphate**	**mg/L PO_4-P**	**x**	**x**	**x**	**x**	**x**
5	Nitrate	mg/L NO_3-N	x	x	x	x	
6	**Nitrite**	**mg/L NO_2-N**	**x**	**x**	**x**	**x**	**x**
7	Organic nitrogen	mg/L N	x				
IV	Organics						
1	**Detergent as MBAS**	**µg/L**	**x**	**x**	**x**	**x**	**x**
2	**Phenol**	**µg/L**	**x**	**x**	**x**	**x**	**x**
3	Fat-oil	µg/L		x	x	x	
V	Heavy metals						
1	Total chromium	mg/L Cr	x				
2	Chromium(IV) oxide	mg/L Cr	x	x	x	x	
3	Nickel	mg/L Ni	x				
4	Total nickel	mg/L Ni	x				
5	**Zinc**	**mg/L Zn**	**x**	**x**	**x**	**x**	**x**
6	Total Zinc	mg/L Zn	x				
7	Copper	mg/L Cu	x	x	x	x	
8	Total copper	mg/L Cu	x				
9	**Lead**	**mg/L Pb**	**x**	**x**	**x**	**x**	**x**
10	Total lead	mg/L Pb	x				
11	**Mercury**	**mg/L Hg**	**x**	**x**	**x**	**x**	**x**
12	Arsenic	mg/L Ar	x				
13	Cobalt	mg/L Co	x				
14	Barium	mg/L Ba	x				
15	Cadmium	mg/L Cd	x	x	x	x	
16	Total Cadmium	mg/L Cd	x				
VI	Ions and minerals						
1	Iron	mg/L Fe	x	x	x	x	
2	Total iron	mg/L Fe	x				
3	Boron	mg/L B	x	x	x	x	
4	Fluoride	mg/L F	x	x	x	x	
5	Potassium	mg/L K	x				
6	Calcium	mg/L Ca	x				
7	Hardness	mg/L $CaCO_3$	x				
8	**Chloride**	**mg/L Cl^-**	**x**	**x**	**x**	**x**	**x**
9	Magnesium	mg/L Mg	x				
10	Manganese	mg/L Mn	x	x	x	x	
11	Total Manganese	mg/L Mn	x				
12	Natrium	mg/L Na	x				
13	%Na	–	x				
14	Sulphate	mg/L SO_4	x	x			
15	Silica reactive	mg/L SiO_2	x				
16	R S C	–	x				
17	S A R	–	x				
18	Cyanide	mg/L CN^-	x				
19	Chlorine	mg/L Cl_2	x				
20	Sulphide	mg/L H_2S	x				
21	Selenium	mg/L	x				
22	Potassium permanganate	$KMNO_4$	x				
VII	Microbiology						
1	Total coliforms	MPN/100 ML	x				
2	**Faecal coliforms**	**MPN/100 mL**	**x**	**x**	**x**	**x**	**x**

Parameters used in each stage of parameter selection are indicated by (x), while the final common parameters used in the AHP are in bold.

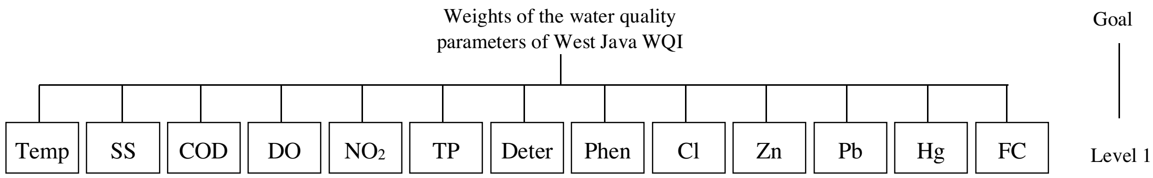


Fig. 2. Hierarchy based on the 13 individual parameters.

ing procedures. Table 1 presents the stages used for the selection of parameters. Using the water quality data from the 30 stations selected in the first screening procedure, 62 different parameters monitored between 2001 and 2012 were compiled (and indicated by (x) in column 4 of Table 1) under 7 water quality groupings (i.e. physical, oxygen depletion, nutrients, organics, ions and minerals, heavy metals and microbiology groups).

The parameters were then subjected to the second and third screening procedures, namely "data availability" and "parameter within permissible limits". Similar to the screening for stations, the parameters that had less than a minimum of six or more consecutive years were excluded. This procedure resulted in only 27 parameters in the 7 different water quality groupings for further analysis (indicated by (x) in column 5 of Table 1). It was also assumed that since the removed parameters were not monitored continually, they were less important to the water authority in the assessment of rivers. Then the third screening procedure, a box plot analysis was used to provide a summary visualization of the data, which was then compared with the permissible criteria (obtained from Government Decree of Government of Indonesia No. 81/2001 concerning surface water quality standards, Class I for drinking water with simple treatment). Using this procedure, one parameter, namely SO_4^{2-}, was excluded from further analysis. The box plot of SO_4^{2-} indicated that this parameter at all 30 stations was within the permissible limit and hence was considered to be not harmful to human or ecological health. Therefore, based on this third screening procedure, the number of parameters was reduced from 27 to 26 parameters (as indicated by (x) in column 6 of Table 1).

Then the statistical assessment for parameter redundancy was undertaken separately at each individual station for these 26 parameters. This statistical assessment was undertaken to assess redundancy among these 26 parameters and to identify the water quality parameters to be continued and discontinued at each monitoring station. There were two main analysis undertaken, namely (i) identifying highly correlated clusters to assess redundancy information among the studied parameters using correlation analysis and (ii) identifying the optimal combinations of continued and discontinued water quality parameters using an enhanced consolidated performance index (which is an aggregated information based on the variance of the mean value estimator among these 26 parameters). As a result, this statistical assessment led to a further reduction in the number of parameters to be monitored without losing a substantial amount of information in representing the water quality.

Applying this statistical assessment at each individual station, the continued parameters should ideally come from all clusters since information about a parameter in a particular cluster cannot be reconstituted from other clusters. Therefore, all single parameter clusters (only one parameter in a cluster) were recommended to be taken as a continued parameter since the information of these parameters cannot be provided by other parameters. Moreover, as our previous study aimed to obtain a minimum number of parameters to be monitored, only one parameter was selected from multiple parameter clusters (more than one parameters in a cluster) to represent its cluster. Therefore, for multiple parameter clusters, only one parameter should be considered to be continued, while the other(s) should be discontinued. However, the results of the statistical assessment revealed that the parameters to be continued and discontinued varied from one station to another station. This result was not acceptable in the development of West Java WQI since a common set of parameters is required for the WQI to assess and compare water quality in rivers of West Java. Therefore, considering this fact, few additional criteria were proposed to be applied to identify common set of parameters to be used in the West Java WQI. These additional criteria were:

(i) Parameter identified as being in single clusters for at least 70% of the total monitoring network were recommended to be selected as the common parameters across all stations (based on results of correlation and on cluster analysis).
(ii) Only parameters that are identified to be monitored continuously (i.e. based on results of single parameter clusters and the enhancement of consolidated index in multiple parameter clusters) for at least 80% of the total monitoring network were proposed to be included in the uniform set of parameters across stations.
(iii) The uniform set of parameters should include at least one parameter belonging to each of the 7 different grouping of water quality parameters. This will ensure that the significance of each grouping of water quality parameters was considered in the final index aggregation of a WQI.

If a particular parameter met any of these criteria, that parameter was recommended to be selected as a common parameter in the development of the West Java WQI. For example, applying the second criteria, in grouping of heavy metal parameters, Cd was excluded from the selected parameters as this parameter was recommended to be monitored continuously for less than 80% of total monitoring stations. On the other hand, Zn, Pb, and Hg were included since they were recommended to be monitored at more than 80% of the stations.

Through the steps aforementioned, it was established that only 13 parameters representing all the 7 different groupings of water quality parameters were needed to be continuously monitored. Thus, those 13 parameters would be used for establishing the weights using the AHP (indicated by (x) in column 8 and are shaded in Table 1). They are were temperature (temp) and suspended solids (SS) representing the physical group, chemical oxygen demand (COD) and dissolved oxygen (DO) in the oxygen depletion group, nitrite (NO_2) and total phosphate (TP) in nutrients group, detergent (Deter) and phenol (Phen) in the organics group, chloride (Cl) in ions and minerals group, Zinc (Zn), Lead (Pb) and mercury (Hg) in the heavy metals group, and faecal coliform (FC) in the microbiology group. The detailed procedure on how to obtain these common parameters to be used in the West Java WQI can be found in (Sutadian et al., 2016b,c).

Two AHP models were developed; the first was based on the 13 individual parameters and the second on the 7 groupings of parameters and their sub-groupings. Figs. 2 and 3 present the structure of the hierarchy for the two AHP models. In the first AHP model, there is only one level of hierarchy that stands for the goal and it consists of the 13 individual parameters. On the other hand, in the

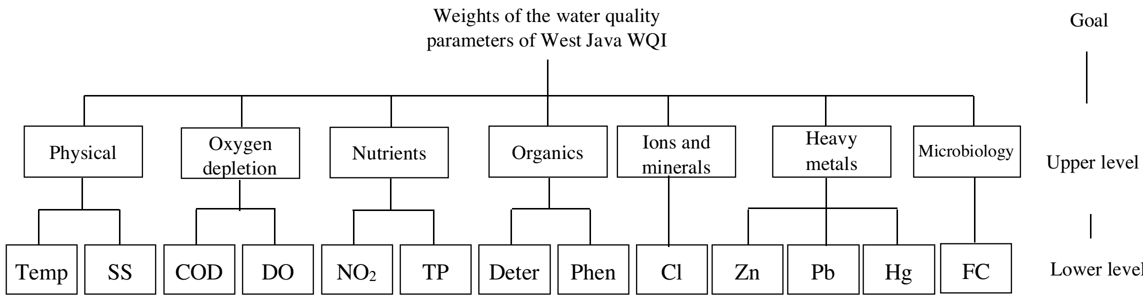


Fig. 3. Hierarchy based on the 7 groupings of parameters.

Table 2
The 1–9 point scale used for the pairwise comparisons (Saaty, 1980).

Relative importance	Scale	Relative importance	Scale
Equally important	1	Equally important	1
Moderately important	3	Moderately less important	1/3
Strongly important	5	Weakly important	1/5
Very strongly important	7	Very weakly important	1/7
Extremely important	9	Extremely weak	1/9
Intermediate values	2,4,6,8	Intermediate reciprocal values	1/2, 1/4, 1/6, 1/8

second AHP model, there are two levels of hierarchy, namely the upper and the lower level. The upper level consists of the 7 groupings of parameters and the lower level encompasses sub-groupings of parameters describing the upper level.

(2) Construct pairwise comparison matrix

The next step is to construct the pairwise comparison matrix, which would be included in the questionnaires that are to be distributed to the respondents. Pairwise comparisons (of the water quality parameters in this study) are a fundamental step in the use of the AHP (Saaty, 1987). Various scales have been proposed to rate the related stakeholders' judgements, such as the 1–9 point scale (Saaty, 1980), the power scale (Harker and Vargas, 1987), the geometric scale (Lootsma, 1989) and logarithmic scale (Ishizaka et al., 2011). However, the 1–9 point scale has strongly been recommended to be used as an acceptable scale in the AHP (Harker and Vargas, 1987; Saaty, 2001). The advantage in using the 1–9 point scale is that it has qualitative distinctions and provides more options to assess the relative importance among the parameters, compared to smaller point scales (Saaty, 1980, 2001). Furthermore, the 1–9 point scale is simple, straightforward, and easy to use (Zhang et al., 2009). Recent studies show that the 1–9 point scale has been widely used in numerous AHP applications (Abdollahzadeh et al., 2016; Ishizaka et al., 2016; Shen et al., 2015; Singh and Nachtnebel, 2016; Wang et al., 2016). Hence, the 1–9 point scale was used in this study to transform the stakeholders' judgements into numerical values in the pairwise comparisons. The detailed interpretation of the 1–9 point scale is described in Table 2, wherein the values the values of the scale range from1/9 to 9.

The pairwise comparisons are undertaken between two parameters, for example, parameter i and parameter j to assess their relative importance. In the scale described in Table 2, a scale value of 1 means that both parameter i and parameter j are equally preferred and a value of 9 gives extreme importance to parameter i over parameter j. Conversely, if one parameter is preferred less than the other in a comparison, the reciprocal values of scale (i.e. column 2 of Table 2) are used to reflect the intensity of lower importance. Using Table 2, then each of stakeholder judgements is recorded in the form of a pairwise comparison matrix A of dimension $N \times N$, where N is the number of parameters to be compared. Fig. 4 presents the pairwise comparison matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & .. & a_{1N} \\ a_{21} & a_{22} & .. & .. & a_{2N} \\ a_{31} & .. & a_{22} & .. & a_{3N} \\ .. & .. & .. & .. & .. \\ a_{N1} & a_{N2} & a_{N3} & .. & a_{NN} \end{bmatrix}$$

Fig. 4. The pairwise comparison matrix used in AHP.

As presented in Fig. 4, it is also worth mentioning that the respondents were required to fill only the upper triangular of the matrix for all pairwise comparisons since the lower triangular is always the positive reciprocal of the upper triangle (i.e. $a_{ij} = 1/a_{ji}$ for all i, j from 1, 2. . . N). The diagonal elements of the matrix (a_{NN}) are all equal to 1. Thus, the lower triangular values were automatically derived from responses of the upper triangular part of the matrices (Inamdar, 2014).

(3) Calculating the weights

In general, the weights are elicited by employing matrix algebra to determine the principal eigenvector $w = (w_1, w_2 . . . w_N)$ from matrix A, where $w_i > 0$ and $\sum_{i=1}^{N} w_i = 1$. The principal eigenvector for each matrix, when normalized, becomes the vector of priorities (i.e. weights) for that matrix (Saaty, 1980). Mathematically, as proposed by Saaty (1980), the principal eigenvector of A as the desired priority vector w can be estimated by solving Eq. (1) below.

$$Aw =_{Max} w \tag{1}$$

where λ_{Max} is the largest eigenvalue of the matrix A and the corresponding eigenvector w. This approach is well known as the eigenvalue method (Dong et al., 2010). The eigenvalue method was then used to estimate the weights of individual parameters/groupings of parameters/sub-groupings of parameters across all hierarchy levels. In this study, the AHP software package Expert Choice was used to undertake the computational procedure for determining the weights.

Table 3
Random Index (RI) values for different values of *N* (Saaty, 1980).

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table 4
Summary of number of respondents initially invited and those finally used with consistent responses.

Respondent groups	Initially invited respondents	Agreed to participate	Number of stakeholder responses			
			Initial C. R[a]		Revised consistent responses	Finally used consistent responses
			< 0.1	> 0.1		
Government officials	7	5	3	2	1	4
Academics	6	5	3	2	2	5
Researchers	6	5	3	2	–	3
Consultants	6	5	3	2	–	3
Total	25	20	12	8	3	15

[a] C.R. < 0.1 indicates acceptable consistency and C.R. > 0.1 indicates inconsistent responses.

(4) Consistency evaluation

Consistency is a measure to evaluate whether relative judgement given by the respondent is consistent or not. A judgement is said to be consistent if it meets the logic of preference of transitive property (i.e. $a_{ij} . a_{jk} = a_{ik}$) (Saaty, 1980). Hence, this step provides a logical consistency of the stakeholders' judgement since perfectly consistent judgement is difficult to attain in practice. Saaty (1980) proved that the λ_{Max} is always greater than or equal to *N* for positive reciprocal matrices and is equal to *N* if and only if the matrix *A* is a consistent matrix. Therefore, the closer λ_{Max} is to *N*, the more consistent the judgement is. In this consistency evaluation step, λ_{Max} is then used as an important validating parameter to measure consistency of stakeholders' judgement and shown in Eq. (2).

$$\mathrm{CI} = \frac{_{\mathrm{Max}} - N}{N - 1} \quad (2)$$

where CI is the consistency index, *N* is the dimension of the matrix, and λ_{Max} is the same as that in Eq. (1).

Furthermore, for different dimension of the matrix (*N*), Saaty (1980) generated random matrices and calculated their mean CI value. These mean CI values are called the random index (RI). Using CI as shown in Eq. (2) and the RI values as presented in Table 3, Saaty (1980) developed the consistency ratio (CR) to measure consistency for a given pairwise comparison matrix with respect to its RI as shown in Eq. (3).

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (3)$$

where if the value of CR is less than 0.10, then the judgement responses in the pairwise comparison matrix can be considered as having an acceptable consistency (Saaty, 1980). The computational procedure for consistency evaluation was undertaken using the AHP software Expert Choice. In this study, to deal with inconsistent responses (when the CR exceeds 0.10), the respective stakeholders were required to re-review their judgements. The new values of pairwise comparisons from the respective stakeholders were then re-assessed again for evaluating their consistency.

(5) Aggregating individual to group weights

For each level of hierarchy, to obtain a set of weights from group judgement responses, the aggregating individual priorities (AIP) method was employed. In the AIP, all different sets of weights from individual responses are first elicited from the pairwise comparisons independently. Then, these different sets of individual weights are aggregated to represent weights of the group judgement responses (a collection of individuals). Such an aggregation of different individual weights can be computed using either an arithmetic or geometric method (Forman and Peniwati, 1998). However, in this study the geometric method is preferred to be used due to two reasons as discussed below:

(v) The geometric method is more consistent with previous steps in the AHP since the stakeholder's judgements used in the pairwise comparison represent relative importance (ratios) of one over another (Forman and Peniwati, 1998).
(vi) Although the arithmetic method provides a simple aggregation, it creates the problem known as "eclipsing", wherein lower values of individual weights are dominated by the higher values of other individual weights or vice versa. With considerably high individual weights, as shown by Ishizaka et al. (2011), the arithmetic method will overrate the group weights (final priorities).

Considering the above reasons, all the different weights obtained from the individual's pairwise comparisons were therefore aggregated using the geometric method. In this study, consensus of the group judgement's responses was neglected. The aggregated weights were then normalized as the sum of weights at each hierarchy should be 1.

Since the first AHP model only had one hierarchy to represent the overall weights of the water quality parameters, all weights were automatically the overall weights corresponding to the 13 individual of parameters. On the other hand, the second AHP model had two levels of hierarchy (i.e. upper and lower levels). Therefore, The overall weights in the lower levels were obtained by multiplying the normalized weights of those levels and the preceding levels (Lewis et al., 2006). As an example, the overall weight of temperature was obtained by multiplying the weight at the upper level (of physical) by its weight at the lower level (of temperature). This multiplication process was continued until all overall weights of the sub groupings of parameters in the lower level were obtained.

4. Identification of water quality-related stakeholders

To obtain an unbiased opinion, in this study, stakeholders in West Java were identified from different groups of experts. Four different groups namely, government officials, academics, researchers, and consultants were chosen and invited for the questionnaire based survey. These are important groups since they

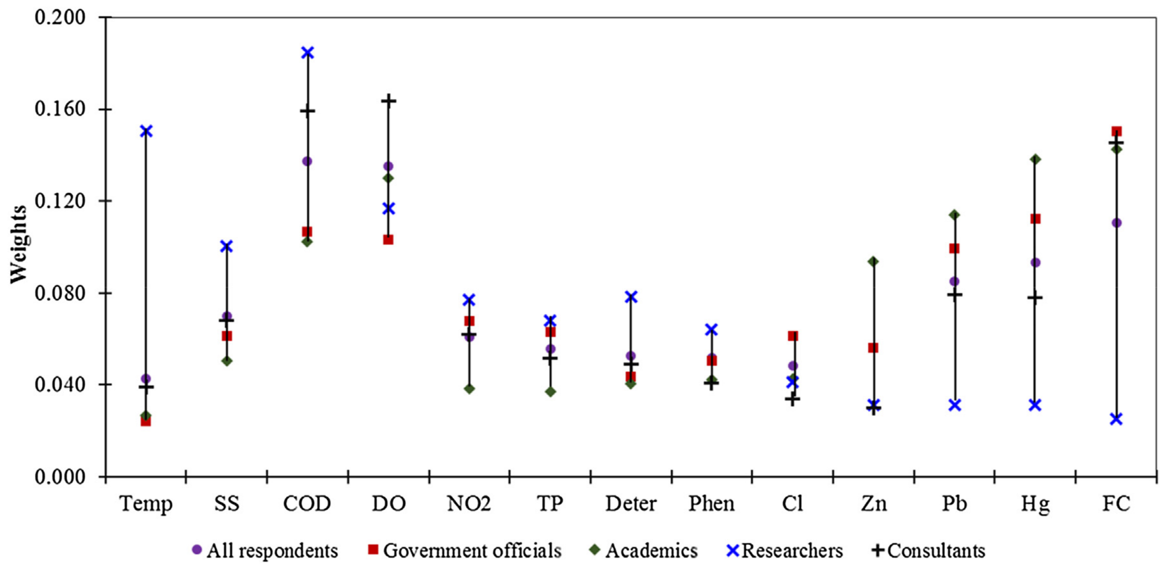


Fig. 5. Weights of 13 individual parameters for the different groups of respondents obtained from the first AHP model.

influence decisions related to water quality management. Even though these groups may have different degrees of influence, but their contributions are useful towards representing the stakeholder(s) with strong interests in the development of the proposed West Java WQI. Juwana et al. (2010) have suggested that the local stakeholders should be preferred when compared to stakeholders from other areas as they are considered to have extensive knowledge of issues related to water resources management in West Java.

In this study, the stakeholders for undertaking the questionnaire based survey were identified in the following manner. First, the stakeholders who are key persons working in the above four groups were long listed. Second, to obtain reliable and accurate judgements, only the stakeholders who have an average working experience of more than 10 years and related educational background in water quality management were identified. With this two-step process in identifying stakeholders, 7 officials from water quality related government organisations, 6 lecturers from 2 universities, 6 researchers from research institutions or water centres and 6 professionals who are working as consultants were identified. Then, they were contacted either via email or phone calls. Most of the contacted stakeholders were willing to participate in this study. Finally, 20 stakeholders confirmed and 5 refused by expressing their unwillingness or by not responding to email invitations. The 20 stakeholders consisted of 5 in each of the four different groups.

5. Results and discussions

5.1. Preparation of AHP questionnaire

Using the basic hierarchic structure described in Figs. 2 and 3, pairwise comparison questionnaire of 13 individual parameters and 7 groupings of parameters were developed. Since subgroupings of parameters in the second AHP model consisted of the same individual parameters as in the first AHP, pairwise comparison for sub-groupings of parameters in the second AHP model were not specifically developed. The reason was to not only reduce the number of questions, but also to avoid repetition of some comparisons. Accordingly, the respondents did not necessarily rate the same comparisons twice and kept maintaining the consistency of the stakeholders' judgement for those respective comparisons. Instead, the stakeholders' judgements on individual parameters were also used to estimate the weights by decomposing into related sub-groupings of parameters. As an example, for the physical grouping, only judgement on temperature and SS of 13 individual parameters pairwise comparison were used to develop its own pairwise comparison.

Before the questionnaire was distributed to the respondents, a mini-survey was carried out to seek preliminary feedback and comments, particularly in relation to the clarity of questions for the pairwise comparison matrices. Since this questionnaire was to be distributed in West Java, Indonesia, a few Indonesian students in Melbourne and colleagues in West Java Environmental Management Agency, were requested to complete the questionnaire form as part of the mini-survey. They were also requested to provide comments for improving the language and quality of translation (since the questions were also provided in Indonesian language). Based on the responses from the mini-survey, a few questions mostly regarding the clarity of questions and vocabulary mistakes in the Indonesian language were refined.

Further, through these questionnaires, the involved respondents were asked about their opinion on the relative importance of one parameter over another for both the 13 individual parameters and the 7 groupings of parameters. Along with the questionnaires, a background of the study and a brief description of the previous research in selecting individual parameters and groupings of parameters were provided to each of the respondents.

5.2. Distribution and collection of the AHP questionnaire

The final version of the AHP questionnaire was sent to the 20 respondents individually through email in order to avoid their interacting with each other. This was aimed to avoid dominance of some respondents over others (Shen et al., 2015; Singh and Nachtnebel, 2016). All the 20 respondents returned the questionnaire and their responses were tabulated into an excel file. Next, the consistency of the pairwise comparison matrix for the two different AHP models were individually checked. It was observed that 8 out of the 20 respondents had inconsistent answers as the values of CR for their responses were more than 0.1. Hence, another request was sent to those 8 respondents to revise their responses. A response was received from 5 out of 8 respondents, who had revised their answers. The consistency of their pairwise comparison matrix was re-checked. However, only 3 out of 5 responses were consistent, and hence another request was sent to the 2 respondents who were still not consistent in their responses.

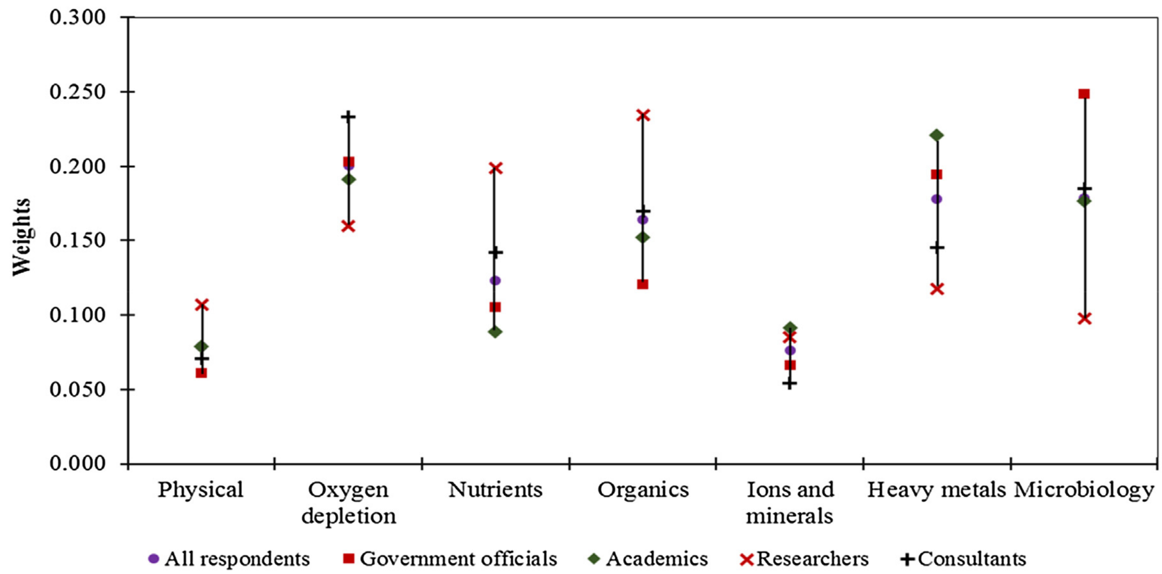


Fig. 6. Weights of 7 grouping of parameters for different groups of respondents obtained from the second AHP model.

With respect to inconsistent and incomplete responses, Al-Barqawi and Zayed (2006); Singh and Nachtnebel (2016) suggested that inconsistent responses, late answers and those who were reluctant to complete the questionnaire were excluded from the analysis. In addition, Qureshi and Harrison (2003) also concluded that re-asking the respondents to revise their judgement would not necessarily remove the problem of inconsistency in AHP. Hence, in this study, 5 respondents were left with inconsistent responses within a set timeframe of 1 month as those respondents neither responded nor revised their judgements. Using this procedure described above, responses of only 15 out of the initially selected 20 stakeholders were used for further analysis to obtain weights of the water quality parameters. A summary of the number of invited respondents and the number of respondents whose responses were finally used is presented in Table 4.

5.3. Establishing the weights of the water quality parameters

As discussed in Section 3 and shown in Figs. 2 and 3, in the first AHP model, there is one level of hierarch with respect to the 13 individual parameters, while the second AHP model has two levels of hierarchy corresponding to 7 groupings of parameters and their sub-groupings. At the upper level in the second AHP model, 5 groupings of parameters had either 2 or 3 sub-groupings of parameters. Meanwhile, the other two groupings (ions and minerals and microbiology) had only one parameter each within their grouping with no other parameter to be compared with. Thus, such sub-groupings of parameters consisting of only a single parameter received a weight of 1.

As mentioned earlier, four groups of respondents participated in the survey to estimate the weights of the water quality parameters. In addition to considering the weights of all respondents together, the weights of different groups of respondents (government officials, academics, researchers and consultants) were also assessed to analyse if any group was dominating the stakeholders' opinions. However, only the overall weights of both AHP models, calculated based on the group of all respondents were compared. The better of the two will be used in the aggregation and further analysis for developing the West Java WQI. The following sub-sections discuss the weights from both the AHP models in detail based on the different groups of respondents. It is worth mentioning that all the weights discussed in the following sub-sections were the averaged weights of the group judgement responses calculated using geometric mean based on the AIP (please refer to Section 3 (5)).

5.3.1. First AHP model based on 13 individual parameters

Fig. 5 presents the weights obtained in the first AHP model for the 13 individual parameters. As can be seen in the figure, all the groups of respondents assigned relatively high weights to COD when compared to the other parameters. The weights of COD ranged from 0.102 to 0.185. The second parameter that received high weights consistently by all groups of respondents was DO, wherein the weights were 0.135 (all respondents), 0.091 (government officials), 0.110 (academics), 0.105 (researchers) and 0.148 (consultants). This was followed by FC, which had a similar pattern to the two-aforementioned parameters. All the groups of respondents, with the exception of researchers, assigned high weights to FC of 0.111, 0.150, 0.142, and 0.145 for group of all 15 respondents, government officials, academics, and consultants, respectively. These groups of respondents were likely to recognise that these parameters (namely COD, DO, and FC) are often well above their permissible limits. Recent studies in West Java have also shown that the water quality of the rivers in West Java have deteriorated because of contamination caused by growing quantities of untreated residential and industrial wastewater (WJEPA, 2014). This fact could be a supporting reason for the respondents judging that COD, DO and FC were largely more important than the other individual parameters.

The above results, which assigned the highest weights to the oxygen depletion parameters and FC were also in line with that of some other popular WQIs, which consider DO and FC as the most important parameters. For example, out of the 9 parameters in the National Sanitation Foundation WQI, the two highest weights were received by DO (0.200) and FC (0.160) (Brown et al., 1970). In the Oregon WQI, the two highest weights from the six selected parameters were also for DO (0.400) and FC (0.200) (Dunnette, 1979). Similar results, particularly for DO, were observed in Dalmatian, Debel's, and Malaysian WQIs, where DO was considered as the most important parameter among others (Debels et al., 2005; Shuhaimi-Othman et al., 2007; Štambuk-Giljanović, 1999). Hence, this indicates that controlling the activities that increase the concentration of FC and deplete the DO should be the top priority for water quality managers in West Java.

Fig. 5 also shows that the group of researchers had a very different opinion about the weights of Temp, SS, Pb, and Hg when

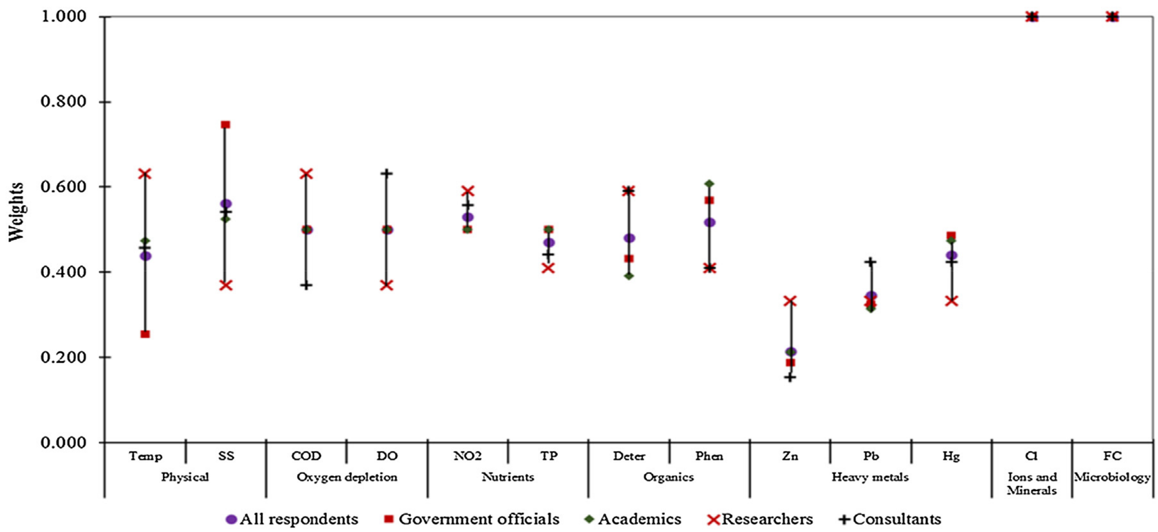


Fig. 7. Weights of the sub-grouping of parameters at the lower level in the second AHP model.

compared to the other groups of respondents. The researcher group assigned relatively high weights to temperature (0.151) and SS (0.100), whereas the other groups of respondents assigned relatively low weights to temperature (0.024–0.043) and SS (0.051–0.073). The high preference to temperature provided by the group of researchers is likely to be because of their knowledge about how temperature influences other parameters (such as DO) as well as other chemical-biological processes in a water body (such as metabolic rates of aquatic organisms and the solubility and reaction rates of chemicals).

On the other hand, the group of researchers assigned relatively low weights to Pb (0.025) and Hg (0.031), whereas the other groups of respondents assigned higher weights to them with values ranging from (0.079 to 0.114) and (0.111 to 0.145) for Pb and Hg, respectively. The higher weights to these heavy metals given by the other groups of respondents (other than researchers) is likely to be driven by the fact that heavy metal contamination, especially in rivers passing through urban and industrial areas in West Java, have been regularly reported through the official reporting process and is widely covered in the public media.

5.3.2. *Second AHP model based on 7 groupings of parameters*

Fig. 6 presents the weights obtained in the second AHP model for the 7 groupings of parameters. All groups of respondents except the researchers assigned relatively high weights to oxygen depletion (0.160–0.233), microbiology (0.098–0.249) and heavy metal parameters (0.117–0.221). Thus, the judgement of all groups of respondents (except researchers) indicate that these three groupings of parameters always receive a higher weight relative to the other groupings of parameters. The researchers on the other hand give lesser preference to oxygen depletion (0.160), microbiology (0.98) and heavy metals (0.117) when compared to the other groupings of parameters.

It can also be seen in Fig. 6 that all the different groups of respondents indicated similiar preference to physical, nutrients, organics and ions and minerals groupings of parameters. The only contradiction to this is the preference of the researchers, who assigned much higher average weights to nutrients (0.199) and organics (0.235). All other groups assigned relatively lower avarage weights to physical, nutrients, organics and ions and minerals groupings of parameters. It is also important to note that the oxygen depletion parameters in the second AHP model and its sub-groupings of parameters (COD and DO) in the first AHP model received relatively high weights in both the AHP models. These were also observed in the other groupings of parameters and sub-groupings of parameters, namely for microbiology, ions and mineral and physical groupings, wherein both AHP models had a similar pattern of weights. In addition, the F-test for each parameter was performed to see if the variances of the overall weights obtained from individual respondents for both AHP models have similar characteristics. In this study, the null hypothesis, i.e. H_0: $\sigma_1 = \sigma_2$ (i.e. the variances of first and the second AHP models were equal) was tested, wherein the critical value of F for a 2-tailed test, $F\text{-}_{Critical(0.025,14,14)}$ for a significance level of 0.05 with 14° of freedom was 2.98. The H_0 was accepted if the $F\text{-}_{Value}$ was less than the $F\text{-}_{Critical}$, otherwise the H_0 would be rejected. As presented in Table A1 in the Appendix A, analysis of variances of both models for each parameter providing $F\text{-}_{Values}$ and *p*-values shows that the variance between the first and the second AHP models were not statistically different, with exceptions for the data of Cl and Zn. These results confirm that the first and the second AHP models were in agreement.

As discussed earlier in Section 5.1, at the lower level of hierarchy in the second AHP model, weights corresponding to the sub-groupings of parameters were generated using the respective pairwise comparison matrix from the 13 individual parameters. Fig. 7 presents these weights of each sub-grouping of parameters at the lower level of hierarchy. It was observed that four of the sub-groupings of parameters, namely Temp-SS (physical), COD-DO (oxygen depletion), NO_2-TP (nutrients), and detergent-phenol (organics), had fairly equal weights. Academics and consultants assigned weights to these sub-groupings of parameters between 0.44 and 0.55, while the government officials and researchers assigned a larger range of weights ranging from (0.25–0.63) and (0.27–0.75) respectively. As can also be seen in Fig. 7, for the sub-groupings of heavy metal parameters, almost all the groups of respondents, except the researchers, assigned a similar pattern of weights. This sub-grouping received weights of (0.19–0.21), (0.31–0.33), and (0.42–0.47) for Zn, Pb, and Hg respectively. It should be noted that the sum of weights in the AHP at any given level of hierarchy is equal to 1. Therefore, sub-groupings of parameters of ions and minerals and microbiology, which were, Cl and FC had weights of 1 since within these groupings had only one sub-grouping of parameters.

5.3.3. *Comparison of the overall weights between first and second AHP models*

Fig. 8 presents a comparison of the overall weights obtained from both the AHP models. As seen in this figure, the overall weights

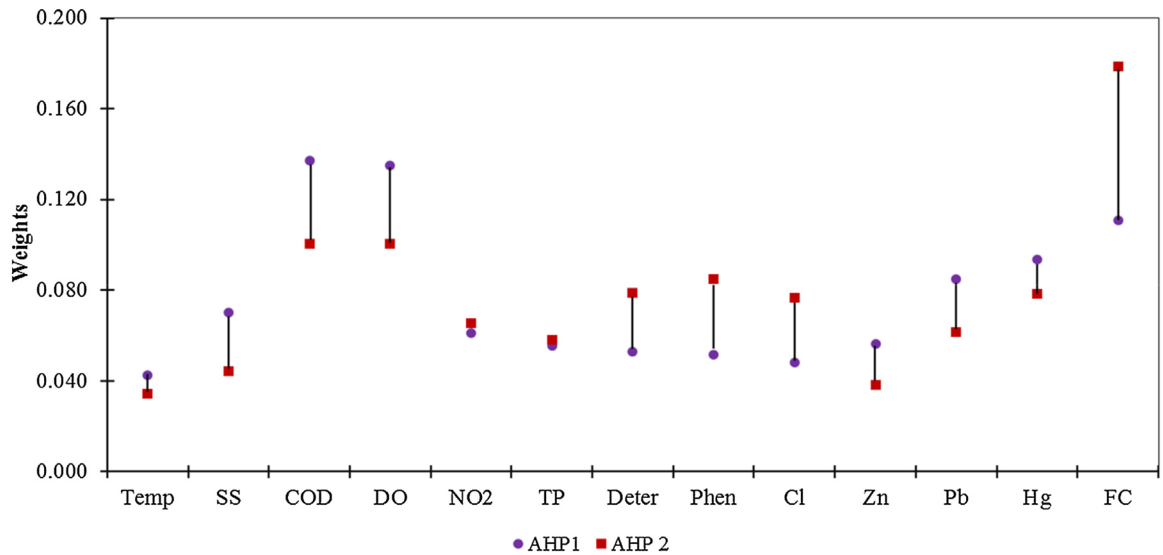


Fig. 8. Comparison of overall weights between the first and second AHP models.

of temperature, NO_2, and TP were not significantly different. Both models also had similar results corresponding to relatively high overall weights for COD, DO and FC and relatively low weights for temperature and Zn. However, when the weights were ranked, there were slight differences between the two models. COD and DO had the highest parameter weights in the first AHP model, whereas FC and COD had the highest parameter weights in the second AHP model. Fig. 8 also shows that the overall weights of FC (0.179) and Cl (0.077) in the second AHP model was significantly higher than that in the first AHP model (0.111 and 0.048, respectively). This is because adding or deleting alternative(s) (which in this study are the parameters to be compared) from the original set of hierarchy change the weights and the rank order (rank reversal) (Hartwich, 1999; Raharjo and Endah, 2006; Warren, 2004). As an example, when Cl in the first AHP model was compared to other 12 parameters, it was less preferred parameter. Nevertheless, considering the fact Cl was the only parameter in the ions and minerals grouping, Cl appeared to be a more preferred parameter when it was compared to other 6 groupings of parameters in the second AHP model.

A comparison of the consistency of the stakeholders' judgement was investigated to identify the better of the two AHP models. Two criteria were applied for this comparison, first being fewer numbers of inconsistent responses and the less average consistency ratio for all respondents being the second criterion. Tables A2 and A3 in the Appendix A presents weights for different respondent groups and their consistency ratios for the first and the second AHP models, respectively. It was observed that the number of inconsistent responses based on the second AHP model was fewer than that of the first AHP model. The result for the second criteria indicated that the average consistency ratio of the second AHP model (0.052 for 15 respondents and 0.072 for 20 respondents) was less than that of the first AHP model (0.059 for 15 respondents and 0.097 for 20 respondents). One of the causes inconsistency mentioned in the literature is the size of dimension of pairwise comparison (N) (Koyun and Ozkir, 2014). This has also been discussed by many researchers, for example and Han (2016). As the size of N increases, the number of pairwise comparisons increases largely by a factor of $N(N-1)/2$ (Harker and Vargas, 1987; Zardari et al., 2015). Consequently, the respondents have difficulty to complete all judgements in the pairwise comparison (Zardari et al., 2015) or in other words, the respondents find it somewhat tedious to go through all the pairwise comparisons, leading to more inconsistency due to some incorrect comparisons (Hartwich, 1999). Accordingly, considering the reliability of judgements obtained from the respondents, the second AHP model appeared to be better than the first model as it had fewer numbers of pairwise comparisons. In addition to the aforementioned reason, the second AHP was also preferred in this study since this model will provide individual parameter weights as well as weights of parameter groupings. This in turn will be useful later when the WQI will be developed. Therefore, the second AHP model will be used in the further steps to be undertaken in the future for the development of a WQI for West Java.

6. Summary and conclusions

This paper presented one of the most important steps in the development of a WQI, which is that of establishing the weights of the water quality parameters. In this study, through reviewing and comparing with other weighting methods, the Analytic Hierarchy Process (AHP) was identified to be a suitable tool to establish the weights of water quality parameters. Therefore, the application of AHP to estimate the parameter weights is an important step in the future work of developing a WQI for rivers in West Java, Indonesia. The AHP was employed based on the thirteen selected parameters from within seven water quality groupings for the rivers in West Java. Thus, there were 13 (individual form) and 7 (grouping form) pairwise comparison questionnaires to be undertaken.

In this study, two different AHPs models were developed. The first AHP model was based on 13 individual parameters and it involved one level of hierarchy to describe the goal of this study. On the other hand, the second AHP model used 7 grouping of parameters in structuring its hierarchy and it comprised of two levels of hierarchy in order to obtain the weights. A pool of respondents from West Java Province with different backgrounds (grouped into government officials, academics, researchers and consultants) were surveyed to give their judgements. Only those respondents whose judgements were consistent were used for the further analysis to obtain the weights. The weights from group judgement responses was then calculated based on the aggregating individual priorities. Furthermore, the weights of different groups of respondents were also assessed to analyse if any group was dominating the stakeholders' opinions. However, only the overall weights of both AHP models, calculated based on the group of all respondents were compared to seek the better of the two AHPs.

In the first AHP model, both chemical oxygen demand and dissolved oxygen, consistently received relatively high weights for all respondent groupings, compared to other water quality parameters. While in the second AHP model, different groups of respondents assigned high weights to oxygen depletion and microbiology. In addition, the overall weights of the two AHP models revealed that both models received relatively high weights for COD, DO and FC. However, of the two AHP models, considering the consistency and the reliability of respondents' judgement, the second AHP model was better than that of the first AHP model. Therefore the results of the second AHP model will be used in the future for the remaining steps of this study, which is that of aggregation of sub-indices to obtain the final WQI index value.

Acknowledgments

The authors would like to acknowledge and thank the Australia Awards, which funded the first author for this study.

Appendix A.

See Table A1–A3

References

Štambuk-Giljanović, N., 1999. Water quality evaluation by index in Dalmatia. Water Res. 33, 3423–3440.
Abbasi, T., Abbasi, S.A., 2012. Water Quality Indices. Elsevier, Amsterdam.
Abdollahzadeh, G., Damalas, C.A., Sharifzadeh, M.S., Ahmadi-Gorgi, H., 2016. Selecting strategies for rice stem borer management using the Analytic Hierarchy Process (AHP). Crop Prot. 84, 27–36, http://dx.doi.org/10.1016/j.cropro.2016.02.004.
Abtahi, M., Golchinpour, N., Yaghmaeian, K., Rafiee, M., Jahangiri-rad, M., Keyani, A., Saeedi, R., 2015. A modified drinking water quality index (DWQI) for assessing drinking source water quality in rural communities of Khuzestan Province, Iran. Ecol. Indic. 53, 283–291, http://dx.doi.org/10.1016/j.ecolind.2015.02.009.
Al-Barqawi, H., Zayed, T., 2006. Assessment model of water main conditions. Pipelines 2006, 1–8, http://dx.doi.org/10.1061/40854(211)27.
Almeida, C., González, S., Mallea, M., González, P., 2012. A recreational water quality index using chemical, physical and microbiological parameters. Environ. Sci. Pollut. Res. 19, 3400–3411, http://dx.doi.org/10.1007/s11356-012-0865-5.
Böhringer, C., Jochem, P.E.P., 2007. Measuring the immeasurable—a survey of sustainability indices. Ecol. Econ. 63, 1–8, http://dx.doi.org/10.1016/j.ecolecon.2007.03.008.
BPS, 2016. Kepadatan Penduduk menurut Provinsi 2000–2014. Badan Pusat Statistik Indonesia (Central Bureau of Statistics Indonesia), https://www.bps.go.id/linkTableDinamis/view/id/842 (Accesed 20.10.2016).
Basak, I., Saaty, T., 1993. Group decision making using the analytic hierarchy process. Math. Comput. Modell. 17, 101–109, http://dx.doi.org/10.1016/0895-7177(93)90179-3.
Bitarafan, M., Hosseini, S.B., Abazarlou, S., Mahmoudzadeh, A., 2015. Selecting the optimal composition of architectural forms from the perspective of civil

Table A1
Analysis of variances for each parameter (F-test) comparing the first and the second AHP models.

WQ parameters	Temp	SS	COD	DO	NO2	TP	Deter	Phen	Cl	Zn	Pb	Hg	FC
F-value	2.439	1.836	1.818	1.375	1.956	1.554	1.493	1.802	9.813	3.619	2.393	0.811	2.138
p-value	0.107	0.268	0.276	0.559	0.222	0.419	0.463	0.282	**0.000**	**0.022**	0.114	0.700	0.167

Bold *p*-values are significant at 0.05.

Table A2
Weights of different groups of respondents and their consistency ratios for the first AHP model.

Individual Parameters	Government officials					Academics					Researchers					Consultants				
	G1	G2	G3	G4	G5	A6	A7	A8	A9	A10	R11	R12	R13	R14	R15	C16	C17	C18	C19	C20
Temp	0.053	0.018	0.014	0.015	0.010	0.024	0.012	0.009	0.012	0.187	0.027	0.078	0.152	0.210	0.018	0.130	0.007	0.020	0.017	0.034
SS	0.076	0.152	0.018	0.041	0.019	0.020	0.079	0.021	0.032	0.137	0.032	0.046	0.152	0.106	0.031	0.130	0.045	0.027	0.066	0.166
COD	0.054	0.152	0.067	0.141	0.175	0.114	0.111	0.097	0.029	0.137	0.072	0.189	0.163	0.149	0.139	0.130	0.114	0.134	0.171	0.102
DO	0.051	0.152	0.062	0.141	0.173	0.149	0.145	0.118	0.046	0.137	0.039	0.046	0.171	0.149	0.139	0.130	0.097	0.145	0.171	0.102
NO2	0.073	0.066	0.034	0.077	0.091	0.031	0.029	0.025	0.040	0.041	0.043	0.098	0.078	0.044	0.066	0.053	0.059	0.050	0.066	0.040
TP	0.072	0.066	0.033	0.061	0.038	0.031	0.029	0.022	0.039	0.041	0.056	0.098	0.053	0.044	0.052	0.053	0.043	0.042	0.045	0.040
Deter	0.037	0.064	0.030	0.031	0.039	0.031	0.045	0.025	0.033	0.041	0.072	0.189	0.044	0.042	0.065	0.053	0.023	0.027	0.060	0.046
Phen	0.086	0.064	0.028	0.025	0.032	0.032	0.046	0.023	0.043	0.041	0.081	0.163	0.028	0.042	0.081	0.053	0.034	0.033	0.029	0.054
Cl	0.068	0.028	0.070	0.063	0.053	0.033	0.045	0.026	0.053	0.031	0.083	0.021	0.059	0.042	0.027	0.040	0.093	0.027	0.027	0.059
Zn	0.090	0.028	0.068	0.035	0.096	0.078	0.099	0.169	0.105	0.023	0.097	0.021	0.025	0.042	0.100	0.026	0.045	0.028	0.027	0.064
Pb	0.096	0.028	0.149	0.146	0.096	0.109	0.099	0.169	0.200	0.023	0.109	0.021	0.025	0.042	0.102	0.026	0.110	0.195	0.072	0.123
Hg	0.147	0.028	0.159	0.146	0.078	0.172	0.099	0.253	0.223	0.023	0.137	0.021	0.025	0.042	0.114	0.026	0.149	0.186	0.072	0.087
FC	0.096	0.152	0.269	0.078	0.100	0.176	0.162	0.045	0.145	0.137	0.152	0.011	0.025	0.042	0.067	0.151	0.182	0.084	0.178	0.082
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Consistency ratio	0.09	0.02	0.09	0.08	**0.13**	0.06	0.06	0.08	0.08	0.06	**0.13**	0.06	0.07	0.01	**0.22**	0.02	**0.32**	0.08	0.03	**0.24**

Consistency ratio values greater than 0.10 are inconsistent and are in bold.

Table A3
Weights of different groups of respondents and their consistency ratios for the second AHP model.

Groupings of Parameters	Government officials					Academics					Researchers					Consultants				
	G1	G2	G3	G4	G5	A6	A7	A8	A9	A10	R11	R12	R13	R14	R15	C16	C17	C18	C19	C20
Physical	0.029	0.182	0.035	0.046	0.045	0.076	0.046	0.038	0.046	0.224	0.029	0.109	0.057	0.143	0.032	0.173	0.037	0.046	0.032	0.140
Oxygen depletion	0.145	0.290	0.131	0.190	0.275	0.260	0.176	0.178	0.071	0.199	0.047	0.109	0.190	0.143	0.202	0.173	0.238	0.185	0.289	0.298
Nutrients	0.078	0.112	0.082	0.105	0.109	0.126	0.056	0.056	0.053	0.117	0.071	0.232	0.172	0.143	0.154	0.173	0.078	0.104	0.116	0.112
Organics	0.089	0.095	0.082	0.186	0.244	0.100	0.242	0.178	0.092	0.093	0.093	0.428	0.154	0.143	0.126	0.188	0.072	0.164	0.116	0.112
Ions and minerals	0.125	0.040	0.052	0.046	0.062	0.155	0.036	0.040	0.202	0.063	0.133	0.048	0.065	0.143	0.120	0.053	0.108	0.051	0.043	0.112
Heavy metals	0.386	0.040	0.219	0.260	0.194	0.142	0.151	0.481	0.243	0.094	0.235	0.048	0.172	0.143	0.200	0.053	0.217	0.366	0.116	0.112
Microbiology	0.148	0.240	0.399	0.166	0.071	0.142	0.293	0.030	0.294	0.210	0.392	0.025	0.190	0.143	0.167	0.188	0.250	0.085	0.289	0.112
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Consistency ratio	0.09	0.03	0.08	0.04	**0.11**	0.07	0.08	0.07	0.08	0.09	**0.22**	0.04	0.03	0.00	**0.11**	0.00	**0.20**	0.06	0.02	0.02

Consistency ratio values greater than 0.10 are inconsistent and are in bold.

defense using AHP and IHWP methods. Archit. Eng. Des. Manag. 11, 137–148, http://dx.doi.org/10.1080/17452007.2013.802982.

Bodin, L., Gass, S.I., 2004. Exercises for teaching the analytic hierarchy process. INFORMS Transactions on Education 4, 1–13, http://dx.doi.org/10.1287/ited.4.2.1.

Brown, R.M., Mc Clelland, N.I., Deininger, R.A., Tozer, R.G., 1970. A water quality index-Do we dare? Water Sewage Works 117, 339–343.

CCME, 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. Canadian Council of Ministers of the Environment Winnipeg, http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf (Accessed 20.01.2015).

Cabrera-Barona, P., Murphy, T., Kienberger, S., Blaschke, T., 2015. A multi-criteria spatial deprivation index to support health inequality analyses. Int. J. Health Geogr. 14, 1–14, http://dx.doi.org/10.1186/s12942-015-0004-x.

Chakraborty, S., Kumar, R.N., 2016. Assessment of groundwater quality at a MSW landfill site using standard and AHP based water quality index: a case study from Ranchi, Jharkhand, India. Environ. Monit. Assess. 188, 1–18, http://dx.doi.org/10.1007/s10661-016-5336-x.

Chunsoon, K., 2014. A study on compilation and improvement of indices for legislative budgetary institutions — with focus on comparative analysis of current institutions in 60 countries. OECD J. Budg. 14, 9–37, http://dx.doi.org/10.1787/budget-14-5jrw6591frbw.

Cude, C., Dunnette, D., Avent, C., Frankin, A., Gross, G., Hartman, J., Hayteas, D., Jenkins, T., Leben, K., Lyngdal, J., Marks, D., Morganti, C., Quin, T., 1997. Exploring possibilities for an international water quality index applied to river system. In: Best, G., Bogacka, T., Niemirycz, E. (Eds.), International River Water Quality: Pollution and Restoration. E & FN, Spoon, London.

Debels, P., Figueroa, R., Urrutia, R., Barra, R., Niell, X., 2005. Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified Water Quality Index. Environ. Monit. Assess. 110, 301–322, http://dx.doi.org/10.1007/s10661-005-8064-1.

Dong, Y., Zhang, G., Hong, W.-C., Xu, Y., 2010. Consensus models for AHP group decision making under row geometric mean prioritization method. Decis. Support Syst. 49, 281–289, http://dx.doi.org/10.1016/j.dss.2010.03.003.

Dorado, R., Gómez-Moreno, A., Torres-Jiménez, E., López-Alba, E., 2011. An AHP application to select software for engineering education. Comput. Appl. Eng. Educ., http://dx.doi.org/10.1002/cae.20546.

Dunnette, D.A., 1979. A geographically variable water quality index used in oregon. J. (Water Pollution Control Federation) 51, 53–61, http://dx.doi.org/10.2307/25040240.

Esty, D.C., Levy, M., Srebotnjak, T., Sherbinin, A.d., 2005. Environmental Sustainability Index: Benchmarking National Environmental Stewardship. Yale Center for Environmental Law & Policy, New Haven.

Fetscherin, M., Stephano, R.-M., 2016. The medical tourism index: scale development and validation. Tourism Manag. 52, 539–556, http://dx.doi.org/10.1016/j.tourman.2015.08.010.

Figueira, J., Roy, B., 2002. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. Eur. J. Oper. Res. 139, 317–326, http://dx.doi.org/10.1016/S0377-2217(01)00370-8.

Forman, E.H., Gass, S.I., 2001. The analytic hierarchy process—an exposition. Oper. Res. 49, 469–486, http://dx.doi.org/10.1287/opre.49.4.469.11231.

Forman, E., Peniwati, K., 1998. Aggregating individual judgments and priorities with the analytic hierarchy process. Eur. J. Oper. Res. 108, 165–169, http://dx.doi.org/10.1016/S0377-2217(97)00244-0.

Franklin, K.K., Hart, J.K., 2007. Idea generation and exploration: benefits and limitations of the policy delphi research method. Innov. Higher Educ. 31, 237–246, http://dx.doi.org/10.1007/s10755-006-9022-8.

Gorane, S., Kant, R., 2016. A case study for predicting the success possibility of supply chain practices implementation using AHP approach. J. Bus. Ind. Mark. 31, 137–151, http://dx.doi.org/10.1108/JBIM-05-2014-0098.

Gupta, H., 2015. Selection of best hospital for surgery using AHP. IUP J. Oper. Manag. 14, 18.

Han, S., 2016. How can we handle too many criteria/alternatives?: A study on AHP structural design. NUCB J. Econ. Inf. Sci. 60, 103–112.

Harker, P.T., Vargas, L.G., 1987. The theory of ratio scale estimation: Saaty's analytic hierarchy process. Manag. Sci. 33, 1383–1403, http://dx.doi.org/10.1287/mnsc.33.11.1383.

Hartwich, F., 1999. Weighing of Agricultural Research Results: Strength and Limitations of the Analytical Hierarchy Process (AHP). Universitat Hohenheim.

Hassan, M.F., Saman, M.Z.M., Sharif, S., Omar, B., 2012. An integrated MA-AHP approach for selecting the highest sustainability index of a new product. Proc.—Soc. Behav. Sci. 57, 236–242, http://dx.doi.org/10.1016/j.sbspro.2012.09.1180.

House, M.A., 1989. A water quality index for river management. Water Environ. J. 3, 336–344, http://dx.doi.org/10.1111/j.1747-6593.1989.tb01538.x.

Hutcheson, G.D., Sofroniou, N., 1999. The Multivariate Social Scientist: Introductory Statistics Using Generalized Linear Models. SAGE, Thousand Oaks, CA.

Inamdar, P.M., 2014. Selection and Evaluation of Potential Stormwater Harvesting Sites in Urban Areas. Victoria University.

Ishizaka, A., Labib, A., 2009. Analytic hierarchy process and expert choice: benefits and limitations. ORI 22, 201–220, http://dx.doi.org/10.1057/ori.2009.10.

Ishizaka, A., Balkenborg, D., Kaplan, T., 2011. Influence of aggregation and measurement scale on ranking a compromise alternative in AHP. J. Oper. Res. Soc. 62, 700–710, http://dx.doi.org/10.1057/jors.2010.23.

Ishizaka, A., Siraj, S., Nemery, P., 2016. Which energy mix for the UK (United Kingdom)? an evolutive descriptive mapping with the integrated GAIA (graphical analysis for interactive aid)-AHP (analytic hierarchy process) visualization tool. Energy 95, 602–611, http://dx.doi.org/10.1016/j.energy.2015.12.009.

Jennings, S., Pascoe, S., Hall-Aspland, S., Le Bouhellec, B., Norman-Lopez, A., Sullivan, A., Pecl, G., 2016. Setting objectives for evaluating management adaptation actions to address climate change impacts in south-eastern Australian fisheries. Fish. Oceanogr. 25, 29–44, http://dx.doi.org/10.1111/fog.12137.

Juwana, I., Perera, B.J.C., Muttil, N., 2010. A water sustainability index for West Java—part 2: refining the conceptual framework using Delphi technique. Water Sci. Technol. 62, 1641–1652, http://dx.doi.org/10.2166/wst.2010.453.

Juwana, I., Muttil, N., Perera, B.J.C., 2016a. Application of west java water sustainability index to three water catchments in west java, Indonesia. Ecol. Indic. 70, 401–408, http://dx.doi.org/10.1016/j.ecolind.2016.06.017.

Juwana, I., Muttil, N., Perera, B.J.C., 2016b. Uncertainty and sensitivity analysis of west java water sustainability index—a case study on citarum catchment in Indonesia. Ecol. Indic. Part 1 61, 170–178, http://dx.doi.org/10.1016/j.ecolind.2015.08.034.

Kamil, K.H., Ismail, A.G., Shahida, S., 2014. Deriving priorities on the economic objectives and social objectives of islamic banking: the analytic hierarchy process (AHP) approach. Res. J. Appl. Sci. 9, 952–961, http://dx.doi.org/10.3923/rjasci.2014.952.961.

Kang, H., Xuxiang, L., Jingjing, W., Jing, Z., 2016. Evaluating ecological vulnerability using the GIS and analytic hierarchy process (AHP) method in Yan'an, China. Polish J. Environ. Stud. 25, 599–605, http://dx.doi.org/10.15244/pjoes/61312.

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., Chebana, F., 2010. A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. J. Hydrol. 386, 173–185, http://dx.doi.org/10.1016/j.jhydrol.2010.03.019.

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., Zanacic, E., 2014. Statistical assessment of the surface water quality monitoring network in saskatchewan. Water, Air, Soil Pollut. 225, http://dx.doi.org/10.1007/s11270-014-2128-1.

Khamkanya, T., Heaney, G., McGreal, S., 2012. Introduction of AHP satisfaction index for workplace environments. J. Corp. Real Estate 14, 80–93, http://dx.doi.org/10.1108/14630011211261687.

Koyun, S., Ozkir, V.C., 2014. Constructing highly consistent pairwise comparison matrices in analytic hierarchy process (AHP). Int. J. Anal. Hierarchy Process.

Kuruoglu, E., Guldal, D., Mevsim, V., Gunvar, T., 2015. Which family physician should I choose? the analytic hierarchy process approach for ranking of criteria in the selection of a family physician. BMC Med. Inf. Decis. Making 15, 1–8, http://dx.doi.org/10.1186/s12911-015-0183-1.

Lewis, G.W., Kit Fai, P., Terrence, R.M.L., 2006. Empirical investigation of the hard and soft criteria of TQM in ISO 9001 certified small and medium-sized enterprises. Int. J. Qual. Reliab. Manag. 23, 964–985, http://dx.doi.org/10.1108/02656710610688167.

Li, X., Zhang, Q., 2015. AHP-based resources and environment efficiency evaluation index system construction about the west side of Taiwan Straits. Ann. Oper. Res. 228, 97–111, http://dx.doi.org/10.1007/s10479-012-1072-y.

Lootsma, F.A., 1989. Conflict resolution via pairwise comparison of concessions. Eur. J. Oper. Res. 40, 109–116, http://dx.doi.org/10.1016/0377-2217(89)90278-6.

MoE, 2003. Keputusan Menteri Negara Lingkungan Hidup Nomor: 115 Tahun 2003 Tentang Pedoman Penentuan Status Mutu Air (Ministrial's Decree No. 115 on Technical guidance for water class determination), in: MoE (Ed.), Jakarta.

Mohd Ali, Z., Ibrahim, N.A., Mengersen, K., Shitan, M., Juahir, H., 2013. The Langat River water quality index based on principal component analysis. AIP Conf. Proc. 1522, 1322–1336, http://dx.doi.org/10.1063/1.4801283.

Mohd Ali, Z., Ibrahim, N.A., Mengersen, K., Shitan, M., Juahir, H., 2014. Robust principal component analysis in water quality index development. AIP Conf. Proc. 1602, 1091–1097, http://dx.doi.org/10.1063/1.4882620.

Mulder, N.G.K., 2011. Validating the Analytic Hierarchy Process for Eliciting Colorectal Cancer Screening Preferences in an Online Questionnaire, Faculty Management and Governance Health Technology and Services Research. University of Twente, http://essay.utwente.nl/63063/ (Accessed 25.02.2016).

Nasiri, H., Boloorani, A.D., Sabokbar, H.A.F., Jafari, H.R., Hamzeh, M., Rafii, Y., 2013. Determining the most suitable areas for artificial groundwater recharge via an integrated PROMETHEE II-AHP method in GIS environment (case study: Garabaygan Basin, Iran). Environ. Monit. Assess. 185, 707–718, http://dx.doi.org/10.1007/s10661-012-2586-0.

OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD, France.

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M., 2006. Assessing water quality in rivers with fuzzy inference systems: a case study. Environ. Int. 32, 733–742, http://dx.doi.org/10.1016/j.envint.2006.03.009.

Oddershede, A., Arias, A., Cancino, H., 2007. Rural development decision support using the Analytic Hierarchy Process. Math. Comput. Modell. 46, 1107–1114, http://dx.doi.org/10.1016/j.mcm.2007.03.006.

Ouarda, T.B.M.J., Rasmussen, P.F., Bobée, B., Morin, J., 1996. Ontario Hydrometric Network Rationalization, Statistical Considerations. Research Report No. R-470. National Institute for Scientific Research, INRS-ETE, University of Quebec, Quebec, Canada.

Panda, S., Chakraborty, M., Misra, S.K., 2016. Assessment of social sustainable development in urban India by a composite index. Int. J. Sustain. Built Environ. 5, 435–450, http://dx.doi.org/10.1016/j.ijsbe.2016.08.001.

Qureshi, M.E., Harrison, S.R., 2003. Application of the analytic hierarchy process to riparian revegetation policy options. Small-scale Forest Econ. Manag. Policy 2, 441–458, http://dx.doi.org/10.1007/s11842-003-0030-6.
Raharjo, H., Endah, D., 2006. Evaluating relationship of consistency ratio and number of alternatives on rank reversal in the AHP. Qual. Eng. 18, 39–46, http://dx.doi.org/10.1080/08982110500403516.
SRDD, 1976. Development of a Water Quality Index. Scottish Research Development Department, Edinburg, UK, pp. 61.
Saaty, T.L., 1980. The Analytic Hierarchy Process McGraw Hill. RWS Publications International, New York, Pittsburgh.
Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. Math. Modell. 9, 161–176, http://dx.doi.org/10.1016/0270-0255(87)90473-8.
Saaty, T.L., 1989. Group decision making and the AHP. In: Golden, B.L., Wasil, E.A., Harker, P.T. (Eds.), The Analytic Hierarchy Process: Applications and Studies. Springer, Berlin Heidelberg, pp. 59–67, http://dx.doi.org/10.1007/978-3-642-50244-6_4.
Saaty T.L., 2001. The Seven Pillars of the Analytic Hierarchy Process, in: Köksalan, M., Zionts, S. (Eds.), Multiple Criteria Decision Making in the New Millennium: Proceedings of the Fifteenth International Conference on Multiple Criteria Decision Making (MCDM) Ankara, Turkey,J uly 10–14, 2000. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 15–37. 10.1007/978-3-642-56680-6_2.
Sahni, M., Das, S.K., 2015. A method of risk analysis and threat management using analytic hierarchy process: an application to air defence. J. Battlefield Technol. 18, 27.
Sargaonkar, A.P., Gupta, A., Devotta, S., 2008. Dynamic weighting system for water quality index. Water Sci. Technol. 58, 1261–1271, http://dx.doi.org/10.2166/wst.2008.468.
Semiromi, F.B., Hassani, A.H., Torabian, A., Karbassi, A.R., Lotfi, F.H., 2011. Evolution of a new surface water quality index for Karoon catchment in Iran. Water Sci. Technol. 64, 2483–2491, http://dx.doi.org/10.2166/wst.2011.780.
Shabbir, R., Ahmad, S.S., 2015. Water resource vulnerability assessment in Rawalpindi and Islamabad, Pakistan using Analytic Hierarchy Process (AHP). J. King Saud Univ.—Sci., http://dx.doi.org/10.1016/j.jksus.2015.09.007.
Shen, L., Muduli, K., Barve, A., 2015. Developing a sustainable development framework in the context of mining industries: AHP approach. Resour. Policy Part 1 46, 15–26, http://dx.doi.org/10.1016/j.resourpol.2013.10.006.
Shuhaimi-Othman, M., Lim, E., Mushrifah, I., 2007. Water Quality Changes in Chini Lake, Pahang, West Malaysia. Environ. Monit. Assess. 131, 279–292, http://dx.doi.org/10.1007/s10661-006-9475-3.
Singh, R.P., Nachtnebel, H.P., 2016. Analytical hierarchy process (AHP) application for reinforcement of hydropower strategy in Nepal. Renew. Sustain. Energy Rev. 55, 43–58, http://dx.doi.org/10.1016/j.rser.2015.10.138.
Smith, D.G., 1990. A better water quality indexing system for rivers and streams. Water Res. 24, 1237–1244, http://dx.doi.org/10.1016/0043-1354(90)90047-A.
Sun, H., 2015. Sports food safety supervision based on AHP and interval fuzzy TOPSIS. Open Cybern. Syst. J. 9, 1905–1910.
Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016a. Development of river water quality indices—a review. Environ. Monit. Assess. 188, 58, http://dx.doi.org/10.1007/s10661-015-5050-0.
Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016b. Parameter selection for cost effective water quality Monitoring—Part 1: developing the methodology. J. Hydrol. (Under review, Unpublished results).
Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016c. Parameter selection for cost effective water quality monitoring—part II: application to monitoring network in west java, Indonesia. J. Hydrol. (Under review, Unpublished results).
Tallar, R.Y., Suen, J.-P., 2016. Aquaculture water quality index: a low-cost index to accelerate aquaculture development in Indonesia. Aquac. Int. 24, 295–312, http://dx.doi.org/10.1007/s10499-015-9926-3.
Tongqian, Z.O.U., Fang, M., Hengyun, L.I., Pei, Z., Yaqing, R.E.N., 2016. Research note: assessment index of international tourism hubs. Tourism Econ. 22, 324–330, http://dx.doi.org/10.5367/te.2016.0552.
WJEPA, 2013. Status Lingkungan Hidup Provinsi Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia.
WJEPA, 2014. Status Lingkungan Hidup Daerah Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia.
Walsh, P., Wheeler, W., 2012. Water Quality Index Aggregation and Cost Benefit Analysis Working Papers #12-05. United States Environmental Protection Agency, Washington DC.
Wang, X., Li, X., Zhen, F., Zhang, J., 2016. How smart is your tourist attraction?: Measuring tourist preferences of smart tourism attractions via a FCEM-AHP and IPA approach. Tourism Manag. 54, 309–320, http://dx.doi.org/10.1016/j.tourman.2015.12.003.
Warren, L., 2004. Uncertainties in the analytic hierarchy process. In: C.a.C.D.I.S (Ed.), Laboratory. DSTO Information Sciences Laboratory, Edinburgh South Australia, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.86.6240&rep=rep1&type=pdf (Accessed 20.05.2016).
Yan, F., Liu, L., Li, Y., Zhang, Y., Chen, M., Xing, X., 2015. A dynamic water quality index model based on functional data analysis. Ecol. Indic. 57, 249–258, http://dx.doi.org/10.1016/j.ecolind.2015.05.005.
Zardari, N.H., Ahmed, K., Shirazi, S.M., Yusop, Z.B., 2015. Weighting Methods and Their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management. Springer International Publishing.
Zhang, Z., lxinbao, X.L., Yang, S., 2009. A note on the 1–9 scale and index scale In AHP. In: yshi, Y.S., sywang, S.W., pengyi, Y.P., ljp, J.L., Zeng, Y. (Eds.), Cutting-Edge Research Topics on Multiple Criteria Decision Making., http://dx.doi.org/10.1007/978-3-642-02298-2_92.

Chapter 5
Applying the West Java Water Quality Index to the Main Rivers in West Java

5.1. Introduction

This chapter presents the development and application of the West Java Water Quality Index (WJWQI) to the main rivers in West Java Province, Indonesia. This included the following four steps:

1) Selection of parameters
2) Obtaining sub-index values (transformation to a common scale)
3) Establishing weights
4) Aggregation of sub-indices to obtain the final index.

As outlined in Section 1.2 of Chapter 1, this study aimed to develop a methodology for selection of parameters for the WJWQI in a cost effective manner. The selection of parameters for the case study area was presented in Chapter 3. The outcome of this first step of parameter selection was the identification of 13 parameters, which were then used for the three remaining steps in the development of WJWQI. In this chapter, the sub-index values of 100 – 5 were obtained from the sub-index functions based on the permissible limits (thresholds) from the legislated water quality standards. This facilitated sub-division of sub-index values and provided more information to the users for management of river quality. Subsequently, as demonstrated in Chapter 4, the 13 parameters were then used to establish the weights of the water quality parameters. These parameter weights were then used for aggregation of sub-indices to produce the final index and to undertake uncertainty and sensitivity analysis of WJWQI. Finally, based on the advantages and disadvantages of the available aggregation methods (which were discussed in Chapter 2), the weighted geometric method was used in this chapter to produce the final index value.

These four steps presented above, particularly that of the selection of parameters in a cost effective manner and the inclusion of local experts' opinion for identifying parameter weights will increase the credibility and acceptability of WJWQI to be used by related authorities and users of WJWQI. Thus, this proposed index can be a more reliable alternative to the currently used WQIs in West Java.

The application of WJWQI in this chapter using monitoring data taken between 2001 and 2011 was used to evaluate the general status of water quality spatially and temporally at monitoring networks of the study area. The application of WJWQI presented in this chapter provided a more accurate and valid comparison between stations and rives as the same parameters were employed to compute the final index values. Moreover, in this chapter, the uncertainty and sensitivity of two sources were undertaken, which were that from the thresholds and weights of the WJWQI parameters. This was undertaken in this study using the 10,000 Monte Carlo (MC) simulations. These sources of uncertainties have not been investigated and discussed yet in available WQIs studies. Therefore, the quantification of the uncertainty and sensitivity in both these sources using the MC simulations provided new insights into the development of a WQI.

This chapter contains the following journal paper, which presents the development of WJWQI based on the four aforementioned steps, its application, and the uncertainty and sensitivity analysis of WJWQI using the MC simulations:

1. Sutadian, A. D., Muttil, N., Yilmaz, A. G., & Perera, B. J. C. (2017). Development of a Water Quality Index for rivers in West Java Province, Indonesia. Submitted to Ecological Indicators.

.

5.2

GRADUATE RESEARCH CENTRE

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS BY PUBLICATION

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Development of a water quality index for rivers in West Java Province, Indonesia

Surname: Sutadian First name: Arief Dhany

College: College of Engineering & Science Candidate's Contribution (%): 85

Status:

Accepted and in press: ☐ Date:

Published: ☐ Date:

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted]	30/03/2017
Signature	Date

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. There are no other authors of the publication according to these criteria;
4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

R Drive

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Arief Dhany Sutadian	85	Research, Analysis, Writing	[redacted]	30/03/2017
Nitin Muttil	5	Feedback and discussion on the research and writing		30/03/2017
Abdullah Gokhan Yilmaz	5	Feedback and discussion on the research and writing		30/03/2017
Chris Perera	5	Feedback and discussion on the research and writing		31/03/2017

Updated: June 2015

Development of a water quality index for rivers in West Java Province, Indonesia by *A.D. Sutadian, N. Mutiil, A.G. Yilmaz and B.J.C. Perera* was published in the peer review journal, *Ecological Indicators, 85, 966-982, 2018.*

The published version is available from the publisher at:
https://doi.org/10.1016/j.ecolind.2017.11.049

5.3 Development of a Water Quality Index for rivers in West Java Province, Indonesia

Arief Dhany Sutadian[1, 2 *], Nitin Muttil[1, 3], Abdullah Gokhan Yilmaz[4], B.J.C. Perera[1, 3]
[1]College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
[2]The West Java Environmental Management Agency, Indonesia, Jl. Naripan No. 25 Bandung, 40111, Indonesia
[3]Institute for Sustainability and Innovation, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
[4]University of Sharjah, Sharjah, College of Engineering, PO Box 27272, United Arab Emirates

(*author for correspondence, e-mail: arief.sutadian@live.vu.edu.au)

Abstract

The West Java Water Quality Index (WJWQI) described in this paper was specifically developed to replace the currently used indices in West Java, Indonesia. The WJWQI addressed the limitations of the currently used indices, namely their inability to make accurate comparison of the general status of water quality between the rivers in West Java, inability to make these comparisons in a cost effective manner, and the lack of credibility and acceptability of the currently used indices by relevant authorities in West Java (since the local conditions and local expert opinion have not been considered in the development of the currently used indices). Addressing these limitations increases the credibility and acceptability of WJWQI to be used by the relevant authorities and the users of WJWQI in West Java. This index was developed using four basic steps, which are selection of parameters, obtaining sub-index values (transformation to a common scale), establishing weights, and aggregation of sub-indices to produce the final index. The methodology for parameter selection used in the development of WJWQI, which considered cost effective monitoring of water quality parameters in West Java rivers and the inclusion of local experts' opinion in establishing the parameter weights will increase the credibility and acceptability of WJWQI among the relevant authorities and the users of WJWQI. The application of WJWQI for the West Java Province was demonstrated using monitoring data taken between 2001 and 2011, to evaluate the general status of water quality spatially and temporally. The results of the application show that most monitoring stations had marginal water quality, indicating that rivers in the West Java Province have been experiencing water quality deterioration significantly.

Moreover, an uncertainty and sensitivity analysis was undertaken through Monte Carlo simulation to determine the robustness of WJWQI, which proved to be robust.

Keywords: West Java WQI, Monitoring, West java province, Application, Robustness analysis

1. Introduction

Having good water quality is important for a healthy river, as it affects the humans, animals and plants that utilise the water. However, it is difficult to quantify the state of river water quality due to the large choice of possible water quality parameters used to describe it. On the other hand, insufficient funding, particularly in developing countries, is one of the most common constraints towards monitoring all water quality parameters of a river as it is laborious and expensive. Thus, Water Quality Indices (WQIs) have been used in the past as one of the most commonly used approaches to evaluate water quality of a water body (Abbasi and Abbasi, 2012; Soliman and Ward, 1994). A WQI is a single dimensionless number expressing the status of water quality of a water body (e.g. river) and is obtained by aggregating the measurement values of the selected water quality parameters.

WQIs have been proposed as early as in 1965, to define the state of river water quality (Horton, 1965). Since then, this approach has been one of the most effective ways to communicate information on water quality (Walsh and Wheeler, 2012). Even though the WQI cannot evaluate the quality of water for all types of uses and all hazards, and nor can it provide complete information on water quality (Cude et al., 1997), it can be a useful tool with the following benefits:

- It is able to express the general state of water quality spatially and temporally; therefore, it can be used to assess water quality improvement programs (Cude et al., 1997).
- It can be used to compare water quality of different water sources and sites, without undertaking highly technical assessment of water quality data. Thus, this approach can be used for reporting the general status of water quality to policy makers and the public in a simple and understandable manner (CCME, 2001; Sarkar and Abbasi, 2006).
- It can be used as a tool for decision making and operational management by water authorities (Gitau et al., 2016; House, 1989; Ocampo-Duque et al., 2006).

Several WQIs have been developed in the past by different agencies and researchers with the aim to establish their own indices or to improve the existing indices (Gitau et al., 2016). However, as highlighted by Lumb et al. (2011), no single WQI has been globally accepted. In West Java and other provinces in Indonesia, the use of WQIs was introduced in early 1990s. The Ministry of

Environment (MoE) in Indonesia has adopted and used with limited success two indices, namely the Storet Index and the Water Pollution Index (WPI) (MoE, 2003). However, both these indices had been developed based on the information on other specific regions and areas and without considering the local conditions of West Java. These include use of parameters in the index which do not suit West Java conditions and parameter weights that do not consider opinion of stakeholders in West Java. Therefore, at a particular monitoring station, many parameters have been monitored, which has led to increased monitoring cost in the field and increased cost in the use of the WQI. Moreover, since the parameters monitored at different stations are different, a comparison of WQI values between stations and river basins is not valid. Therefore, there is a need for a new WQI that is specifically developed to address the above limitations of the currently used indices in West Java, namely to provide a more accurate comparison of the general status of water quality among rivers in West Java and also to undertake these comparisons in a more cost effective manner.

This paper aims to develop a new WQI (which is referred to as the West Java Water Quality Index (WJWQI) in this paper) for use in rivers across West Java, Indonesia by addressing the limitations of the currently used indices, and also by considering water quality monitoring in a more cost effective manner. The statistical assessment developed by Ouarda et al. (1996) for hydrometric network rationalization and later adopted by Khalil et al. (2014; 2010) for parameter redundancy was enhanced in this study to select water quality parameters for WJWQI (Sutadian et al., 2017a, b). This enhanced statistical assessment which included three critical factors (based on the cost of laboratory analysis of parameters, and the magnitude and frequency of the parameters exceeding their permissible limits), reduced the number of water quality parameters to be measured. This in turn reduced the cost of monitoring and the cost of using WJWQI. Next, the local experts in West Java were consulted to identify parameter weights of the selected parameters. These two steps increase the credibility of WJWQI to be used as a tool to communicate the general status of water quality to scientists, decision-makers, and the general public, and to design appropriate programs to improve water quality of rivers throughout the province. This paper also presents the application of WJWQI to several main rivers in West Java using water quality data from the West Java Environmental Protection Agency's (WJEPA) network. The results of this application can provide basis for recommendations to the relevant authorities to improve the management of water quality in those rivers. Furthermore, this paper discusses the uncertainty and sensitivity analysis undertaken in the development and application of WJWQI, which uses the Monte Carlo (MC) simulation approach. This uncertainty and sensitivity analysis was used to assess the robustness of WJWQI, which further increases the credibility of WJWQI.

The structure of this paper is as follows. Firstly, the study area and the data used are presented in Section 2. The development of WJWQI is then presented in Section 3. This is followed by a discussion of the application of WJWQI in the study area presented in Section 4. Section 5 presents the uncertainty and sensitivity analysis of the WJWQI. Finally, a summary and conclusions drawn from this study are presented in Section 6.

2. Study area

The West Java Province is situated in the western part of Java Island, Indonesia. It occupies an area of 37,095 km^2, which can be divided into 26 cities or regencies. It has population of 46.71 million inhabitants, and it is the second most densely populated province in the country (BPS, 2015). As shown in Figure 1, the West Java shares borders with Jakarta (capital of Indonesia) and the Banten Province to the west, the Central Java Province to the east, the Java Sea to the north, and the Indian Ocean to the south.

The West Java has two seasons, namely wet season (October – April) and the remaining months are the so-called transition or dry season. In general, West Java receives high annual rainfall ranging from 500 – 4,000 mm (BMKG, 2017). Across West Java, there are several main rivers flowing from the springs mostly in the upstream mountainous regions, towards either the estuary in the Northern or Southern Coast of Java Island. However, due to data availability, only seven rivers across West Java as can be seen in Figure 1, namely Citarum, Ciliwung, Cileungsi, Cimanuk, Cilamaya, Citanduy, and Cisadane River were considered as the study area. All these rivers have several tributaries and pass through various cities or regencies within the province. Figure 1 also shows 48 monitoring stations used in the application of WJWQI, wherein 10, 9, 9, 5, 4, 3, and 8 monitoring stations were located in Citarum, Ciliwung, Cileungsi, Cimanuk, Cilamaya, Citanduy, and Cisadane River respectively. This monitoring network is managed by the West Java Environmental Protection Agency (WJEPA).

These rivers play an important role in the country as they are valuable sources of water for various needs such as agriculture and industry. They also provide bulk water supply for many cities across the region, including Jakarta. However, most of these rivers are vulnerable to pollution and have poor water quality, particularly those rivers that are near or are passing through urban and industrial areas. Pollutants entering the catchment and its rivers come from various activities, mostly domestic and industrial within the catchment. In addition to those two sources of pollutants, the agriculture and livestock have also contributed to river pollution in the rivers

(Juwana et al., 2014; WJEPA, 2015). As a result, the water quality of these rivers has deteriorated significantly.

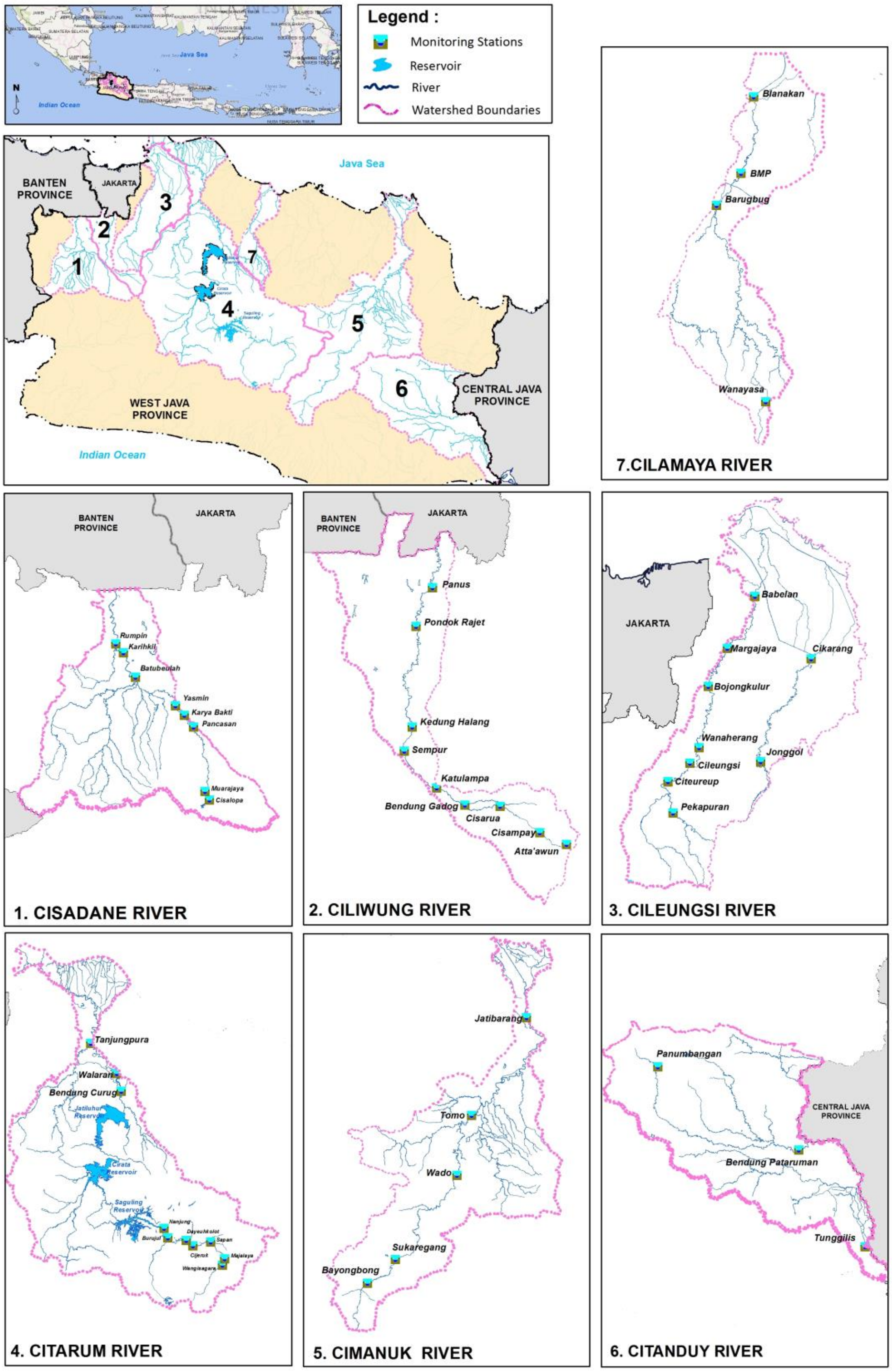


Figure 1 Water quality network of West Java Province used for application of WJWQI

Water quality data from the WJEPA's monitoring network were used in this study. The study period was considered as 2001-2011. However, due to budgetary constraints and change of institutional settings and laws in monitoring the water quality data, not all 48 stations had data for the above study period, as the WJEPA did not monitor the water quality data regularly for each station. The WJEPA also conducted irregular sampling frequencies, ranging from zero to five measurements per year. As a consequence, in the development and application of the WJWQI, not all monitoring stations even within the same river had either the same period of monitoring or the number of water samples. For example, in the application of WJWQI, the final index was computed at the station CTM1 in the Citarum River for the period between 2001 and 2010, while in the CTM3 in the same river, it was computed for the period 2003 – 2010.

3. Development of West Java Water Quality Index

The WJWQI was developed using four steps that have been used in the past to develop a WQI (Abbasi and Abbasi, 2012; Dojlido et al., 1994; Smith, 1990). These steps are selection of parameters, obtaining sub-index values (transformation to a common scale), establishing weights and aggregation of sub-indices to produce the final index A thorough review of the four-steps aforementioned can be found in Sutadian et al. (2016), while the use of these four steps in the development of WJWQI are discussed in the following sub sections.

3.1. Selection of parameters

Parameter selection is an essential step in the development of a WQI as the selected parameters are the main constituents of an index. In our previous study (Sutadian et al. (2017a, b)), an enhanced version of the statistical assessment for parameter redundancy developed by Khalil et al. (2014; 2010) was applied to obtain the selected water quality parameters for WJWQI. This was undertaken using three sequential stages, namely two screening procedures, statistical assessment for parameter redundancy, and finally the identification of common parameters across stations.

In the first stage, two screening procedures were carried out to exclude parameters that did not meet the minimum data criteria and parameters that are within the permissible limits. In the first screening procedure, the parameters that have less than a minimum of six or more consecutive years of data during the considered monitoring period were excluded from further analysis since they cannot be used in the subsequent step of the statistical assessment. In the second screening procedure, the parameters that are always 'within the permissible limits' were not considered for further analysis as the pollutants defined by these parameters were not present in significant amounts to be harmful to human or ecological health. It is important to note that 62 different parameters were subjected to this stage of parameter selection. These 62 parameters were categorised under 7 water quality groupings (of physical, oxygen depletion, nutrients, organics, ions and minerals, heavy metals and microbiology groups).

Then in the second stage, the statistical assessment for parameter redundancy was performed to identify the parameters to be removed from further monitoring (and their subsequent use in WJWQI) based on the methodology developed by Ouarda et al. (1996), and later adopted by Khalil et al. (2014; 2010). In this stage, the statistical assessment was developed through the inclusion of critical factors (i.e. the cost of parameter monitoring, and the magnitude and frequency of the parameter exceeding its permissible limits). This statistical assessment was undertaken to assess redundancy among the studied parameters and to identify the water quality parameters to be continued and discontinued at each monitoring station. There were two main analysis undertaken, namely (i) identifying highly correlated clusters to assess redundancy information among the studied parameters using correlation analysis and (ii) identifying the optimal combinations of continued and discontinued water quality parameters using an enhanced consolidated performance index (which is an aggregated information based on the variance of the mean value estimator among parameters investigated, wherein different weights for each parameter were included based on the cost of parameter monitoring, and the magnitude and frequency of the parameter exceeding its permissible limits). As a result, this statistical assessment led to a further reduction in the number of parameters to be monitored without losing a substantial amount of information in representing the water quality in the rivers.

The continued parameters obtained from this statistical assessment should ideally come from all clusters since information about a parameter in a particular cluster cannot be reconstituted from other clusters. There are two type of parameters clusters, those which included a single parameter (only one parameter in a cluster) and those with multiple (more than one parameters in a cluster) parameters. Applying this statistical assessment for each single monitoring station, all single parameter clusters were recommended to be taken as a continued parameter since the information of these parameters cannot be provided by other parameters. On the other hand, for multiple parameter clusters, only one parameter should be considered to be selected to represent its cluster as our previous study aimed to obtain a minimum number of parameters to be monitored.

Finally in the last stage, since the results of the statistical assessment revealed that the parameters to be continued for monitoring varied from one station to another station, the identification of a uniform set of selected parameters across stations for use in the WJWQI was undertaken. The uniform set of selected parameters is required for comparison of the water quality across rivers of West Java and also for the comparison of the general status of water quality from one monitoring station to another through the use of the WJWQI. Therefore, few additional criteria were proposed to be applied to identify the common set of selected parameters, which are as follows:

(1) Parameter identified as being in single clusters for at least70% of the total monitoring network were recommended to be selected as the common parameters across all stations (based on results of correlation and cluster analysis).
(2) Only parameters that are identified to be monitored continuously (i.e. based on results of single parameter clusters and the enhancement of consolidated index in multiple parameter clusters) for at least 80% of the total monitoring network were proposed to be included in the uniform set of parameters across stations.
(3) The uniform set of parameters should include at least one parameter belonging to each of the 7 different grouping of water quality parameters. This will ensure that the significance of each grouping of water quality parameters was considered in the final aggregated index.

Through the first stage (two screening procedures) aforementioned, the number of water quality parameters was initially reduced from 62 to 26. Then, using the next two stages, it was established that only 13 parameters representing all the 7 different groupings of water quality parameters would be used for the further steps in the development of the WJWQI. The final uniform set of selected parameters of the WJWQI is shown in Table 1. These 13 parameters were temperature (temp) and suspended solids (SS) representing the physical group, chemical oxygen demand (COD) and dissolved oxygen (DO) in the oxygen depletion group, nitrite (NO_2) and total phosphate (TP) in nutrients group, detergent (Deter) and phenol in the organics group, chloride (Cl) in ions and minerals group, Zinc (Zn), Lead (Pb) and mercury (Hg) in the heavy metals group, and faecal coliform (FC) in the microbiology group. The detail procedure of enhanced statistical assessment for parameter selection for a WQI and its application in the development of WJWQI are described in Sutadian et al. (2017a) and Sutadian et al. (2017b).

Table 1 Final set of selected parameters of the WJWQI

Grouping of Parameters	Water Quality Parameters	Units
Physical	Temperature	^oC
	Suspended solids	mg/L
Oxygen depletion	Chemical oxygen	mg/L
	Dissolved oxygen	mg/L O_2
Nutrients	Nitrite	mg/L NO_2-N
	Total phosphate	mg/L PO_4-P
Organics	Detergent as MBAS	µg/L
	Phenol	µg/L
Ions and minerals	Chloride	mg/L Cl^-
Heavy metals	Zinc	mg/L Zn
	Lead	mg/L Pb
	Mercury	mg/L Hg
Microbiology	Faecal coliforms	MPN/100 mL

3.2. Obtaining sub-index values

Sub-index functions are employed to compute the sub-index values of water quality parameters, which transforms the parameter values into a common scale. This process, which is commonly known as rescaling or standardisation, is necessary to use the parameters in the development of a WQI, since the actual values of the parameters have their own units. For example, DO has the unit of milligram per litre, while FC is presented in most probable number per hundred millilitre (MPN/100 mL). Furthermore, the ranges of these parameters vary greatly from parameter to parameter; for example, DO would rarely be beyond the range 0–12 mg/L, whereas FC can be in the range 0–millions MPN/100 mL.

The sub-index functions based on the permissible limits from the legislated water quality standards had been used in the past, since the use of water quality standards has different intended uses or water classes, and provide more information to the users for operation management of river quality (House, 1989; Liou et al., 2004; Thi Minh Hanh et al., 2011). In the development of WJWQI, the thresholds defining sub-index functions were obtained using the permissible limits for various levels of intended uses or water classes. For example, the thresholds for COD were considered as 10, 25, 50, 100 and >100 mg/L for water classes 1, 2, 3, 4 and 5 respectively based on the permissible limits of various classes, which is defined in the Government Decree of Government of Indonesia No. 81/2001 concerning Water Quality Control and Management (MoE, 2001). Based on different thresholds, 5 different water classes for sub-index values were determined. However, if the thresholds for particular classes are not available in Indonesia's surface water quality standards for certain WJWQI parameters, water quality standards of other countries that have similar conditions to Indonesia, international agencies, e.g. in EU (2007) and WHO (2011), and other WQI studies were used (Liou et al., 2004; Stoner, 1978; Thi Minh Hanh et al., 2011). This approach has been also used in in Liou et al. (2004) and Thi Minh Hanh et al. (2011).

With respect to common scale used, House (1989) proposed a non-zero value for the lower end of each sub-index scale instead of a value of 0, since water will always has an economic value. Therefore, the sub-index for each parameter receives a scale of 100 (the best case) – 5 (the worst case) in WJWQI. The 13 water quality parameters, their thresholds, and sub-index values for 5 different classes defining for sub-index functions are presented in Table 2. Note that temperature in Table 2 has one threshold.

Table 2 Water quality parameters, their thresholds, and sub-index values

No	Selected parameters	Units	Parameter		Sub-index values (S_i)
			Min	Max	(between 100 and 5)
(1)	(2)		(3)	(4)	(5)
1	Temperature (temp)	°C			
	Class 1-4		<40[b]		$S_i = 100$
	Class 5		≥40[b]		$S_i = 5$
2	Suspended solids (SS)	mg/L			
	Class 1		0	20[b]	$S_i = 100$
	Class 2		>20[b]	30[b]	$100<S_i\leq75$
	Class 3		>30[b]	50[a]	$75<S_i\leq50$
	Class 4		>50[a]	400[a]	$50<S_i\leq5$
	Class 5		>400[a]		$S_i = 5$
3	Chemical oxygen demand	mg/L			
	Class 1		0	10[a]	$S_i = 100$
	Class 2		>10[a]	25[a]	$100<S_i\leq75$
	Class 3		>25[a]	50[a]	$75<S_i\leq50$
	Class 4		>50[a]	100[a]	$50<S_i\leq5$
	Class 5		>100[a]		$S_i = 5$
4	Dissolved oxygen (DO)	mg/L O_2			
	Class 1			≥6[a]	$S_i = 100$
	Class 2		<6[a]	4[a]	$100<S_i\leq75$
	Class 3		<4[a]	3[a]	$75<S_i\leq50$
	Class 4		<3[a]	2.04[d]	$50< S_i\leq5$
	Class 5		0	>2.04[d]	$S_i = 5$
5	Nitrite (NO_2)	mg/L NO_2-			
	Class 1		0	0.01[b]	$S_i = 100$
	Class 2		>0.01[b]	0.02[b]	$100< S_i\leq75$
	Class 3		>0.02[b]	0.04[b]	$75< S_i\leq50$
	Class 4		>0.04[b]	0.06[a]	$50< S_i\leq5$
	Class 5		>0.06[a]		$S_i = 5$
6	Total phosphorous (TP)	mg/L PO_4-P			
	Class 1		0	0.2[a]	$S_i = 100$
	Class 2		>0.2[a]	0.4[c]	$100<S_i\leq75$
	Class 3		>0.4[c]	1[a]	$75<S_i\leq50$
	Class 4		>1[a]	5[a]	$50< S_i<5$
	Class 5		>5[a]		$S_i = 5$
7	Detergent as MBAS	µg/L			
	Class 1		0	0.00[f]	$S_i = 100$
	Class 2		>0.00[f]	200[a]	$100<S_i\leq75$
	Class 3-4		>200[a]	500[c]	$75<S_i\leq5$
	Class 5		>500[c]		$S_i = 5$
8	Phenol (Phen)	µg/L			
	Class 1		0	1[a]	$S_i = 100$
	Class 2		>1[a]	5[c]	$100<S_i\leq75$
	Class 3-4		>5[c]	10[c]	$75<S_i\leq5$
	Class 5		>10[c]		$S_i = 5$
9	Chloride (Cl)	mg/L Cl^-			
	Class 1		0	200[c]	$S_i = 100$
	Class 2-3		>200[c]	250[e]	$100<S_i\leq50$
	Class 4		>250[e]	600[a]	$50<S_i\leq5$
	Class 5		>600[a]		$S_i = 5$
10	Zinc (Zn)	mg/L Zn			
	Class 1		0	0.05[a]	$S_i = 100$

	Class 2		>0.05[a]	1[c]	$100<S_i<75$
	Class 3-4		>1[c]	2[a]	$75<S_i\leq5$
	Class 5		>2[a]		$S_i = 5$
11	Lead (Pb)	mg/L Pb			
	Class 1		0	0.02[b]	$S_i = 100$
	Class 2		>0.02[b]	0.03[a]	$100<S_i\leq75$
	Class 3		>0.03[a]	0.05[c]	$75<S_i\leq50$
	Class 4		>0.05[c]	1[a]	$50< S_i\leq5$
	Class 5		>1[a]		$S_i = 5$
12	Mercury (Hg)	mg/L Hg			
	Class 1		0	0.0005	$S_i = 100$
	Class 2		>0.0005[b]	0.001[a]	$100<S_i\leq75$
	Class 3		>0.001[a]	0.002[a]	$75<S_i\leq50$
	Class 4		>0.002[a]	0.005[a]	$50< S_i\leq5$
	Class 5		>0.005[a]		$S_i = 5$
13	Faecal coliforms (FC)	MPN/100			
	Class 1		0	50[b]	$S_i = 100$
	Class 2		>50[b]	100[a]	$100<S_i\leq75$
	Class 3		>100[a]	1000[a]	$75<S_i\leq50$
	Class 4		>1000[a]	2000[a]	$50< S_i\leq5$
	Class 5		>2000[a]		$S_i = 5$

[a] Indonesia's water quality standards (MoE, 2001)
[b] Vietnam's regulation surface water quality (MONRE, 2008)
[c] Guide or mandatory level using Directive 75/440/EEC (EU, 2007)
[d] Value's sub-indices developed by Liou et al. (2004)
[e] WHO's Guidelines for drinking-water quality (WHO, 2011)
[f] Ideal concentration for MBAS for drinking water (Stoner 1978)

On the basis of these thresholds (column 3 and column 4 of Table 2), the actual parameter values can be transformed into a common scale of sub-index values (i.e. 100 – 5) through either categorical scaling or linear interpolation rescaling methods. The categorical scaling method was used for only for temperature since this parameter has only one threshold as stated earlier, and it is shown in Eq. (1) and Eq. (2).

$$S_i = 5 \; if \; X_i \; is \; equal \; or \; above \; the \; threshold \tag{1}$$

$$S_i = 100 \; if \; X_i \; is \; below \; the \; threshold \tag{2}$$

where S_i is the i^{th} sub-index value and X_i is the i^{th} actual parameter value.

The linear interpolation rescaling method was used for the other WJWQI parameters. The linear interpolation rescaling is a method used to produce a common scale of sub-index values, wherein the thresholds for each class has different sub-index values (Dojlido et al., 1994; House, 1989; Liou et al., 2004; Prati et al., 1971; Štambuk-Giljanović, 2003; Thi Minh Hanh et al., 2011). In this method, the following general equations were used to calculate the sub-index values use. Equation (3) was used to generate sub-indices when a parameter has a decreasing level of water quality with the increase in actual parameter values (e.g. COD). Equation (4) was used if a parameter has an increasing level of water quality with the increase in actual parameter values (e.g. DO).

$$S_i = S_1 - \left[(S_1 - S_2)\left(\frac{(X_i - X_1)}{X_2 - X_1}\right)\right] \tag{3}$$

$$S_i = S_1 - \left[(S_1 - S_2)\left(\frac{(X_1 - X_i)}{X_1 - X_2}\right)\right] \tag{4}$$

where S_i is i^{th} sub-index value, Xi is the measurement data, S_1 and S_2 are the sub-index values corresponding to upper and lower threshold of the class respectively, and X_1 and X_2 are values of the permissible upper and lower thresholds of the class.

3.3. Establishing weights

Weights were assigned to the selected parameters in a WQI with regard to their relative importance and their influence on the final index. Taking into account the advantages, along with its recent successful applications to identify weights of indicators in water and environmental fields (Al-Barqawi and Zayed, 2006; Do et al., 2013; Huang et al., 2013; Qureshi and Harrison, 2003), the AHP method is found to be more appropriate for use in this study. As discussed in Sutadian et al. (2017c), this method was selected due to few reasons. First, it can be easily implemented for eliciting weights, compared to other methods. Second, the AHP enables to quantify both the experts' objective and subjective judgments. Finally, this method has been also used for parameter weights in previous WQI studies, such as in Ocampo-Duque et al. (2006), Karbassi et al. (2011), and Tallar and Suen (2016).

In this study, local experts' opinion was considered in identifying the parameter weights to address one of the limitations of the currently used indices (of not involving local expertise considered in developing the index). This also increases the acceptability of WJWQI as a tool for water resources management for use by relevant authorities in West Java. Table 3 presents the weights assigned to the selected parameters of WJWQI using the AHP. As can be seen from Table 3, COD, DO and FC had relatively high weights of 0.1, 0.1, 0.179 respectively, because the local experts recognised that these parameters are often well above their permissible limits. These three parameters are important for aquatic life and human health. Assigning higher weights for these parameters by the local experts indicates that controlling the activities that increase the concentration of FC and deplete the oxygen level in the rivers should be the top priority for water quality managers in West Java. The high weights of DO and FC were also in line with those of other popular WQIs such as National Sanitation Foundation Index, Dalmatian Index, Oregon Index, which show that DO and FC are the most important parameters (Brown et al., 1970, Dunnette, 1979, Štambuk-Giljanović, 1999, Debels et al., 2005).

The detailed procedure of the AHP can be found in (Saaty, 1980), whereas the detailed application of AHP and the results of identifying parameters weights for WJWQI can be found in Sutadian et al. (2017c).

Table 3 Weights assigned to the selected parameters using the AHP

WJWQI parameters	Final weights
Temperature	0.034
Suspended solids	0.044
Chemical oxygen	0.100
Dissolved oxygen	0.100
Nitrite	0.065
Total phosphate	0.058
Detergent	0.079
Phenol	0.085
Chloride	0.077
Zinc	0.038
Lead	0.061
Mercury	0.079
Faecal coliform	0.179

3.4. Aggregation of sub-indices to produce the final index

An aggregation is performed after the assignment of weights and calculating the sub-index values, to obtain the final index value in a WQI. Numerous aggregation methods are available in the literature, such as arithmetic (Bordalo et al., 2006; Brown et al., 1970; Dunnette, 1979; House, 1989; Prati et al., 1971; Sargaonkar and Deshpande, 2003; Semiromi et al., 2011; SRDD, 1976), geometric (Almeida et al., 2012; SRDD, 1976; Walski and Parker, 1974), minimum operator (Smith, 1990), combined arithmetic and geometric (Liou et al., 2004; Thi Minh Hanh et al., 2011), harmonic square (Cude, 2001; Dojlido et al., 1994), Canadian Council of Ministers of the Environment,(CCME, 2001), and specific linear (Said et al., 2004). Detailed discussion of these aggregation methods can be found in (Sutadian et al., 2016).

In this study, the non-equal geometric method was used to produce the final index due to its simplicity and extensive use. More importantly, this aggregation method was chosen since it does not create perfect substitutability and compensability among the sub-index values, wherein the higher values will not compensate or hide the lower values (Juwana et al., 2016b; OECD, 2008). Since one of the aims of developing the WJWQI is to increase the credibility and acceptability by involving the opinion of local experts, the non-equal weights of parameters have been established using AHP (Section 3.3), where the water related stakeholders in West Java considered some parameters to be more important than the others. The final index value is calculated using the following equation:

$$AI = \prod_{i=1}^{n} Si^{\omega_i} \qquad (5)$$

where AI is the aggregated index; n is the number of sub-indices; w_i is i^{th} weight and S_i is the i^{th} sub-index. The weights (w_i) indicate the relative importance of water quality parameter i in WJWQI.

Adopting boundary values from other WQIs, particularly for water quality classifications proposed in Hanh et al (2012), AI is classified into 5 different water quality as presented in Table 4.

Table 4 Water quality classifications as determined by the final aggregated index

Final aggregated index	Water quality classification
100 >= AI >= 90	Excellent
90 > AI >=75	Good
75 > AI >= 50	Fair
50 > AI >= 25	Marginal
25 > AI >=5	Poor

4. Application of WJWQI to Study Area Rivers

The WJWQI was applied for 1,271 water samples taken from 48 water monitoring stations between 2001 and 2011 in the seven main rivers. Since the general status of water quality refers to a specific time and location where a water sample was taken, the application of WJWQI was conducted (hence the final index computed) on each individual sample rather than one average value for a year. Table 5 presents the calculation of WJWQI for the water sample taken on 22 July 2003 at water quality station CTM7 of the Citarum River, as an example. Columns 1 and 2 of Table 5 present WJWQI parameters and their units respectively. Column 3 presents the measurement data for the sample on 22 July 2003. Column 4 presents the sub-index values for each WJWQI parameters, which were obtained using one of either Eq. (2), (3), or (4), while column 5 presents weights of WJWQI parameters as discussed in Section 3.3 (Table 3). Then, the final index, which was computed using the Eq. (5), is presented in column 6. The status of water quality of this final index was classified in column 7 as poor water quality (Table 5), as its value was lower than 25. The calculation of the sub-index values presented in column 4 of Table 5 shows that only 5 parameters, namely temperature, chloride, lead, zinc, and nitrite had high values of 87.50 – 100. The remaining parameters had low to moderate sub-index values. The sub-indices for dissolved oxygen, detergent, phenol, and faecal coliform had values of 5 (which is the lowest sub-index value a parameter can have in WJWQI).

Table 5 Example of WJWQI calculation for CTM7 for water sample on 22 July 2003

Water quality parameters (1)	Unit (2)	Measurement (3)	Sub- (4)	Weights (5)	Final (6)	Status of water (7)
Temperature	(°C)	28.00[a]	100[2]	0.034	21.86[5]	Poor
Suspended solids	mg/L	50.00[c]	50.00[3]	0.044		
Chemical oxygen demand	mg/L	66.00 [c]	35.60[3]	0.100		
Dissolved oxygen	mg/L O_2	0.50[b]	5.00[4]	0.100		
Nitrite	mg/L NO_2-N	0.015 [c]	87.50[3]	0.065		
Total phosphate	mg/L PO_4-P	0.71 [c]	62.08[3]	0.058		
Detergent as MBAS	µg/L	680 [c]	5.00[3]	0.079		
Phenol	µg/L	73.00 [c]	5.00[3]	0.085		
Chloride	mg/L Cl^-	68.00 [c]	100[3]	0.077		
Zinc	mg/L Zn	0.080 [c]	99.21[3]	0.038		
Lead	mg/L Pb	0.000 [c]	100[3]	0.061		
Mercury	mg/L Hg	0.001 [c]	75.00[3]	0.079		
Faecal coliforms	MPN/100 mL	110000 [c]	5.00[3]	0.179		

[a] Categorical parameter; [2] Sub-index value computed using Eq. (2)
[b] Non-categorical parameters where the-sub index value increases with the increase in measurement value; [3] Sub-index value computed using Eq. (3)
[c] Non-categorical parameter where the sub-index value decreases with the increase in measurement value; [4] Sub-index value computed using Eq. (4)
[5] Final index value computed using Eq. (5)

Figure 2 (a-g) shows the application of WJWQI tor each station in Citarum, Ciliwung, Cileungsi, Cimanuk, Cilamaya, Citanduy, and Cisadane Rivers. This figure also presents yearly pie charts for each station indicating the number of water samples taken per year during the study period, along with the dates showing when the water samples were taken. Blue, green, yellow, orange, and red in these pie charts show the status of river water quality as excellent, good, fair, marginal, and poor water quality respectively for each water sample, determined based on the final index (Table 4). As seen from Figure 2a-g, there were many stations showing either marginal or poor water quality (shown with the colours orange or red respectively).

In general, the status of water quality in these rivers are far from satisfactory. Very few of the monitoring stations across these seven main rivers were classified as either excellent or good water quality based on the water samples that had been taken during the study period (shown with the colours blue or green respectively). These results during the monitoring period are not surprising, as industrial, domestic and agricultural discharges pollute these rivers. WJEPA (2014) stated that there were 3,500 big industries and more than a hundred thousand medium and small industries in West Java, majority being textile, food, and beverage industries. A subsequent report WJEPA stated that the effectiveness and performance of the wastewater treatment of these industries is still questionable, and hence many of these industries were polluting rivers in West Java (WJEPA 2015). These rivers also suffered from the improper discharge of domestic waste of millions of people in West Java. It was observed that only 2 out of 27 cities in West Java, namely Bandung and Cirebon, have centralized sewer systems (USAID, 2006), and 46.16% of households in West Java do not have access to either on or off-site sanitation system (WJEPA, 2015). In addition, to some extent, agriculture and livestock have also contributed to river pollution in the rivers (Juwana et al., 2016a). As a consequence of industrial, domestic and agricultural pollution in these rivers, the measured values of many water quality parameters were often well above the permissible limits. Therefore, intermediate and complementary measures are needed to improve river water quality in the rivers in the study area.

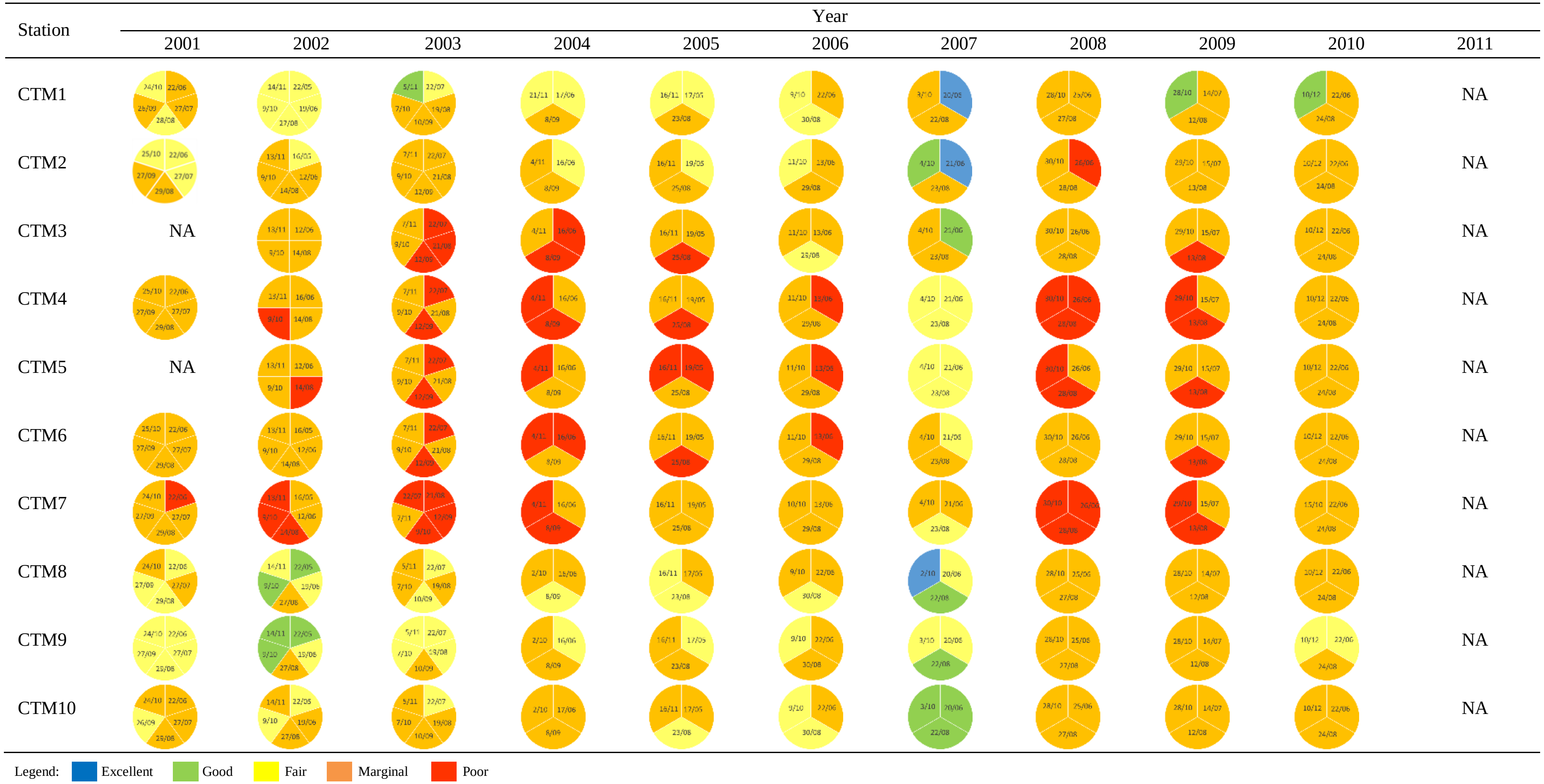


Figure 2a water quality as determined by WJWQI for each monitoring station in Citarum River (2010 – 2010)

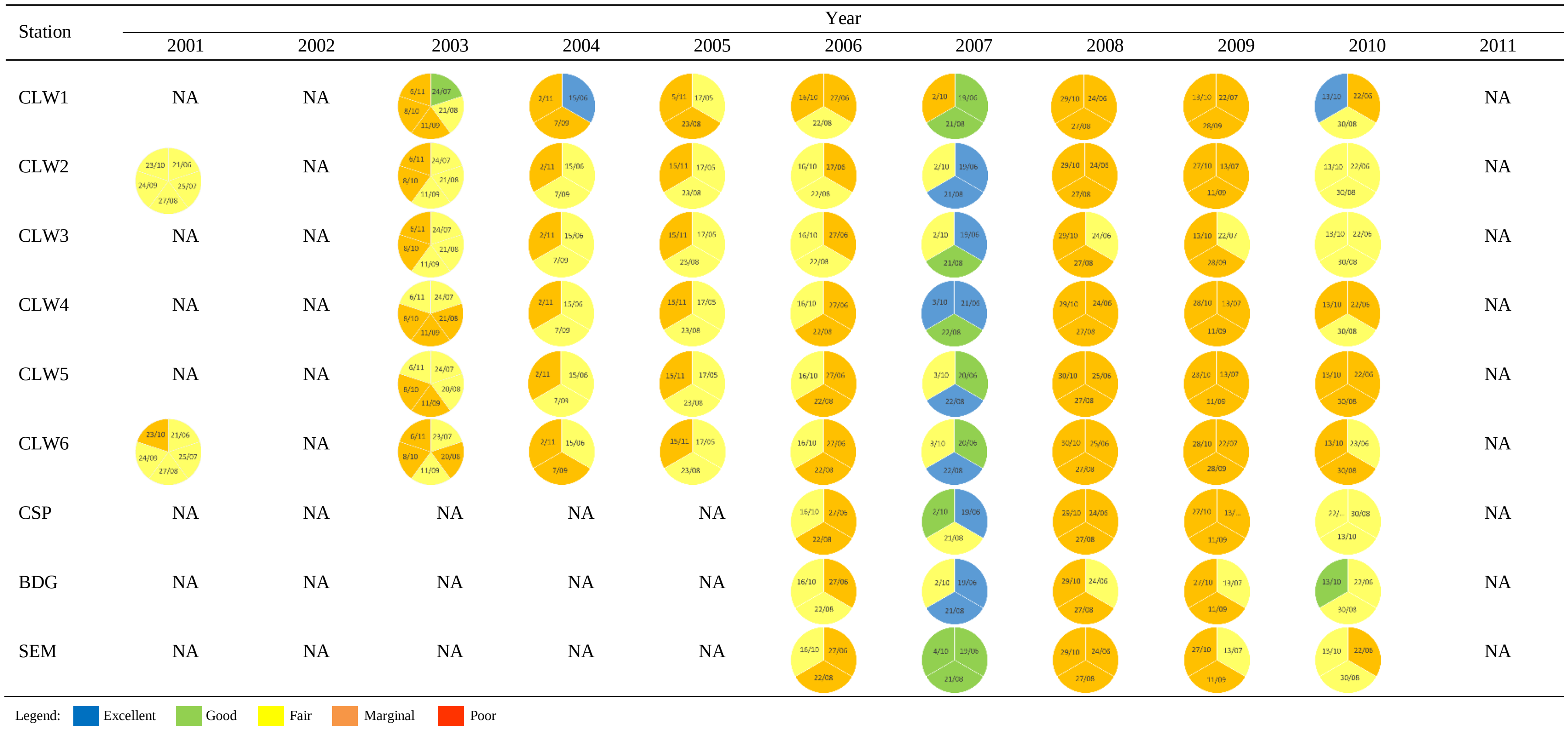


Figure 2b water quality as determined by WJWQI for each monitoring station in Ciliwung River (2010 – 2010)

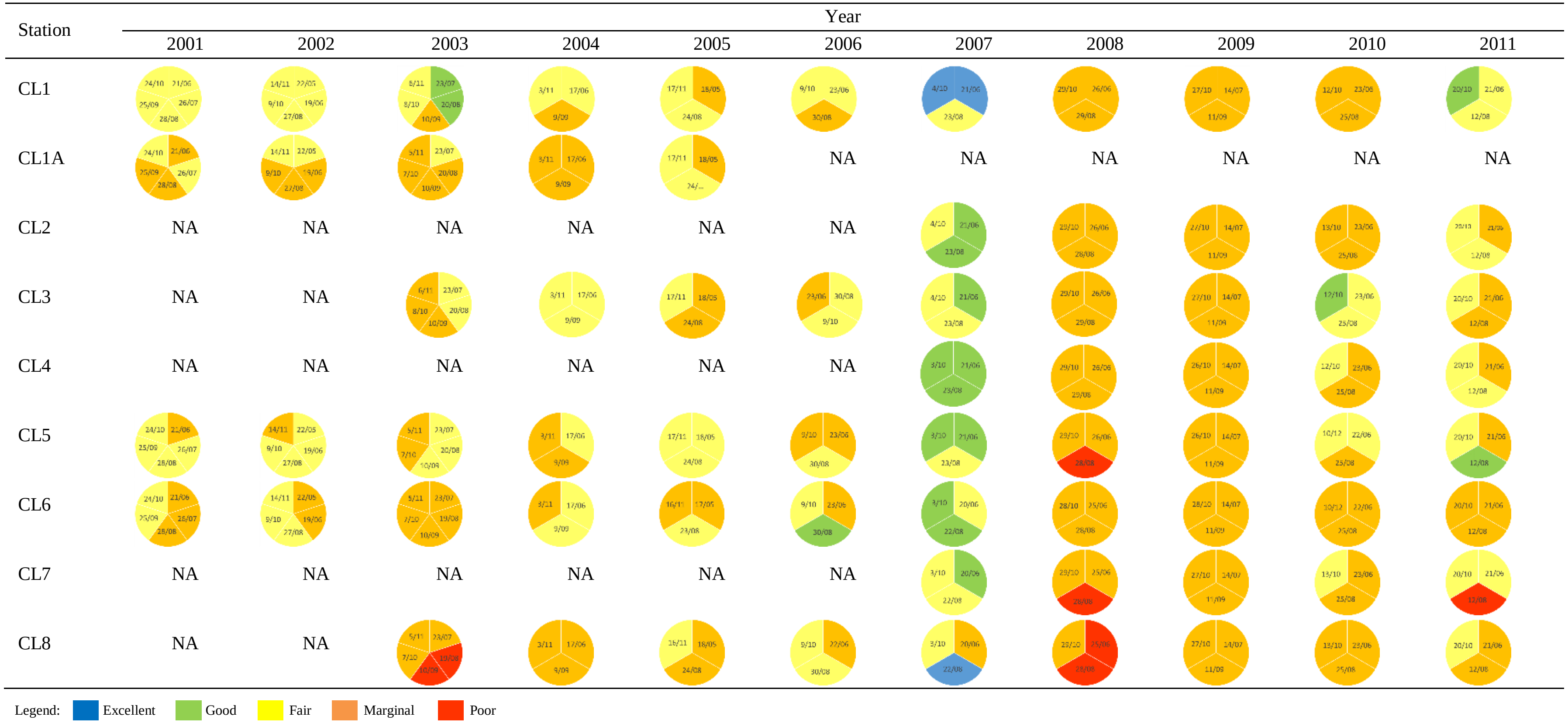


Figure 2c water quality as determined by WJWQI for each monitoring station in Cileungsi River (2010 – 2011)

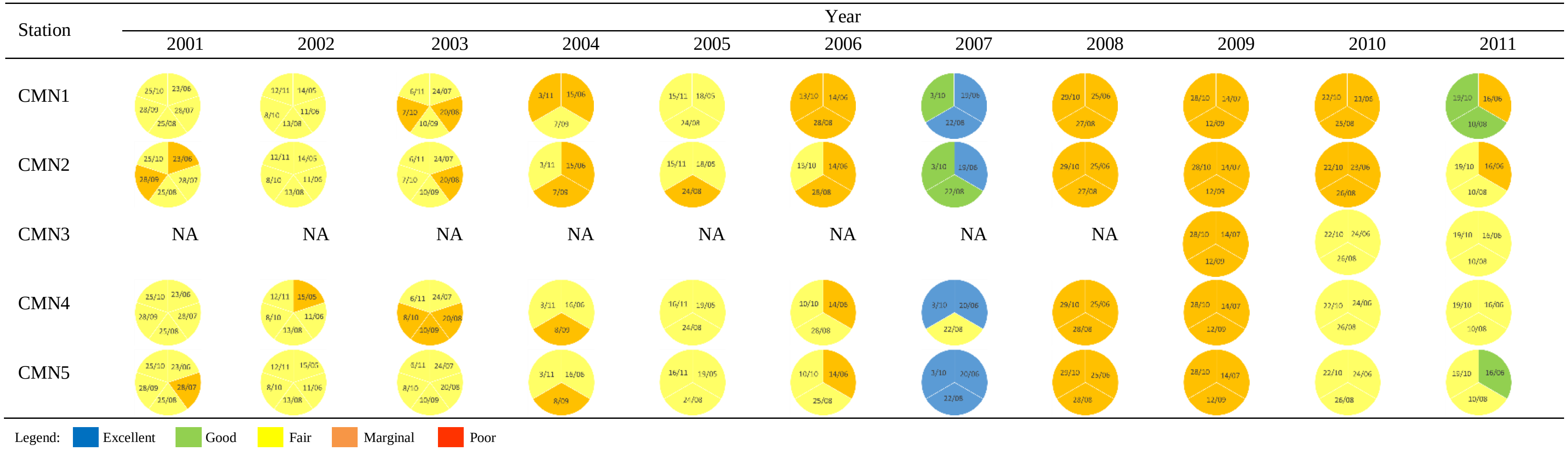


Figure 2d water quality as determined by WJWQI for each monitoring station in Cimanuk River (2010 – 2011)

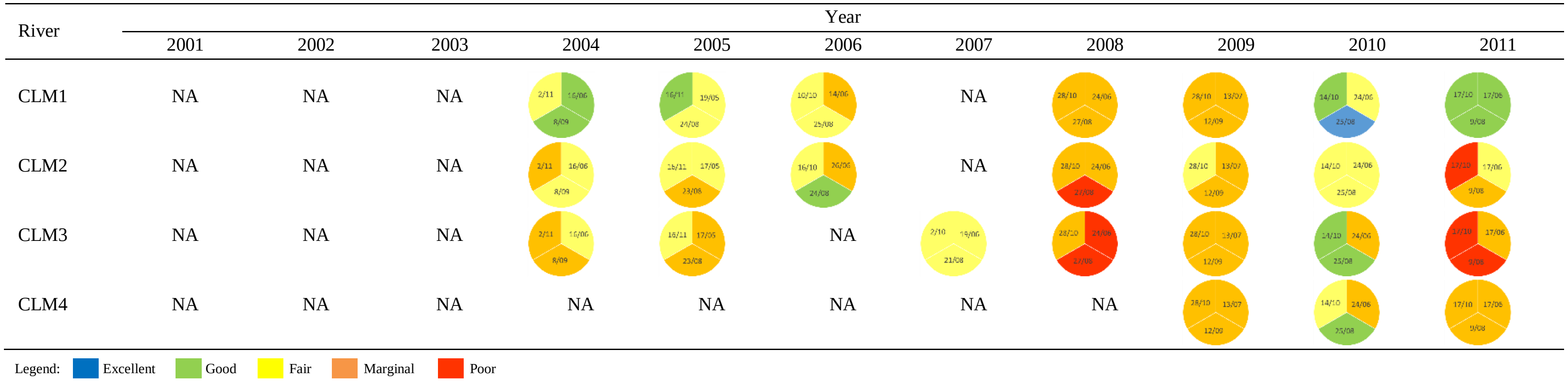
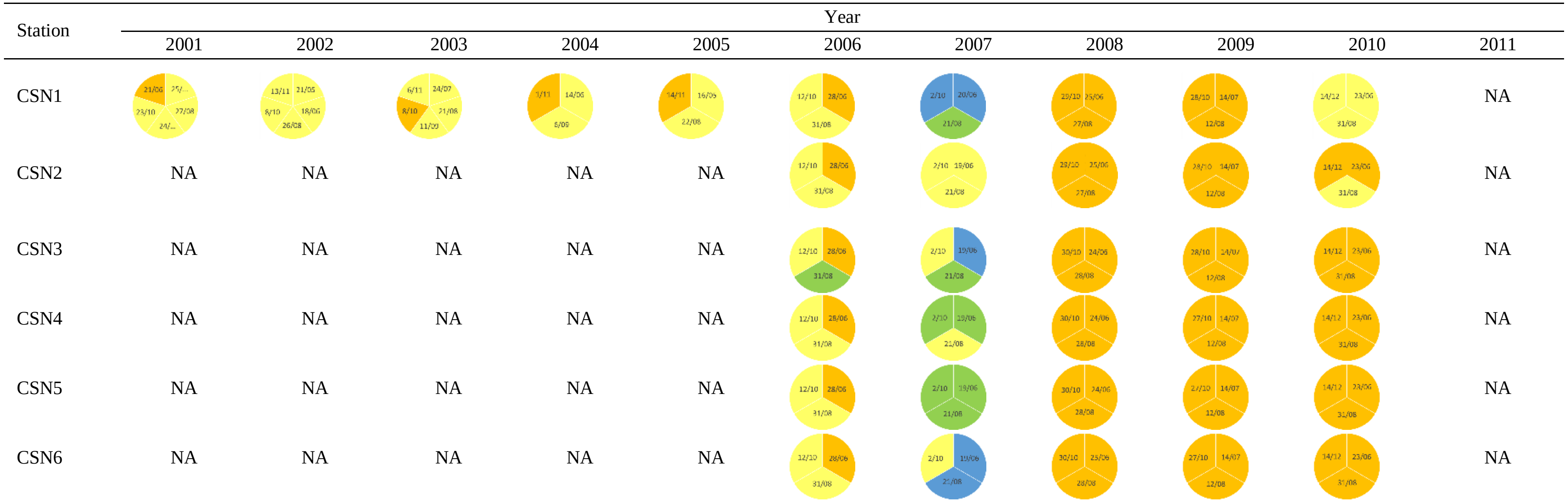


Figure 2e water quality as determined by WJWQI for each monitoring station in Cilamaya River (2010 – 2011)

Figure 2e water quality as determined by WJWQI for each monitoring station in Citanduy River (2010 – 2010)



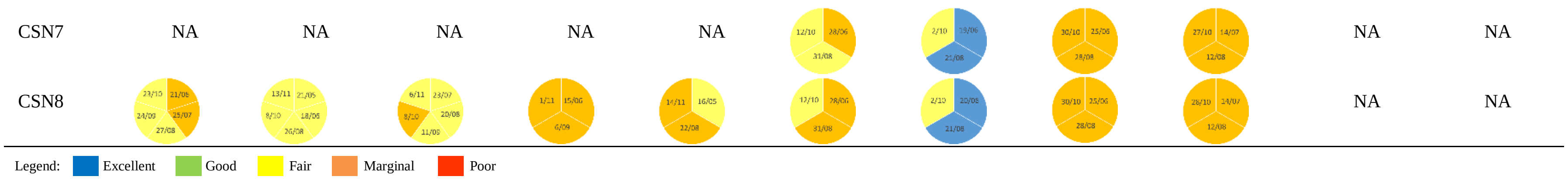


Figure 2g water quality as determined by WJWQI for each monitoring station in Cisadane River (2010 – 2010)

Figure 2 (a-g) also shows that the monitoring stations CTM2 – CTM7 in the Citarum River, CL5, CL7, and CL8 in the Cileungsi River, and CLM2 – CLM 3 in the Cilamaya River had experienced poor water quality during 2001 – 2011. These stations were the sites most susceptible to pollution among all monitoring stations in the study area. This is because they are located in more urbanized areas, wherein rapid urbanization and industrial growth have resulted in growing quantities of untreated wastewater and industrial effluents discharged to these rivers. In addition to the above monitoring stations mentioned, several other monitoring stations, for examples, CTM8 – CTM10 in the Citarum River, CL1A in the Cileungsi River, CSN3 – CSN 6 in the Cisadane River had nearly similar water quality in terms of more frequent marginal water quality.

As can be seen in Figure 2a, CTM7 was the monitoring station which is most susceptible to pollution in these rivers. During the period of monitoring between 2001 and 2011, the water quality of CTM7 had only once fair water quality (on 23 August 2007), while the remaining samples had either poor or marginal water quality. This station had the highest frequency of poor water quality status, as indicated in yearly pie charts in red (i.e. 15 out of 36 samples), compared to other stations in all these rivers. CTM7 also did not have either excellent or good water quality.

Table 6 presents the percentages of 5 different water quality status (or classifications) as determined by the final index of WJWQI for each station in the seven rivers in the study area, considering all water samples of all years in the monitoring period. In general, most of the monitoring stations across the rivers had high percentages of marginal and fair water quality. This was followed by those of low percentages of poor, good and excellent water quality. As can be seen in Table 6, CTM6 in the Citarum River had the highest percentages of marginal water quality (77.8%), while CTM2 in the same river had fair water quality more frequently (66.67%) than the other stations in the rivers across the study area. CTM7 in the Citarum River was the station that had the highest percentages of poor water quality (41.7%). It was also observed that CLM1 in the Cilamaya River had the highest percentages of good water quality (33.3%). Meanwhile, CSN7 in the Cisadane River was recorded as the station had the highest percentages of excellent water quality (16.7%), compared to other stations across rivers in the study area. The water quality in Cisadane River is relatively better as all the monitoring stations are located in the stream of this river (only upper stream of this river located in the West Java was considered as the study area).

Table 6 Percentage of water quality status as determined by WJWQI for each station in each river in the study area

River	Excellent	Good	Fair	Marginal	Poor
Citarum					
CTM1	5.6	8.3	41.7	44.4	-
CTM2	2.8	2.8	22.2	69.4	2.8
CTM3	-	3.3	3.3	66.7	26.7
CTM4	-	-	8.3	58.3	33.3
CTM5	-	-	10.0	60.0	30.0
CTM6	-	-	2.8	77.8	19.4
CTM7	-	-	2.8	55.6	41.7
CTM8	2.8	8.3	33.3	55.6	-
CTM9	-	11.1	47.2	41.7	-
CTM10	-	8.3	19.4	72.2	-
Ciliwung					
CLW1	7.7	15.4	15.4	61.5	-
CLW2	6.5	-	58.1	35.5	-
CLW3	3.8	3.8	57.7	34.6	-
CLW4	3.8	7.7	30.8	57.7	-
CLW5	3.8	3.8	30.8	61.5	-
CLW6	3.2	3.2	38.7	54.8	-
CSP	6.7	6.7	33.3	53.3	-
BDG	13.3	6.7	46.7	33.3	-
SEM	-	20.0	26.7	53.3	-
Cileungsi					
CL1	5.1	7.7	53.8	33.3	-
CL1A	-	-	33.3	66.7	-
CL2	-	13.3	20.0	66.7	-
CL3	-	6.9	44.8	48.3	-
CL4	-	20.0	20.0	60.0	-
CL5	-	7.7	51.3	38.5	2.6
CL6	-	7.7	25.6	66.7	-
CL7	-	6.7	33.3	46.7	13.3
CL8	3.4	-	17.2	65.5	13.8
Cimanuk					
CMN1	5.1	7.7	41.0	46.2	-
CMN2	2.6	5.1	43.6	48.7	-
CMN3	-	-	66.7	33.3	-
CMN4	5.1	-	64.1	30.8	-
CMN5	7.7	2.6	59.0	30.8	-
Cilamaya					
CLM1	4.8	33.3	28.6	33.3	-
CLM2	-	4.8	42.9	42.9	9.5
CLM3	-	9.5	23.8	47.6	19.0
CLM4	-	11.1	11.1	77.8	-
Citanduy					
CTD1	11.5	7.7	50.0	30.8	-
CTD2	7.7	7.7	38.5	46.1	-
CTD3	11.5	3.8	34.6	50.0	-
Cisadane					
CSN1	5.6	2.8	58.3	33.3	-
CSN2	-	-	40.0	60.0	-
CSN3	6.7	13.3	13.3	66.7	-
CSN4	-	13.3	20.0	66.7	-
CSN5	-	26.7	6.7	66.7	-
CSN6	13.3	-	20.0	66.7	-
CSN7	16.7	-	25.0	58.3	-
CSN8	6.1	-	45.5	48.5	-

Table 6 also shows that Ciliwung, Cimanuk, Citanduy and Cisadane River had better water quality, showing either excellent or good water quality status more frequently, compared to the monitoring stations in other rivers. These four rivers, even though are polluted by industrial waste, they did not receive as much as that of other three rivers (Citarum, Cilamaya, and Cileungsi are close by most of industries in West Java). For example, all stations in the Ciliwung River had some level of either excellent or good water quality during the monitoring period, while in the Cimanuk River, there were 4 out of 5 stations that had excellent or good water quality at least once during the monitoring period. Moreover, the monitoring stations in these two rivers did not have poor water quality (0%) during 2001-2011.

Using two criteria, namely the number of stations that experienced poor water quality and the percentages of stations that had of poor and marginal water quality more frequently, as can be seen in Table 6, the Citarum River is the most critical river, when compared to the other main rivers in West Java. Table 6 shows that there were 6 out of the 10 monitoring stations in the Citarum River, which had experienced poor water quality at some stage during the monitoring period. All these stations are located in the middle part of the river, except for CTM2, is located in the upper stream of the river. The river between CTM3 and CTM7 is close to densely populated settlements and industrial zones. Even though there is a centralized sewerage and wastewater treatment systems in the area, it covers only a small portion of population living this urbanized area (Prihandrijanti and Firdayati, 2011), and therefore poor water quality in this part of the river.

Even though CTM2 is located in the upstream of the river, it only had slightly better water quality than CTM3 – CTM7. This is because FC, COD, DO, and SS often exceeded the permissible limits based on the measurement data, producing low values of the final index. For example, FC had been recorded by 11 million MPN/100 mL or 55 thousand times the permissible limit (the highest in the study area), indicating this station had severe contamination of FC. This could be because many villagers use livestock farming as their major source of income, and majority of them did not implement sustainable livestock farming practices, which contributed significantly to the FC pollution in this part of the river (Sutadian et al., 2015).

5. Uncertainty and sensitivity analysis of WJWQI

In the development of WQIs, uncertainties exist in the following steps: (1) the selection of parameters, threshold values for obtaining sub-index values and parameter weights, and (2) the aggregation of sub-indices to produce the final index. The new approach for parameter selection as described in Section 3.1 was applied through a statistical assessment for parameter redundancy, was expected to remove uncertainties in the selection of parameters (Sutadian et al., 2016), and therefore the uncertainty related to the selection of parameters was not considered in this study. Although the aggregation method in index development is a source of uncertainty as each method might result in different final index values (Esty et al., 2005; Juwana et al., 2016b), this uncertainty was also not considered in this study, since the weighted geometric method was used to produce the final index in WJWQI. The reasons for using the weighted geometric method were discussed in Section 3.4. Therefore, only the other uncertainties in relation to the selection of threshold values for obtaining sub-index values and parameter weights are addressed through the uncertainty and sensitivity analysis in this study.

The uncertainty analysis of WJWQI focuses on how the variations in parameter thresholds and parameter weights propagate into the final index values. This uncertainty propagation was studied through 10,000 Monte Carlo (MC) simulations, and then calculating the coefficient of variation (CV) of parameter thresholds, parameter weights, and the final index values. Higher variability of parameter thresholds, parameter weights, and final index values indicate their higher uncertainty. The use of CV in the uncertainty analysis had been done by Håkanson (2000) and Juwana et al. (2016b). The sensitivity analysis of WJWQI evaluates the importance of both parameter thresholds and parameter weights in determining the final index values. The sensitivity of the final index values to changes in parameter thresholds and parameter weights was analysed by comparing those CV values (as obtained in the uncertainty analysis), as had been done by Weber et al. (2004) and Juwana et al. (2016b). If the CV of the final index values is less than those of WJWQI parameter thresholds and parameter weights, then it can be said that the uncertainty of parameter thresholds and weights have not propagated to the final index. The sensitivity analysis of the final index values was also analysed by comparing the classification of 10,000 water quality status (of excellent, good, fair, marginal and poor) obtained from the outputs of the MC simulations with that of the measurement. If there is less than 10% change in water quality status of the 10,000 MC simulations over that of the measurement, then it indicates the WJWQI is insensitive to the uncertainties in the parameter thresholds and parameter weights. This approach has been used in Esty et al. (2005) and (Juwana et al., 2016b).

As was done Juwana et al. (2016b), those two analysis methods together determine the robustness of an index. If the uncertainty of parameter thresholds and parameter weights has not propagated to the final index value as obtained from the uncertainty analysis and if the final index values and the classification of water quality status are insensitive to changes in the parameter thresholds and parameter weights, then it can be said that WJWQI is robust. It is worth noting here that when the uncertainty and sensitivity analysis was undertaken for parameter thresholds, all parameter weights were kept at their base values as in Table 3. Similarly, when the uncertainty and sensitivity analysis was undertaken for parameter weights, all parameter thresholds were kept at their base values as in Table 2.

The steps for uncertainty and sensitivity analysis for the parameter thresholds and parameter weighs of WJWQI are presented in Figure 3. As can be seen from Figure 3, the uncertainty and sensitivity analysis of both parameter thresholds and parameter weights follow the same procedure, the only difference being when either the uncertainty of parameter thresholds or parameter weights was considered, the other was kept at their base values as outlined earlier. The CTM7 monitoring station located in the Citarum River was used for conducting the uncertainty and sensitivity analysis of WJWQI. This monitoring station was selected because it was the most critical station in terms of water quality (i.e. the one that has the highest percentage of poor water quality) among all stations in the study area. Another reason for selecting CTM7 was that most of the selected parameters at this station had relatively higher variability when compared to the other stations (Sutadian et al. 2015). All 5 water samples of 2003 (which was the year with the worst water quality) were used for the uncertainty and sensitivity analysis. The final index values of each sample with respect to their measurements were 21.86 (in July), 16.90 (in August), 17.13 (in September), 23.06 (in October) and 31.86 (in November) respectively. The first four values were classified as poor (Table 4), while the fifth value had marginal water quality (Table 4). The uncertainty and sensitivity analysis was performed using @Risk software of Palisade Corporation (Clemen and Reilly, 2001).

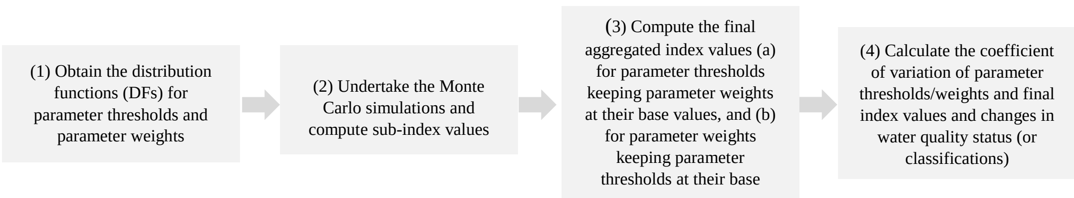


Figure 3 Steps used for uncertainty and sensitivity analysis of parameter thresholds and parameter weights of WJWQI

The Step 1 of the uncertainty and sensitivity analysis is to obtain the distribution functions for parameter thresholds and parameter weights of WJWQI. As the triangular distribution function was found to be the most suitable distribution function for use in uncertainty and sensitivity analysis in the index development compared to other distributions (Juwana et al., 2016b; Kawai and Teixeira, 2012; Mauelshagen et al., 2014; Sinija and Mishra, 2011; Tait et al., 2012), it was used in this analysis, defining the distribution through base, lower and upper values for each parameter threshold and parameter weight. The most likely value of parameter thresholds was used the base value of respective parameter thresholds and these values are listed in Table 2. Similarly for the parameter weights, the base values are listed in Table 3. Then, as was done by Juwana et al. (2016b) the lower and upper values for the triangular distribution were obtained as ± 10% of the base value of respective parameter thresholds or weights for each WJWQI parameter.

An example of obtaining the distribution function (DF) using the triangular distribution for WJWQI temperature parameter for both threshold and weight and the related MC simulations are presented in Figure 4. This figure shows the lower, base and upper values of temperature threshold as 36, 40 (Table 2), and 44ºC respectively. This figure also shows that the statistics of 10,000 samplings from the triangular distribution, which were generated through the MC simulation. These statistics were 36.02, 40.00 and 43.97ºC respectively for 95% lower confidence limit, mean and 95% upper confidence limit. For parameter weights of temperature, the lower, base and upper values were 0.030, 0.034 (Table 3), and 0.037, while the lower confidence limit, mean and upper confidence limit generated through the MC simulation were 0.031, 0.034, and 0.038 respectively. It should be noted that temperature (considered in Figure 4) has only 2 class categories defined by one threshold which is 40ºC (Table 2). However in the uncertainty and sensitivity analysis, the thresholds related to all classes (Table 2) were considered, similar to one threshold in temperature.

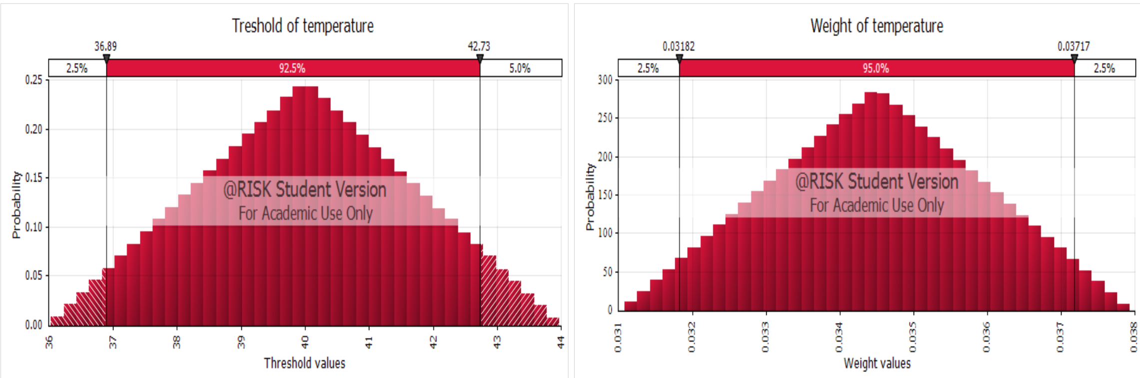


Figure 4 Distribution function for parameter threshold and parameter weight of temperature

These distribution functions of parameter thresholds and parameter weights were then used in Step 2 to generate 10,000 sampling points using the MC simulation. This means 10,000 values of combinations of thresholds with respect to each water quality parameter considering also their water classes produced 10,000 sub-index values of parameters. Also in Step 2, these sampling points of each threshold were used to compute 10,000 sub-index values of each WJWQI parameter.

In Step 3, the 10,000 sub-index values of each WJWQI parameter based on the MC simulation of parameter thresholds were aggregated using the geometric method keeping the parameter weights at their base values (Table 3), which produced 10,000 values of the final index. Similar procedure was followed for parameter weights, but keeping the parameter thresholds at their base values as in Table 2.

Finally, Step 4 calculates the CV of the final index values to analyse the uncertainty and sensitivity of WJWQI. The calculation of CV of the final index with respect to parameter thresholds and parameter weights were undertaken separately with their respective 10,000 values. Step 4 also calculates the percentage of water quality status or classifications (i.e. excellent, good, fair, marginal and poor water quality) corresponding to 10,000 values of the final index for both uncertainty and sensitivity analysis of parameter thresholds and parameter weights.

Figure 5 shows the results of uncertainty and sensitivity analysis of WJWQI to parameter thresholds for the monitoring station CTM7 of the Citarum River for the 2003 monitoring year. As stated earlier, this analysis was performed for each water sample considering 10,000 MC samplings for each event. It is important to note that when performing this uncertainty and sensitivity analysis for parameter thresholds, as discussed earlier, all parameters weights were kept at their base values as in Table 3. The final index values of the 10,000 MC simulation ranged 21.84 – 22.24 (21.88) in July, 16.64 – 17.29 (16.95) in August, 17.01 – 17.27 (17.13) in September, 21.99 – 23.83 (23.03) in October, and 31.53 – 32.14 (31.85) in November, where the numbers within brackets show the final index values of WQWQI corresponding to measurements. Figure 5 also shows that there was hardly any differences between the mean values of final index computed based on the 10,000 MC simulations and the final index value computed using the measurements. As indicated by numbers within brackets of Figure 5, the CV of the final index values, which were computed using the 10,000 MC simulations for all samples, had low variability of 0.005 – 0.01. These CV values are very low compared to the CV values of all thresholds of WJWQI parameters which had low variability of the order of 0.04. This indicates that the relatively higher variability of parameter thresholds has not propagated to the final index values and the final index values have low uncertainty.

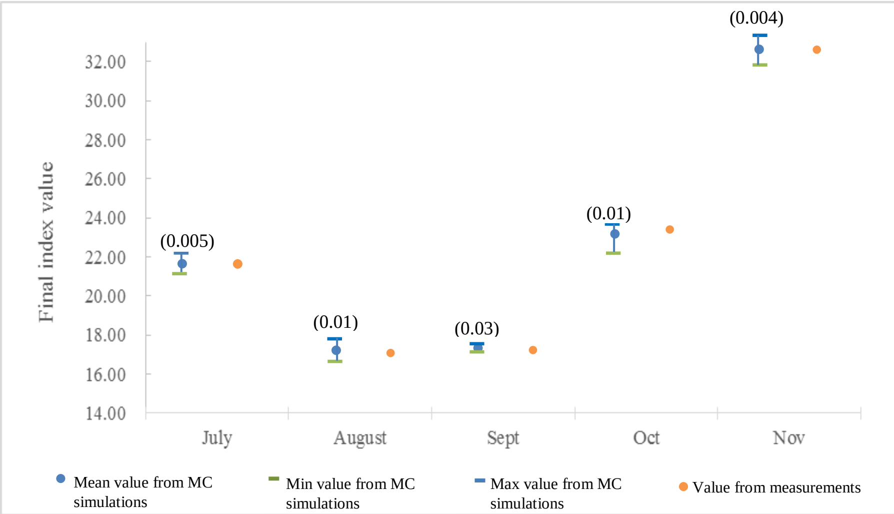


Figure 5 Uncertainty and sensitivity analysis of WJWQI to parameter thresholds for the CTM7 monitoring station

Results of the uncertainty and sensitivity with respect to the parameter weights for CTM7, is presented in Figure 6. Also, in this analysis, all parameter thresholds were kept at their base values as in Table 2. This figure has similar information to Figure 5 and the information that can be drawn from this figure are similar to that of Figure 5 in terms of the differences between the mean values of the final index computed based on the 10,000 MC simulations and the final index value obtained from the measurements, and the CV values of the parameter weights and the final index values. The final index values of the 10,000 MC simulations ranged 20.53 – 23.45 (21.87) in July, 16.01 – 18.62 (16.90) in August, 16.15 – 18.58 (17.13) in September, 21.85 – 24.77 (23.07) in October, and 29.88 – 33.90 (31.87) in November, with the numbers within the brackets showing the final index values with respect to the measurements. Figure 6 also shows that the CV of the final index values with respect to the MC simulations as 0.02. This CV is much low compared to the CV of parameter weights of the MC simulations (each parameter weight having a CV of 0.04). This indicates similar to the analysis of parameter thresholds, that the relatively higher variability of parameter weights has not propagated to the final index values and the final index values have low uncertainty.

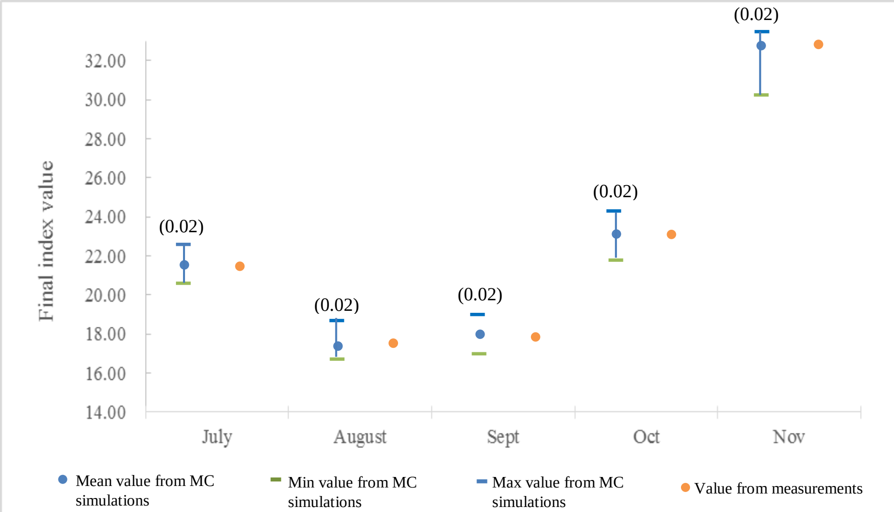


Figure 6 Uncertainty and sensitivity analysis of WJWQI to parameter weights for the CTM7 monitoring station

As discussed earlier, the sensitivity of WJWQI can also be analysed through their water quality status (or classifications) corresponding to the 10,000 of MC simulations. For each final index value of 10,000 of the MC simulations, the water quality status was determined as either excellent, good, fair, marginal or poor, for all 5 events using Table 4. These water quality status (or classifications) were then compared against that of measurements. Results of this analysis revealed that there were no changes (0%) in the water quality status. Similar result was obtained with respect to the analysis of parameter weights. This analysis concludes that the water quality status determined through the final index are not sensitive to changes in the parameter thresholds and parameter weights.

The results of the uncertainty and sensitivity analysis through MC simulations indicated that the uncertainty of both parameters thresholds and parameter weights has not propagated to the final index, and no changes in water quality status, and therefore it can be concluded that WJWQI is a robust index. However this analysis was done for considering only one station (CTM7) and data from 2003. Since CTM7 had relatively higher variability in water quality parameter measurement values compared to the other stations in the study area and year 2003 which was the year with worst water quality, there is a high probability that these results are equally valid for all rivers in the study area and for all years

6. Summary and Conclusions

A West Java Water Quality Index (WJWQI) was developed in this study to evaluate water quality in rivers of the West Java Province, Indonesia and presented in this paper. This index aims to address the limitations of the currently used indices in West Java, namely the inability of making accurate comparisons of the general status of water quality in West Java rivers, the inability to make these comparisons in a cost effective manner and the lack of credibility and acceptability of the currently used indices by relevant authorities in West Java (since the local conditions and local expert opinion have not been considered in the development of these indices).

The WJWQI was developed using four basic steps, namely (1) the selection of parameters based on a statistical assessment for parameter redundancy and inclusion of three factors representing the criticality of cost effective water quality monitoring, (2) Obtaining the sub-index values based on the permissible limits from the legislated water quality standards, (3) Establishing parameter weights based on local experts' opinion, and (4) Aggregation of sub-indices to produce the final index using the weighted geometric method. This paper also demonstrated the application of WJWQI to several rivers in West Java using the monitoring data taken between 2001 and 2011, to evaluate the general status of water quality in these rivers spatially and temporally. The application of WJWQI provided a more accurate and valid comparison of water quality among these rivers. Moreover, this paper also presented an uncertainty and sensitivity analysis to determine the robustness of WJWQI, considering two sources of uncertainties, namely the selection of parameter thresholds and parameter weights.

Conclusions drawn from this study are as follows:

- The parameter selection methodology used in the development of WJWQI, which considered cost effective monitoring of water quality parameters in West Java rivers and the inclusion of local experts' opinion in establishing the parameter weights will increase the credibility and acceptability of WJWQI among the relevant authorities and the users of WJWQI. Thus, WJWQI could be a more reliable alternative to the currently used WQIs in West Java.
- The parameter selection methodology developed and used for WJWQI found that 13 water quality parameters are adequate to monitor water quality of rivers in West Java, as they collectively are representative of the water quality of these rivers. Those 13 parameters were temperature, suspended solids, chemical oxygen demand, dissolved oxygen, nitrite, total phosphate, detergent, phenol, chloride, zinc, lead, mercury, and faecal coliform.
- The results of the application showed that most monitoring stations had marginal water quality, indicating that the rivers in the West Java Province have been experiencing water

quality deterioration significantly. Also it was found that Citarum (CTM3 – CTM7), Cileungsi (CL5, CL7, CL8), and Cilamaya (CLM2 – CLM3) Rivers had poorer water quality, when compared to the other rivers in West Java. Thus, these rivers should have higher priority, particularly in implementing comprehensive measures to reduce and treat high concentration of pollutants, which contributed significantly to the pollution of these three rivers.

- The results of the uncertainty and sensitivity analysis for parameter thresholds and parameter weights showed that the variability of the final index values were lower than those of parameter thresholds and parameter weights of WJWQI. This indicates that the relatively higher variability of parameter thresholds and parameter weights has not propagated to the final index values and the final index values have low uncertainty.
- The uncertainty and sensitivity analysis also showed that changes in parameter thresholds and parameter weights did not result in any changes in the water quality status.
- Finally it can be concluded that WJWQI is a robust water quality index, which had been applied to the rivers in West Java successfully, and hence the relevant authorities in West Java and the users of WJWQI will be able to use it for evaluating the general status of river water quality confidently.

Acknowledgments

The authors would like to acknowledge and thank the Australia Awards, which funded the first author for this study as part of his PhD and the West Java Environmental Protection Agency, Indonesia, which has provided the data used in this study.

References

Abbasi, T., Abbasi, S.A., 2012. Water Quality Indices. Elsevier, Amsterdam

Al-Barqawi, H., Zayed, T., 2006. Assessment Model of Water Main Conditions. Pipelines 2006, 1-8.10.1061/40854(211)27

Almeida, C., González, S., Mallea, M., González, P., 2012. A recreational water quality index using chemical, physical and microbiological parameters. Environ Sci Pollut Res 19, 3400-3411.10.1007/s11356-012-0865-5

BMKG, 2017. Peta Curah Hujan Jawa Barat (Rainfall of West Java) 1980-2010. Indonesia Buerau of Meteorological, Climatological and Geophysics

Bordalo, A., Teixeira, R., Wiebe, W., 2006. A Water Quality Index Applied to an International Shared River Basin: The Case of the Douro River. Environmental Management 38, 910-920.10.1007/s00267-004-0037-6

BPS, 2015. Jawa Barat in Figures 2015.

Brown, R.M., Mc Clelland, N.I., Deininger, R.A., Tozer, R.G., 1970. A water quality index-Do we dare? . Water and Sewage Works 117, 339-343

CCME, 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. Canadian Council of Ministers of the Environment Winnipeg.http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).pdf (accessed 20.01.2015)

Clemen, R., Reilly, T., 2001. Making Hard Decisions with Decision Tools. Duxbury Press, Pacific Grove., California

Cude, C., Dunnette, D., Avent, C., Frankin, A., Gross, G., Hartman, J., Hayteas, D., Jenkins, T., Leben, K., Lyngdal, J., Marks, D., Morganti, C., Quin, T., 1997. Exploring Possibilities for An International Water Quality Index Applied to River System, in: Best, G., Bogacka, T., Niemirycz, E. (Eds.), International River Water Quality: Pollution and restoration. E & FN Spoon, London

Cude, C.G., 2001. Oregon water quality index a tool for evaluating water quality management effectiveness. JAWRA Journal of the American Water Resources Association 37, 125-137.10.1111/j.1752-1688.2001.tb05480.x

Do, H.T., Lo, S.-L., Thi, L.A.P., 2013. Calculating of river water quality sampling frequency by the analytic hierarchy process (AHP). Environmental Monitoring and Assessment 185, 909-916.10.1007/s10661-012-2600-6

Dojlido, J., Raniszewski, J., Woyciechowska, J., 1994. Water quality index - Application for rivers in Vistula river basin in Poland. Water Science and Technology 30, 57-64

Dunnette, D.A., 1979. A Geographically Variable Water Quality Index Used in Oregon. Journal Water Pollution Control Federation 51, 53-61.10.2307/25040240

Esty, D.C., Levy, M., Srebotnjak, T., Sherbinin, A.d., 2005. Environmental Sustainability Index: benchmarking national environmental stewardship. Yale Center for Environmental Law & Policy, New Haven

EU, 2007. Council Directive 75/440/EEC of 16 June 1975 concerning the quality required of surface water intended for the abstraction of drinking water in the Member States. Consolidated Text Produced by the CONSLEG System of the Office for Official Publications of the European Communities 31975L0440, in: Council, E. (Ed.)

Gitau, M.W., Chen, J., Ma, Z., 2016. Water Quality Indices as Tools for Decision Making and Management. Water Resour Manage 30, 2591-2610.10.1007/s11269-016-1311-0

Håkanson, L., 2000. The role of characteristic coefficients of variation in uncertainty and sensitivity analyses, with examples related to the structuring of lake eutrophication models. Ecological Modelling 131, 1-20.http://dx.doi.org/10.1016/S0304-3800(00)00219-2

Horton, R.K., 1965. An index number system for rating water quality. Journal of Water Pollution Control Federation 37, 300-306

House, M.A., 1989. A Water Quality Index for River Management. Water and Environment Journal 3, 336-344.DOI:10.1111/j.1747-6593.1989.tb01538.x

Huang, W., Yano, S., Zhang, J., Wang, Y., 2013. Application of analytic hierarchy process in selecting a biological indicator for a river flow restoration. Ecological Indicators 25, 180-183.http://dx.doi.org/10.1016/j.ecolind.2012.09.017

Juwana, I., Muttil, N., Perera, B.J.C., 2014. Application of West Java water sustainability index to Citarum catchment in West Java, Indonesia. Water Science and Technology: Water Supply 14, 1150-1159.10.2166/ws.2014.075

Juwana, I., Muttil, N., Perera, B.J.C., 2016a. Application of west java water sustainability index to three water catchments in west java, Indonesia. Ecological Indicators 70, 401-408.http://dx.doi.org/10.1016/j.ecolind.2016.06.017

Juwana, I., Muttil, N., Perera, B.J.C., 2016b. Uncertainty and sensitivity analysis of West Java Water Sustainability Index – A case study on Citarum catchment in Indonesia. Ecological Indicators 61, Part 2, 170-178.http://dx.doi.org/10.1016/j.ecolind.2015.08.034

Karbassi, R.A., Mir Mohammad Hosseini, F., Baghvand, A., Nazariha, M., 2011. Development of water quality index (WQI) for gorganrood river. International Journal of Environmental Research 5, 1041-1046

Kawai, H., Teixeira, J., 2012. Probability Density Functions of Liquid Water Path and Total Water Content of Marine Boundary Layer Clouds: Implications for Cloud Parameterization. Journal of Climate 25, 2162-2177.10.1175/jcli-d-11-00117.1

Khalil, B., Ou, C., Proulx-McInnis, S., St-Hilaire, A., Zanacic, E., 2014. Statistical Assessment of the Surface Water Quality Monitoring Network in Saskatchewan. Water, Air, & Soil Pollution 225.10.1007/s11270-014-2128-1

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., Chebana, F., 2010. A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. Journal of Hydrology 386, 173-185.http://dx.doi.org/10.1016/j.jhydrol.2010.03.019

Liou, S.M., Lo, S.L., Wang, S.H., 2004. A generalized water quality index for Taiwan. Environmental Monitoring and Assessment 96, 35-52

Lumb, A., Sharma, T.C., Bibeault, J.-F., 2011. A Review of Genesis and Evolution of Water Quality Index (WQI) and Some Future Directions. Water Qual Expo Health 3, 11-24.10.1007/s12403-011-0040-0

Mauelshagen, C.W., Pollard, S.J.T., Owen, D., Herndlhofer, S., Firth, P., McKenna, J., Bingley, N., Jenson, P., 2014. Protecting asset value and driving performance with a dynamic, risk-based contingency fund. Environment Systems and Decisions 34, 417-424.10.1007/s10669-014-9508-3

MoE, 2001. Peraturan Pemerintah Nomor 82 Tahun 2001 tentang Pengelolaan kualitas air dan pengendalian pencemaran air (Government Regulation No. 82 on Water quality control and management) in: MoE (Ed.). The Government of Indonesia Secretary of State, Jakarta

MoE, 2003. Keputusan Menteri Negara Lingkungan Hidup Nomor : 115 Tahun 2003 Tentang Pedoman Penentuan Status Mutu Air (Ministrial's Decree No. 115 on Technical guidance for water class determination), in: MoE (Ed.), Jakarta

MONRE, 2008. National Technical Regulation on Surface Water Quality, in: Environment, M.o.N.R.a. (Ed.), QCVN 10:2008/BTNMT, Vietnam

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M., 2006. Assessing water quality in rivers with fuzzy inference systems: A case study. Environment International 32, 733-742.http://dx.doi.org/10.1016/j.envint.2006.03.009

OECD, 2008. Handbook on constructing composite indicators: methodology and user guide. OECD, France

Ouarda, T.B.M.J., Rasmussen, P.F., Bobée, B., Morin, J., 1996. Ontario Hydrometric Network Rationalization, Statistical Considerations, Research Report No. R-470. National Institute for Scientific Research, INRS-ETE, University of Quebec, Quebec, Canada, p. 75

Prati, L., Pavanello, R., Pesarin, F., 1971. Assessment of surface water quality by a single index of pollution. Water Research 5, 741-751.http://dx.doi.org/10.1016/0043-1354(71)90097-2

Prihandrijanti, M., Firdayati, M., 2011. Current Situation and Considerations of Domestic Wastewater Treatment Systems for Big Cities in Indonesia (Case Study: Surabaya and Bandung) Journal of Water Sustainability 1, 97-104

Qureshi, M.E., Harrison, S.R., 2003. Application of the analytic hierarchy process to riparian revegetation policy options. Small-scale Forest Economics, Management and Policy 2, 441-458.10.1007/s11842-003-0030-6

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw Hill. RWS Publications International, New York; Pittsburgh

Said, A., Stevens, D.K., Sehlke, G., 2004. An innovative index for evaluating water quality in streams. Environmental Management 34, 406-414

Sargaonkar, A., Deshpande, V., 2003. Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. Environmental Monitoring and Assessment 89, 43-67

Sarkar, C., Abbasi, S.A., 2006. Qualidex – A New Software for Generating Water Quality Indice. Environmental Monitoring and Assessment 119, 201-231.10.1007/s10661-005-9023-6

Semiromi, F.B., Hassani, A.H., Torabian, A., Karbassi, A.R., Lotfi, F.H., 2011. Evolution of a new surface water quality index for Karoon catchment in Iran. Water Science and Technology 64, 2483-2491.10.2166/wst.2011.780

Sinija, V.R., Mishra, H.N., 2011. Fuzzy analysis of sensory data for quality evaluation and ranking of instant green tea powder and granules. Food and Bioprocess Technology 4, 408-416

Smith, D.G., 1990. A better water quality indexing system for rivers and streams. Water Research 24, 1237-1244.http://dx.doi.org/10.1016/0043-1354(90)90047-A

Soliman, W.R., Ward, R.C., 1994. The Evolving Interface between Water Quality Management and Monitoring. Water International 19, 138-144.10.1080/02508069408686217

SRDD, 1976. Development of a water quality index. Scottish Research Development Department, Edinburg, UK, p. 61

Štambuk-Giljanović, N., 2003. Comparison of Dalmatian water evaluation indices. Water Environment Research 75, 388-405

Stoner, J.D., 1978. Water Quality Indices for Specific Water Uses, in: Interior, U.S.D.o.t. (Ed.). United States Department of the Interior, Arlington, VA 22202

Sutadian, A.D., Muttil, N., Yilmaz, A., Perera, C., 2015. Use of exploratory data analysis for cost effective monitoring of water quality data, 36 th Hydrology and Water Resources Symposium Hobart, Tasmania

Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2016. Development of river water quality indices—a review. Environmental Monitoring and Assessment 188:58.10.1007/s10661-015-5050-0

Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2017a. Parameter Selection for Cost Effective Water Quality Monitoring – Part 1: Developing the Methodology Journal of Environmental Management Under review (Unpublished results)

Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2017b. Parameter Selection for Cost Effective Water Quality Monitoring – Part II: Application to Monitoring Network in West Java, Indonesia. Journal of Environmental Management Under review (Unpublished results)

Sutadian, A.D., Muttil, N., Yilmaz, A.G., Perera, B.J.C., 2017c. Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index. Ecological Indicators 75, 220-133.http://dx.doi.org/10.1016/j.ecolind.2016.12.043

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, 15-21.http://dx.doi.org/10.1016/j.ecolecon.2011.12.009

Tallar, R.Y., Suen, J.-P., 2016. Aquaculture Water Quality Index: a low-cost index to accelerate aquaculture development in Indonesia. Aquaculture International 24, 295-312.10.1007/s10499-015-9926-3

Thi Minh Hanh, P., Sthiannopkao, S., The Ba, D., Kim, K., 2011. Development of Water Quality Indexes to Identify Pollutants in Vietnam's Surface Water. Journal of Environmental Engineering 137, 273-283.doi:10.1061/(ASCE)EE.1943-7870.0000314

USAID, 2006. Comparative Study Comparative Study Centralized Wastewater Treatment Plants In Indonesia, in: Program, E.S. (Ed.)

Walsh, P., Wheeler, W., 2012. Water Quality Index Aggregation and Cost Benefit Analysis. Working Papers # 12-05. United States Environmental Protection Agency, Washington DC

Walski, T.M., Parker, F.L., 1974. Consumers water quality index. ASCE J Environ Eng Div 100, 593-611

Weber, E.U., Shafir, S., Blais, A.-R., 2004. Predicting Risk Sensitivity in Humans and Lower Animals: Risk as Variance or Coefficient of Variation. Psychological Review 2, 430-445.http://dx.doi.org/10.1037/0033-295X.111.2.430

WHO, 2011. Guidelines for drinking water quality Fourth ed, Malta

WJEPA, 2014. Status Lingkungan Hidup Daerah Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia

WJEPA, 2015. Status Lingkungan Hidup Daerah Jawa Barat (The State of Environmental Report). Badan Pengelolaan Lingkungan Hidup Daerah Jawa Barat, Bandung, Indonesia

Chapter 6
Summary, Conclusions and Recommendations

6.1. Summary

The Water Quality Indices (WQIs) have been proposed as early as in 1965, to express the state of water quality, by aggregating the measured values of selected parameters. It aims to define the general status of river water quality in a simple form. Even though there are a few limitations of the use of the WQIs, considering the easiness of their use and the scientific basis, WQIs have become one of the most effective ways to communicate information about river water quality.

Several WQIs have been developed by different agencies and researchers with the aim to establish their own indices or improve the existing indices. However, no single WQI has been globally accepted. In West Java and other provinces in Indonesia, the use of WQIs were introduced in the early 1990s. Hence, there is a continuing interest to develop accurate WQIs that suit a local or regional area. To develop a WQI, a thorough review and comprehensive understanding on available WQIs is essential, as they will provide a strong basis that underpin the development of an index for a particular local or regional area.

In Chapter 1 of this thesis, the limitations of the currently used indices for rivers in West Java were reviewed with the aim of addressing these limitations in a new WQI for use in West Java. Three specific challenges need to be considered in the study area for developing its WQI, namely obtaining a uniform set of parameters, reducing the associated costs of monitoring, and the involvement of local expert's opinion. With the specific aim of reducing the associated costs of monitoring in the field significantly by obtaining a uniform set of parameters in a more cost effective manner, a new methodology for optimal selection of water quality parameters to be used in the development of a WQI was proposed and developed in this research. Therefore, this research aimed to develop a new index, which is called the West Java Water Quality Index (WJWQI), which not only addresses the limitations of the currently used indices in the study area, but also provides a more accurate comparison of the general status of water quality for rivers in West Java.

In Chapter 2 of this thesis, steps in the development of available WQIs were reviewed. The four steps to develop a WQI included the selection of parameters, method to obtain sub-index values, establishing weights and aggregation of sub-indices to produce the final index. The index developers might consider all the four steps or they could consider some of the steps.

In Chapter 2, seven WQIs (out of thirty reviewed WQIs) were identified as the most important based on their wider use. These seven WQIs were the Canadian Council of Ministers of the Environment (CCME) WQI, the National Sanitation Foundation (NSF) WQI, Oregon Index, Bascarón Index, House's Index, Scottish Research Development Department Index and Fuzzy-based indices. Chapter 2 also addressed the three specific challenges of this research (as discussed in Chapter 1) by reviewing 30 available WQIs and discussed them in light of the four steps that should be considered in the development of WQIs. Future directions for developing WQIs were also presented in this chapter.

Chapter 3 demonstrated one of the main tasks for developing WJWQI. To achieve the aim of the thesis outlined in Section 1.2 of Chapter 1, in the third chapter, a new methodology using an enhancement of statistical assessment for parameter redundancy and the use of three critical factors (based on the cost of the laboratory analysis of parameters, and the magnitude and frequency of the parameters exceeding their permissible limits) was presented. This methodology was then demonstrated for a case study based on monitoring stations located at rivers across the West Java Province, Indonesia. This case study was used to answer the first-two specific challenges for developing WJWQI, which were regarding obtaining a uniform set of parameters and reducing the associated costs of monitoring. Through application of the proposed methodology as demonstrated in Chapter 3, a uniform set of parameters for use across the study area was developed. This uniform set of parameters was then used in the further steps to develop the WJWQI.

In Chapter 4, weighs of the uniform set of parameters were sought through application of Analytical Hierarchal Process (AHP). In this study, two different AHPs models were developed. The first AHP model was based on individual parameters and it involved one level of hierarchy to describe the goal of this study. On the other hand, the second AHP model was based on grouping of parameters in structuring its hierarchy and it comprised of two levels of hierarchy in order to obtain the weights. A pool of respondents from West Java Province with different backgrounds (grouped into government officials, academics, researchers and consultants) were surveyed to give their judgements. Only those respondents whose judgements were consistent were used for the further analysis to obtain the weights. Chapter 4 was used to address the third specific challenge in the study area with respect to the involvement of local experts' opinion in the development of WJWQI. Therefore, the application of AHP to estimate the parameter weights was an important step for developing a WQI for rivers in West Java.

Once the uniform set of parameters were identified, thresholds of the parameters were sought from the legislated water quality standards of Indonesia. If such thresholds were not available, thresholds that have been widely used globally were adopted. These thresholds were used to establish the sub-index functions to transform all parameters into a common scale. In Chapter 5, these thresholds of parameters, along with weights of parameters obtained through application of AHP (as discussed in Chapter 4), was finalised into the development of WJWQI. The geometric aggregation method was then applied to aggregate the sub-index values across all monitoring stations located along the seven main rivers in the study area. The application of WJWQI will provide more accurate and valuable information regarding the status of water quality in the rivers of West Java. It will also allow comparison of water quality spatially across rivers and also temporally, as the same set of parameters were employed to compute the final index values. In each monitoring station at rivers across the study area, the following information was obtained:

1) Sub-index values of parameters
2) Aggregated index value
3) Interpretation of the index value

In Chapter 5, the robustness analysis of WJWQI was undertaken by performing uncertainty and sensitivity analysis of the index based on the measurement at station CTM7. This monitoring station was selected because it was the most critical station in terms of water quality, and it had relatively higher variability when compared to the other stations. There were 5 water samples used for the uncertainty and sensitivity analysis from the year 2003 (which was the year with the worst water quality). In this study, the uncertainties in relation to the selection of threshold values for obtaining sub-index values and parameter weights were addressed through the uncertainty and sensitivity analysis.

6.2. Conclusions

In conclusion, this thesis has demonstrated the development of a new water quality index, which is called the West Java Water Quality Index (WJWQI) for rivers in West Java, Indonesia, as per the research aims stated in Section 1.2 of Chapter 1. The WJWQI considered three specific challenges in the study area, namely obtaining a uniform set of parameters, reducing the associated costs of monitoring, and the involvement of local expert's opinion. Thus, the index was expected to not only address limitations of the currently used indices in the study area, but also provide more accurate comparison on the general status of water quality for rivers in West Java in a more cost effective manner. This thesis was also able to achieve all specific aims outlined in Section 1.2.

The following sub-sections present the major conclusions drawn from this study. They are presented under different headings, namely parameters selection for cost effective monitoring, the use of AHP for parameter weights, applications of WJWQI, and robustness of the index performing uncertainty and sensitivity analysis of WJWQI.

6.2.1. Parameters selection for cost effective monitoring

In Chapter 3, a new methodology for parameters selection for parameter redundancy, leading to a cost effective monitoring of the parameters was developed. To select most significant parameters for cost effective water quality monitoring, the number of selected parameters should be kept to a minimum and potentially be representative of a larger list or grouping of parameters. Thus, the exclusion of redundant parameters without losing important information in representing the surface water quality is important. In this study, the proposed methodology for parameter redundancy provided a novel contribution to the previous WQIs studies.

The methodology consisted of three sequential steps, namely screening, the statistical assessment for parameters redundancy and the inclusion of three critical factors (based on cost of the laboratory analysis of the parameters and magnitude and frequency of the parameter exceeding its permissible limits), and identifying a uniform set of common parameters across all stations. An enhanced performance consolidated index was also developed to identify the best combination of parameters to be continued and discontinued to be monitored at each monitoring station.

Through the statistical assessment of parameter redundancy and the inclusion of three factors that represented criticality for cost effective monitoring used in the parameter selection stage for WJWQI, it was found that 13 parameters will be adequate to be "basic parameters" needed to monitor water quality of rivers in West Java, as they collectively are representative of water quality of these rivers. Those 13 parameters were temperature, suspended solids, chemical oxygen demand, dissolved oxygen, nitrite, total phosphate, detergent, phenol, chloride, zinc, lead, mercury, and faecal coliform.

6.2.2. The use of AHP for parameter weights

As in the previous applications of AHP technique in various fields of study, the AHP used in this study has provided numerous benefits when it was used to establish weights of a uniform set of parameters of WJWQI. The main benefit from the use of AHP technique in this study was that the AHP is easy to use due to the use of pairwise comparisons, and it even enables to quantify both the experts' objective and subjective judgments in order to determine relative weight of each parameter. More importantly, it does not require large amount of time and several rounds of questionnaires, compared to other participatory based-techniques used to identify parameter weights. This has resulted in an effective utilisation of time in the overall management of this study. Hence, the AHP is an attractive tool that can be used to establish weights of different water quality parameters. In this study, faecal coliform, dissolved oxygen, and chemical oxygen demand received high weights, when compared to that of the other parameters. Once these weights were obtained, as demonstrated in Chapter 4, further steps were undertaken towards the development of the WJWQI.

6.2.3. Applications of WJWQI

Applications of WJWQI using monitoring data provide more accurate and valuable information about the status of water quality in rivers and also allow valid comparison across stations and rivers as the same parameters were employed to compute the final index values. The results of applications of WJWQI showed that most of monitoring stations had marginal water quality (the final index values were between 25 and 50), indicating that rivers along West Java have been experiencing water quality deterioration significantly. It was not surprising that the status of water quality across main rivers in the study area tended towards marginal water quality because of growing quantities of untreated residential and industrial wastewater being dumped into the rivers.

It can be also concluded that the comparison of the application of WJWQI to different rivers undertaken in this study was able to identify that Citarum River (stations CTM3 – CTM7), Cileungsi River (stations CL, 5, CL7, CL8), and Cilamaya River (stations CL2 – CL3) had more critical events of poor water quality as compared to the other rivers. Thus, these three rivers should have higher priority, particularly in implementing comprehensive measures to reduce pollutants, which contributed significantly to the pollution of these rivers.

6.2.4. Uncertainty and Sensitivity of WJWQI

There is a lot of subjectivity and uncertainty involved in the steps for developing and applying a WQI. Therefore, minimizing subjectivity and uncertainty should be included as one of the steps in the development of a WQI. The uncertainty analysis of the index, undertaken in this study, was able to identify the sources of uncertainty in developing WJWQI. This included how the uncertainty of parameter thresholds and parameter weights propagated into the final index value. The uncertainty and sensitivity analysis was based on its application to the most critical station (which was station CTM7 in Citarum River) and the analysis indicated that all thresholds and weights of WJWQI parameters had low variability. This indicated lower uncertainties of both thresholds and weights of WJWQI.

This uncertainty and sensitivity analysis used the Monte Carlo (MC) simulation approach. The results of the uncertainty and sensitivity analysis for parameter thresholds and parameter weights, as shown by their coefficient of variation (CV) indicated that the relatively higher variability of parameter thresholds and parameter weights have not propagated to the final index values and the final index values have low uncertainty. The uncertainty and sensitivity analysis through the MC simulation also showed that changes in thresholds and weights did not result in any changes in the water quality status. Therefore, it can be concluded that the WJWQI is robust, and hence the relevant authorities in West Java and the users of WJWQI will be able to use it for evaluating the general status of river water quality confidently.

6.3. Recommendations

The following sub-sections present two sets of recommendations drawn from this study, namely recommendations for further research and recommendations for the practical application of the knowledge created in this research.

6.3.1. Recommendations for further research

It is worth mentioning that this water quality index, particularly the methodology developed for parameter selection has the potential for use in other provinces in Indonesia or in other countries. Therefore, the index users in other provinces or countries might consider developing a uniform set of parameters as was demonstrated in this study through the case study of main rivers of West Java. In addition, considering the importance of local experts’ opinion in the steps in the development of a WQI is also important to ensure that the review on parameter weights is undertaken through the involvement of relevant water quality-related stakeholders.

Another area for improvement of the study was identified during the application of parameters selection for cost effective monitoring. In this study, the proposed methodology was only applied in monitoring stations which had the required water quality data. As consequence, only stations and parameters which had a minimum number of consecutive years of monitoring data were selected in this study. In future applications, screening and identification of the parameters that are recommended to be continuously monitored and those to be discontinued should be re-undertaken regularly using longer time series of water quality data. The longer time series of water quality data will allow the index developers and users to have a more reliable set of parameters.

In similar studies, additional criteria for critical factors can be included through involvement of local experts' opinion. If it is considered in the future, the AHP can be also used to define additional critical factors. The survey using AHP for obtaining the weights (as was done in this study) can also include questions on critical factors as part of the questionnaire. Thus, combining the survey on additional critical factors through local experts' opinion with that for weights would result in more effective time management.

With regards to uncertainty and sensitivity analysis, in this study, only two sources of uncertainties were considered, which were due to the range of possibilities for parameter thresholds and weights. In similar future studies, the uncertainty and sensitivity analysis due to other uncertainties, such as selection of different aggregation methods and using different weighting methods, can be also undertaken. With respect to uncertainty due to parameters selection, the proposed methodology used in this study to define the WJWQI parameters was expected to remove uncertainties in the selection of parameters. However, since the criteria associated with the percentage value used to identify a uniform set of parameters involved in the development of the WQI was somewhat subjective, the index developers or water authorities can decide this criteria based on their preferences or their own studies. Therefore, uncertainty and sensitivity of this criteria can be also undertaken in the future.

6.3.2. Recommendations for practical implementation

The water authorities in West Java can be benefited from the development of WJWQI and the results of its application since the WJWQI provides a more accurate comparison of the general status of river water quality in a more cost effective manner (when compared to the currently used WQIs in West Java). Thus, the comparison of the general status of water quality in monitoring stations, located along the main rivers can be used by the provincial government of West Java to improve their water quality management programs. It can also be used as a better starting point to establish important measures for improving water quality in the rivers of West Java.

Results from the application of WJWQI have provided information on the general status of water quality, spatially and temporally. The application of WJWQI in this study can also be used to identify rivers that need higher priorities, to communicate the water quality in respective rivers among scientists, decision-makers, and the general public and to propose relevant programs to the water authorities. Appropriate programmes can then be designed to improve the water quality of rivers throughout the province.

The applications of WJWQI have also indicated that the final index values for most of the rivers had either poor or marginal water quality status due to faecal coliform contamination, which in turn indicates a failure or a less coverage of residential and industrial wastewater treatment. Therefore, urgent intermediate measures, such providing improved wastewater treatment either on site or off site, particularly for sources of this pollutant are needed to improve river water quality across the study area.

Finally, it is important to note that WQIs have also been considered as a pivotal component or indicators of the wider environmental or natural resource indices. In the study area of West Java, there is another index, which is the West Java Water Sustainability Index that has been developed earlier than the WJWQI. The West Java Water Sustainability Index is used as a tool to improve the water resources management in West Java in a more wider and general way. One of the indicators of the West Java Water Sustainability Index is water quality computed through the calculation of water quality index using the currently used indices. Since the WJWQI provides more accurate results in a more cost effective manner (when compared to the currently used indices for the study area), it is recommended that the WJWQI can be used to replace the currently used water quality indices in West Java. Accordingly, it can be used as one of the indicators of the West Java Water Sustainability Index in future applications.

References

The following references are cited in the body text of Chapter 3. Remaining references are cited within the papers in each chapter.

Brown, R. M., N. I. Mc Clelland, R. A. Deininger, and R. G. Tozer. 1970. A water quality index-Do we dare? Water and Sewage Works 117:339-343.

Cude, C. G. 2001. Oregon water quality index a tool for evaluating water quality management effectiveness. JAWRA Journal of the American Water Resources Association 37:125-137.

Dunnette, D. A. 1979. A Geographically Variable Water Quality Index Used in Oregon. Journal Water Pollution Control Federation 51:53-61.

Hurley, T., R. Sadiq, and A. Mazumder. 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Research 46:3544-3552.

Kannel, P. R., S. Lee, Y. S. Lee, S. R. Kanel, and S. P. Khan. 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environmental Monitoring and Assessment 132:93-110.

Liou, S. M., S. L. Lo, and S. H. Wang. 2004. A generalized water quality index for Taiwan. Environmental Monitoring and Assessment 96:35-52.

Said, A., D. K. Stevens, and G. Sehlke. 2004. An innovative index for evaluating water quality in streams. Environmental Management 34:406-414.

Thi Minh Hanh, P., S. Sthiannopkao, D. The Ba, and K. Kim. 2011. Development of Water Quality Indexes to Identify Pollutants in Vietnam’s Surface Water. Journal of Environmental Engineering 137:273-283.